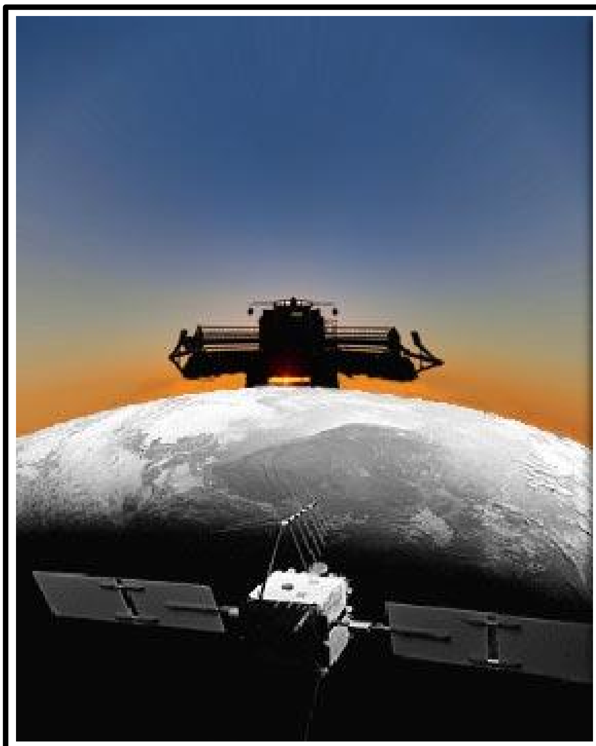
Australian Centre for Precision Agriculture

PRECISION AGRICULTURE

An Introduction to Concepts, Analysis & Interpretation



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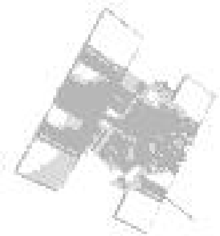


TOPICS

Ageneral inroduction to Precision Agriculture and the underlying philosophy

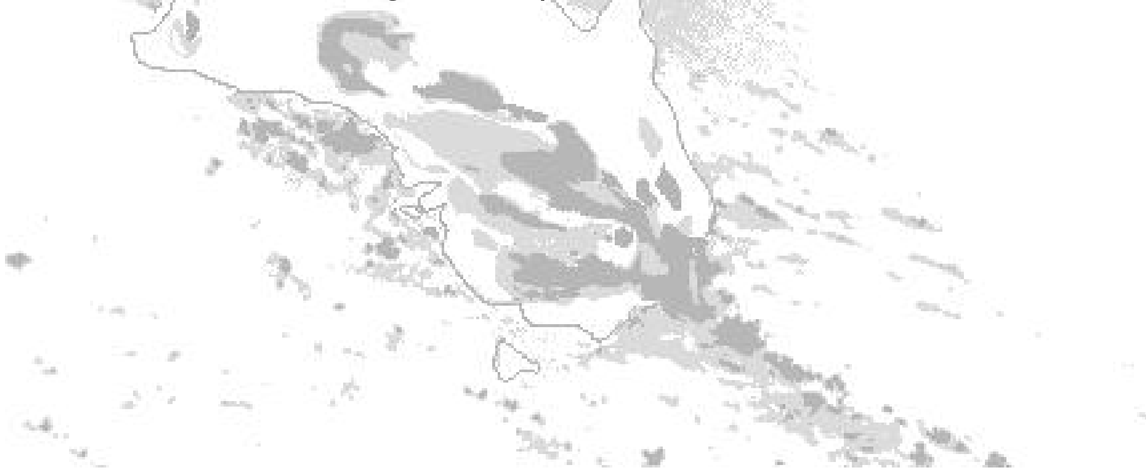
Global Navigation Satellite System operation theory and implications for farming applications

The spatial variability in soil and crop attributes

Yield monitor development, operation and accuracy

A look at the current methods for yield and soil map production

PA management options



1

Precision Agriculture

Information is an economic necessity in any productive industry. The technology is now becoming available to monitor agricultural input/output at an increasingly detailed level. At present, it is necessary to gather data on output to characterise the variability that may be expected over space and time. Understanding the causes will be more difficult at this scale and require committed research from the agricultural industry and improvements in soil sampling and analysis technology. Ultimately, these will be available but the impact of Precision Agriculture in Australia will depend on ensuring only suitable techniques are adopted within a fertile research, educational and political framework.

As farm machinery has increased in size, there has been a tendency to treat individual paddocks as uniform in respect to important yield controlling factors such as soil physical condition and nutrition. This is basically known as operating under an increasing economy of scale – bigger, faster, and cheaper per hectare. To make this feasible, an increase in farming area or more profitable ways of utilising the time saved using this machinery is required. Now however, farmers and the wider rural and urban communities are thinking a little harder about this practice of managing agriculturally productive land as uniform across each field. It is now being argued that such practices could lead to a poor use of resources (fertilisers, pesticides, fuel) and subsequently impose financial, environmental and social costs. The significance of these costs (such as input waste, yield reduction and soil, water and air contamination) to whole farming systems has only recently received serious consideration.

What is Precision Agriculture?

This concern is encompassed in the philosophy of Precision Agriculture. In general the term refers to a process of observing the variation in the controlling factors of an agricultural production process, assessing the problems that may be caused, and then providing timely and targeted treatments. This philosophy may be eventually applied to many agricultural industries, for helping farmers manage both quantity and quality of product.

The form of Precision Agriculture that relates to crop management is often termed Site-Specific Crop Management (SSCM). It relies on matching resource application and agronomic practices with the variation in soil attributes and crop requirements across a paddock. This sort of treatment is known as the 'differential' treatment of field variation, as opposed to the 'uniform' treatment that underlies the traditional agricultural management systems. The simple rationale that justifies and supports SSCM is founded on both financial and biophysical levels (Figure 1-1).

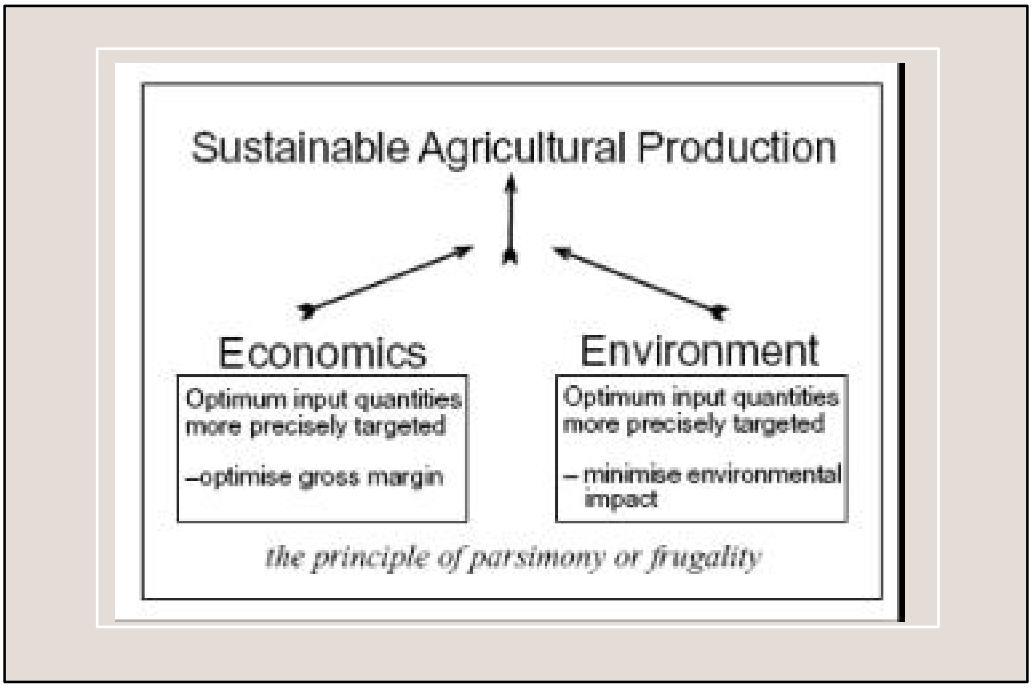


Figure 1-1. The economic-environmental basis for a site-specific management system.

Precision Agriculture

an integrated information- and production-based farming system that is designed to increase long term, site-specific and whole farm production efficiency, productivity and profitability while minimizing unintended impacts on wildlife and the environment.

Site-Specific Crop Management (SSCM)

A form of PA whereby decisions on resource application and agronomic practices are improved to better match soil and crop requirements as they vary in the field.

How might Precision Agriculture work?

In economic terms, the precise calculation and placement of input resources suggests a more efficient and profitable use of enterprise resources. Figure 1-2 depicts the generalised gains that may be achieved through targeting resources to the most responsive areas within a field without necessarily increasing resources. If the mean field treatment is aimed at the optimum economic application for response 1, then areas of the field characterised by response 2 will be underachieving.

By reallocating enough resources (DA) to achieve optimal application in areas characterised by response 2, the yield gain (DY_2) is greater than the yield loss (DY_1). This is likely to be the most simplistic form of SSCM but serves to demonstrate the basic principle. It is important however, to acknowledge that such gains require a suitably detailed knowledge of the within-field variability in response to an action.

From an environmental point of view, this precision may offer the prospect of reducing the environmental risk associated with blanket field treatments and provide the ability to work with the natural diversity within each field. By more closely aligning yield goals to the variation in yield potential induced by natural and anthropogenic diversity, it may be possible to improve the sustainability of modern farming systems.

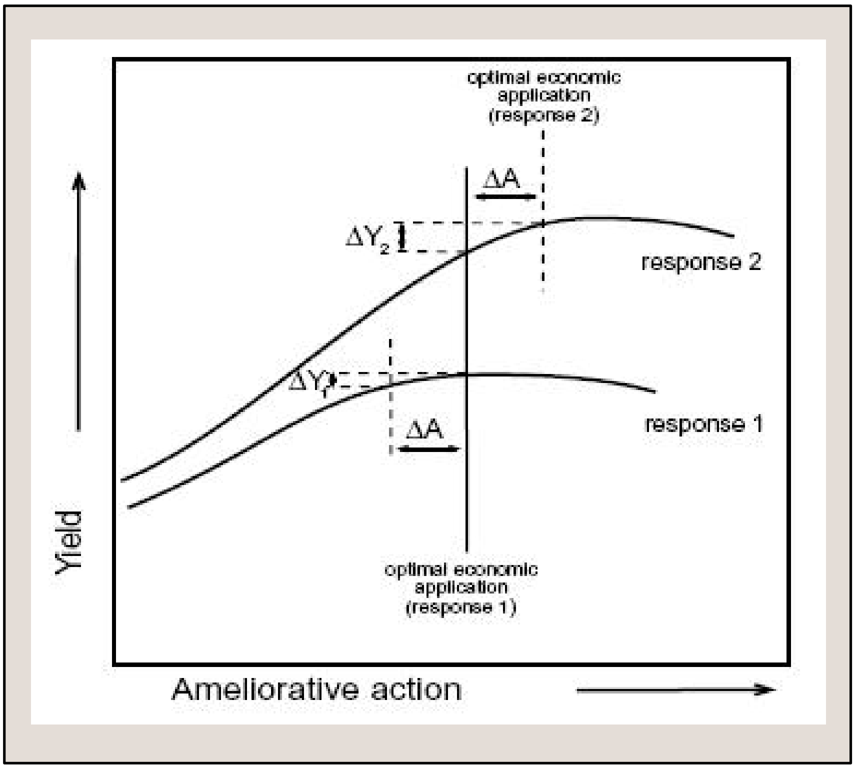


Figure 1-2. Generalised production impetus for site-specific management.

Components of a Site-Specific Crop Management System

There are 5 components to consider in the development of a Site-Specific Crop Management system (Figure 1-3). Because the complete process cannot be made in a single pass of the field, the site-specificity is made possible, and indeed relies upon, the ability to accurately resolve ground position during all facets of field operation. The remaining components of the system operate in a cyclical fashion.

Influential factors effecting crop yield, along with the crop yield itself, must be monitored at a fine-scale and maps of variation in these factors for an entire field subsequently constructed. The degree of variability across a paddock will determine whether different treatment is warranted in certain parts of the paddock. Linking the variation seen in crop yield with the measured factors influencing crop yield can be done using suitable modelling procedures. Armed with this information it may then be possible to devise treatment strategies that are agronomically sensible. If these treatment strategies suggest that differential management is warranted, operations such as fertiliser, lime and pesticide application, tillage, sowing rate etc. may then be varied in real-time across a paddock using available technology.

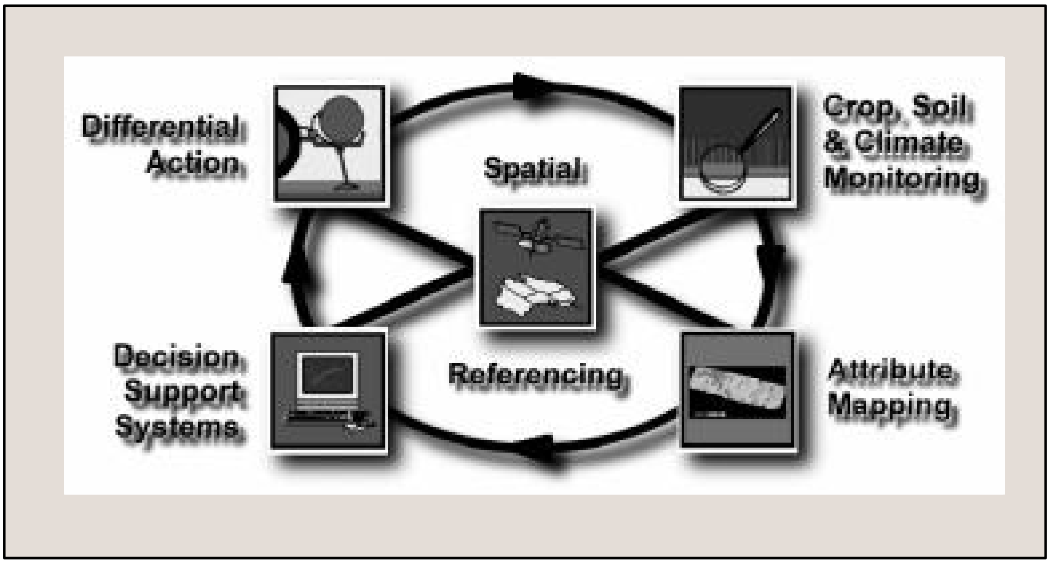


Figure 1-3. Components of a site-specific crop management (SSCM) system.

Development of the SSCM System

These components are at different stages of development and implementation. The technology required to gather detailed data and enact a differential treatment leads the agricultural science of deciphering and formulating responses to the information obtained. Preliminary research provides evidence that yield can vary widely within a field and that the spatial pattern of this variation may change over time. This reflects interactions between influential field attributes and also between these attributes and the environment. Identifying a significantly yield limiting factor in one year may have limited bearing on the next growing season if its influence is considered singularly.

At present, it is necessary to gather data to characterise the small-scale variability that may be expected over space and time. Research is required to ensure the data gathered is representative of the true variation at this scale, to provide insights into it's implications and use, and to maximise the benefits obtained for agricultural farm management. We will examine these aspects breifly in the following chapters.

2

Global Navigation Satellite Systems

Global navigation satellite systems are truely the enabling technology of Precision Agriculture. They provide a relatively simple and robust technique for identifying any location on the earth's surface, or, in the case of aircraft, relative to the surface. Until it is possible to sense, assess and respond to within-field variability during a single pass of the field, Site-Specific Crop Management will rely heavily on the location and navigation opportunities provided by these systems.

Two systems have been developed. The NAVSTAR Global Positioning System (GPS) is owned by the government of the United States of America, and the Global Navigation Satellite System (GLONASS) is controlled by a consortium headed by the Russian Government. Both systems are built using a space segment comprising a constellation of dedicated satellites, a control segment that monitors, manoeuvres and updates information to the satellites, and a user segment trying to determine accurate ground position. The systems are basically similar however far more receivers have been developed by commercial enterprises to utilise the information from the GPS satellites so its operation will form the basis of the following review.

GPS Operation

In basic terms a GPS user's position is determined by resection using the distances measured to the satellites. There are three techniques for calculating these distances based on information provided on two transmission frequencies from the satellites. These techniques are known as C/A - code (Coarse/Aquistion), P-code (Precision) and Codeless. The C/A-code technique is also known as the

Standard Positioning Service (SPS) and is available for all civilian use and is most commonly used in PA. The P-code technique is reserved for military use and the Codeless techniques require more sophisticated and expensive recievers. With the C/A-code technique distances are estimated by measuring the travel time of a coded signal from each satellite and multplying it by the transmission velocity (the speed of light). The information coded onto the signal includes satellite orbit, current position and time information. The time information is provided by four extremely accurate atomic clocks on-board the satellites.

The distance to four satellites must be instantaneously determined by a user's receiver (remote reciever) in order to obtain a point position in latitude, longitude and elevation . One satellite each is required for resolving latitude, longitude and elevation and the fourth is required to determine errors between the satellite and receiver time pieces. This 4th measurement greatly improves the measurement accuracy and allows comparitively cheap time pieces to be used in the recievers. Given that the travel time of the signal to the reciever is about 0.07 seconds, the clocks must still be capable of accurately measuring small time periods.

GPS Accuracy

Selective Availability

The GPS satellites are currently controlled by the U.S. Department of Defense who have the ability to regulate the quality of information available to civilian users. This regulation, known as 'selective availability' (SA), is initiated by dithering the satellite clock and position information that is included in the coded signals available to non-military users. A reduction in the accuracy of satellite distance determination and therefore remote receiver position results. This is especially the case in the 'stand-alone' mode of operation whereby a ground position is calculated using a single receiver that tracks and obtains data from the satellites. The specified accuracy with SA has a 95% confidence interval of ±100 metres (m). Without SA the 95% confidence intervals are 3-35 m.

However, on May 1, 2000 , the President of the USA (and Commander-in-Chief of the US Armed Forces) decreed that SA would be removed from the civilian signal.Figure 2-1 shows a time series of the horizontal and vertical errors experienced by a high quality GPS as the SA switch was turned off on May 2, 2000. However, as can be seen, the 'stand-alone' positioning without SA will remain outside the ±1 to 2 metre accuracy desired for most Precision Agriculture operations.

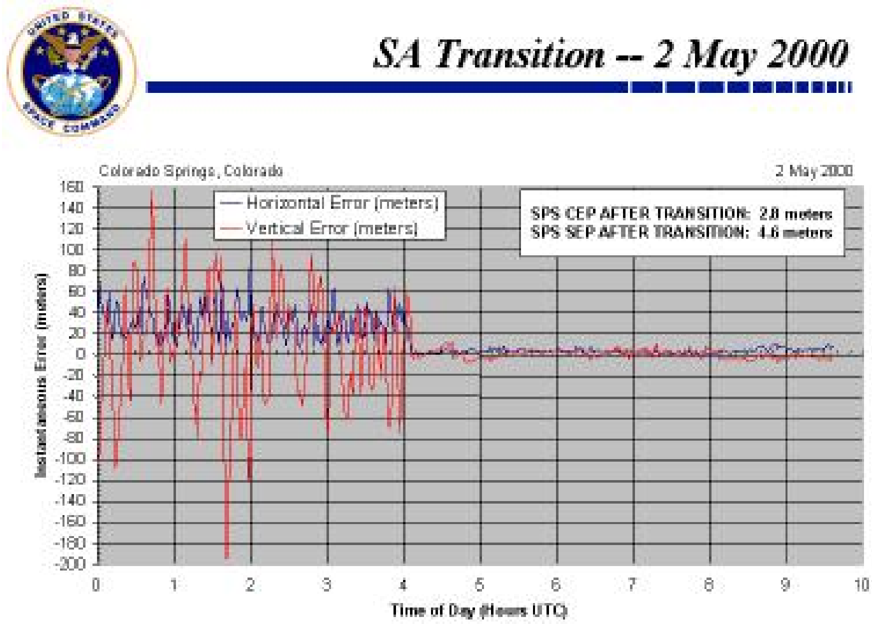


Figure 2-1. Operational configuration of a real-time Differential GPS (DGPS).

DGPS

This remaining error can be reduced by the Differential GPS (DGPS) operational mode. This requires at least one other reciever located at a previously surveyed location and calculating the position discrepancy between the GPS calculation and the known location.

There are now numerous DGPS receivers commercially available with manufacturer reported accuracy of ± 1.0m (2 □ RMSE). This performance will be conditional on receiver specification and will be location and time dependent.

As an example, Figure 2-6 shows a surveyor's trigonometric point (where the exact location is known to within 0.001 m) which has been monitored once per second over a 2 minute period. The results show that in the dGPS mode, accuracy reaches the sub-metre level (mean = 15cm east/4cm south) with a precision of 1 metre (97cm 2RMS). These results are only a guide to the quality of position determination as the error budget for the system varies with time as earlier discussed.

In general, the code-based pseudorange DGPS method of position determination would appear to adequately fulfil the requirements for monitoring crop yield and possibly directing spray operations. It is not yet suitable for accurate spray overlap control, vehicular guidance or digital terrain modelling. The more expensive carrier

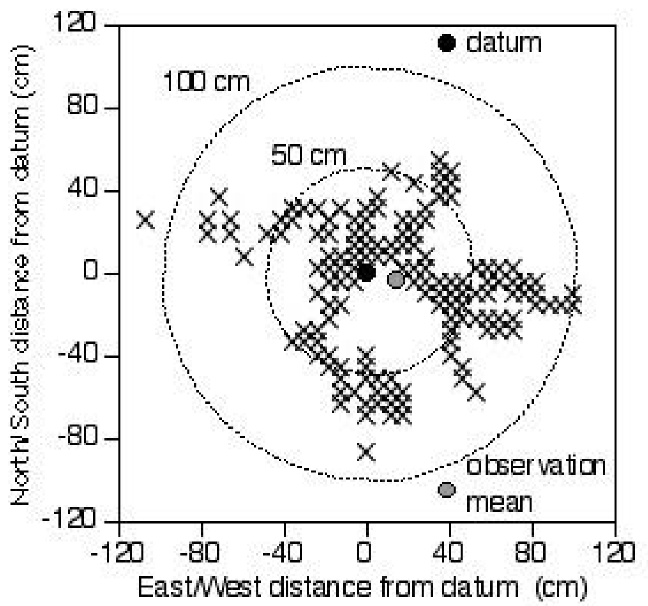


Figure 2-6. dGPS accuracy and precision determination from 100 observations at a known trigonometric station.

phase DGPS which have been shown to produce centimetre level accuracy and precision should be employed for these tasks.

DEVELOPMENTS

It is now possible to combine the GPS and GLONASS systems to increase the number of satellites visible at one time and improve reliability and accuracy. GLONASS may bring a number of benefits such as a constant and more easily modelled bias because S/A is not imposed and a higher satellite inclination (65 deg compared to 55 deg) which improves satellite visibility. The European Union is now wavering on the development a competing satellite navigation system called Galileo.

The correction signal providers are also continually working towards higher accuracy in the service they provide. The John Deere Starfire system offers 3 levels of correction signal, the optimum service providing decimetre level correction. Omnistar have also just released a system called Omnistar HP which offers a decimetre level correction. The GPS receiver manufacturers will also be continuing to reduce the cost of the higher accuracy carrier phase systems. With S/A disabled, the access to greater accuracy using the cheaper recievers should see a proliferation in use and a comensurate decrease in the cost for code and carrier phase systems alike. Satellite-based systems for location and navigation are here to stay.

3 Within-Field Variability

The successful implementation of Precision Agriculture will be dependent on the ability of individual growers to differentially manage their crops to achieve the twin goals of maximising yield or profit whilst simultaneously minimising environmental impact. The major obstacle to this is the lack of, and uncertainty in, local information. That is, information pertaining to the spatial and temporal variation in crop yield and soil attributes.

The importance of such information is not a recent concept. It has been a long held and widely identified idea that field heterogeneity in influential cropping system components will affect crop yield. At the regional scale, the variation in crop yield can be considered the consequence of variability in the interaction between crop genetics and environmental factors. However, at the field scale, site-specific variation in soil type/texture, soil structural integrity, soil moisture content and soil nutrient chemistry will significantly contribute to the spatial variability in crop yield.

The variability in these soil attributes (and therefore crop production potential) displayed at a given site, at a given time, is in turn controlled by a number of important processes. The most important of these are the soil forming processes that define the soil type and govern the majority of the fixed soil properties e.g. texture, horizon colour and cation exchange capacity. Other effects on the variability of soil attributes are contributed by soil management practices and cropping systems. These can greatly change the more dynamic soil properties such as nutrient, water, air and solute regimes. The amount of variability is generally lower in the fixed (e.g. soil texture) compared with the dynamic properties (e.g. soil nitrate). Variation in crop yield at the within-field scale is also a known to be influenced by crop insect pests, diseases and weeds, which may all reduce yield significantly.

Quantification of Variability

While within-field variability of soil attributes, crop pest infestations and the resultant crop yield is obvious, the magnitude varies with attribute, location and time. Table 3-1 lists median CV values which may be taken as a general, simple guide to the magnitude of variation that may be expected at the within-field scale. These may possibly be used as a basic benchmark for variability at this scale.

Offering a more comprehensive view of the spatial variability in a number of these attributes are the figures in Table 3-2. They may also be considered as generalised representations of expected variability at the within-field scale and could be used as surrogates for the parameters in unsampled fields or initial estimates in modelling procedures. The provision of a spatially dependent range (*a*) may also prove useful in establishing the sample spacing for initial sampling schemes in unsampled fields. With the exception of soil moisture, these figures tend to suggest a sample spacing of approximately 60m as a maximum required to accurately capture the spatial variability in most soil attributes with one soil sample.

Attribute		Median CV (%)
Soil Texture	Sand	37
	Silt	18
	Clay	18
Soil Structure	Bulk density	5
Soil O.M.		18
Soil Moisture	θg	11
	θv	9
Soil Nutrients	N	38
	P	38
	K	23
Soil pH		5
Crop Yield		14

Table 3-1. Median CV values for important soil /crop system attributes.

	Median Variogram Parameters				
Attribute	C0	C	C0 + C	a (m)	spatial structure
Soil Texture ($\%^2$)	2.4	9.3	11.7	63	strong
Soil Moisture ($\%^2$)	0.00049	0.00045	0.00094	22	moderate
Soil Nitrogen (mg/kg^2)	1.2	2.0	3.2	117	moderate/strong
Soil Phosphorus (mg/kg^2)	26.9	11.0	37.9	180	moderate/weak
Soil Potassium (mg/kg^2)	887	391	1278	157	moderate/weak
Soil pH ($units^2$)	0.021	0.15	0.171	105	strong
Crop Yield (t/ha^2)	0.37	0.63	1.0	83	moderate/strong

Table 3-2. Median semivariogram model parameters for important soil /crop system attributes.

This degree of spatial variability and the spatially dependent ranges suggested that management at the 1m to 100m unit scale is potentially useful. Always with the proviso that attributes that display a moderate to weak spatial structure will prove more difficult to compartmentalise or classify into homogenous management units.

Importantly, the variation in attributes of the soil–crop system highlighted here may give rise to economic, environmental and societal problems on cropping enterprises under traditional 'uniform' management. In general, the problems as summarised in Table 3-3, arise from a decision to use 'mean-of-field' information to guide the amelioration of an area which may result in zones being under- or over- treated.

For the majority of impacts listed in Table 3-3, the implications are obvious and require no further elaboration. The significance of excess denitrification products provides an exception. In areas with soil nitrogen levels above crop requirements, there is a greater opportunity for the excess nitrogen to result in increased production of nitrous oxide (N_2O) through the denitrification process. N_2O release is believed to contribute to the global greenhouse effect and is instrumental in the breakdown of stratospheric ozone.

Attribute	Economical y Significant Yield Loss	Excess Fertiliser Cost	Excess Fertilisers in Tailwater or Groundwater	Excess Denitrification Products	Excess Pesticide Cost	Excess Pesticide in Tailwater or Groundwater	Pesticide Residues in Soil
Soil Type / Texture	√	√	√	√	√	√	√
Soil Structure	√	√	√	√	√	√	
Soil O.M %	√	√	√	√	√	√	√
Soil Moisture	√	√	√	√		√	
Soil Nutrients	√	√	√	√			
Soil pH	√	√	√	√			
Pest Infestations	√				√	√	√

Table 3-3. Problems associated with not treating spatial variation in influential soil/crop system components.

At present, the problems of input resource waste and failure to attain optimum yield remain economic dilemmas of the individual producer. Escaped fertiliser and pesticide, along with contamination of follow-on enterprises with residual pesticides, has entered the public domain. Legislation has been foreshadowed on the right to use and apply chemicals, and on containment strategies to reduce the contamination of waterways and food chains. Failure to comply will undoubtedly bring another economic dilemma for the individual producer.

Technology is now becoming available to tackle the operational difficulties inherent in the problems raised by spatial variability. Providing further impetus is the now greater general awareness of the natural boundaries limiting resource requirements, availability and application. Given that the documented variability points to the conclusion that a much finer delineation of homogeneity in management units is required than presently utilised, it may therefore be efficacious to attempt to account for, and operate with, spatial variation as the solution to the potential problems of soil spatial variability.

4

Gathering Information for Precision Agriculture

Variability exists in the major components of crop production systems. It would appear that the scale of spatial variation in crop yield is critically dependent on the scale of spatial variation in significant field-based factors that contribute to crop yield. This interrelationship has tended to be overlooked by farm managers as operational logistics enticed them towards larger field sizes. This in turn makes it is entirely feasible that the incorporation of more variability within each field may have occurred. Precision Agriculture aims to identify and optimally treat this spatial variability.

With the advent of tools such as the differential Global Positioning System (DGPS), Geographical Information Systems (GIS), and miniaturised computer components there is now an increasing interest in, and quantification of, the variability in soil attributes, crop yields, pest infestations and climatic factors. These tools allow agricultural enterprises to gather more comprehensive data on this production variability in both space and time and has fostered a new attempt to understand and manage the variation at the within-field scale.

The desire, and ability, to monitor and respond to variation on a fine-scale is the goal of Precision Agriculture. This desire has both an economical and environmental basis. Matching inputs to crop and soil requirements as they vary within a field should improve the efficiency of resource use and minimise adverse environmental impact.

At present, monitoring and mapping the spatial variation in small-grain crop yields is receiving much publicity in Australia. Yield mapping is only one component of a

Precision Agriculture system and small-grains is not the only enterprise to embrace the ideas. Crop yield monitors are also available for cotton, potato, peanut, sugarcane and forage harvesters and are under development for a range of horticultural crops.

Achieving the operational harmony called for in a site-specific crop management system will require a holistic approach to describing, and delineating suitable responses to, the spatial variation found in the influential components of a cropping system. A union of data acquisition operations, information processing and decision formulation procedures would be necessary to successfully complete this process. Ideally, for many ameliorative operations the whole process would be undertaken in 'real-time' as depicted in Figure 4-1, however many technological and agronomic barriers remain.

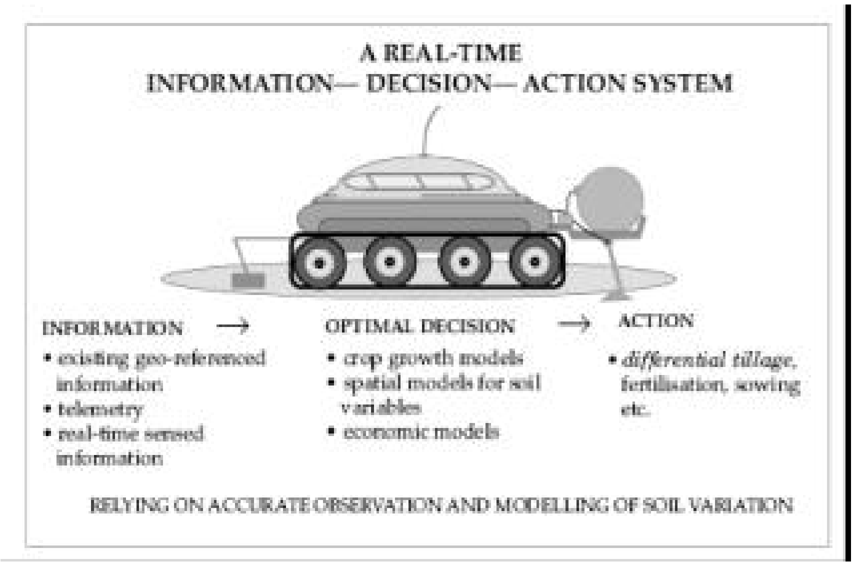


Figure 4-1. A proposed real-time system linking information acquisition, decision making and action operations.

Collecting Data On Spatial Variability

A critical requirement for collecting data on the spatial variation in any land-based attribute is an ability to accurately resolve ground positions in the field. All data must be geo-referenced so that a representative field map may be built and for the purpose of correlating the information on various attributes obtained from a field.

Attribute Observation Strategies

Some data on soil and crop variability may already be available. Regional soil maps are compiled from coarse-scale survey information but may be useful as an initial indication of the soil variation to be expected on a farm level. Soil sampling and testing that may have been carried out in previous years would also provide useful data on temporal variation and soil response to treatment strategies.

Discrete Sampling

Field observation has been traditionally based on discrete sampling procedures using either a grid-based or statistically based random sampling strategy. Sampling by grid is at present a laborious procedure if large areas are to be tested. For the production of accurate maps, the appropriate sampling scheme and minimum lag must be determined. The inherent variability expected in most attributes would suggest the principal sampling distance should be as small as possible. This inevitably leads to a conflict between accuracy and sampling cost.

Grid Sampling

Much of the soil and crop attribute sampling for Precision Agriculture has been conducted manually on grids of 100m or larger. A number of soil studies have shown that a great deal of information is lost when a sampling grid is increased from 25m to 100m. The common choice of grid size appears to indicate that reducing sampling cost has triumphed over accurate spatial resolution.

It is not difficult to see why this has occurred. Chapter 3 suggests that different soil attributes have different spatial ranges over which samples may be correlated. The rule of thumb is to sample at 2/3 the spatial range, but in practice, sampling operations are not going to be undertaken at different sample spacings for each attribute. Given that the mean spatially dependent range of the soil attributes in Table 3-2 is 103 metres, then a sample spacing of 60 - 70 m would be as wide a spacing as possible to map the real variability.

Table 4-1 shows estimates of the analytical costs to describe the variability in a 100ha field. While the costs in Australia are high, the figures suggest why the USA has taken more keenly to grid soil analysis on the 1-5 ha basis.

Grid Sampling for Precision Agriculture

Most studies into the spatial patterns of soil attributes show that the trade-off between information loss and sampling grid size becomes generally unacceptable above a grid spacing of between **60 - 70** metres.

Soil Attribute	Samples/ha	Unit cost in Aust. (A$)	Unit cost USA. (A$)	1 ha in Total cost in Aust. (A$)	1 ha Total cost in USA (A$)	100 ha Total cost in Aust. (A$)	100 ha Total cost in USA (A$)
Nitrate N	2.04	30.00	10.00	61.20	20.40	6120.00	2040.00
Phosphorus	2.04	23.00	7.00	46.90	14.30	4690.00	1430.00
Potassium	2.04	20.00	7.00	40.80	14.30	4080.00	1430.00
pH	2.04	18.00	5.00	36.72	10.20	3670.20	1020.00
Org. Carbon	2.04	22.00	7.00	44.88	14.30	4480.80	1430.00
Comprehensive	2.04	60.00	15.00	122.40	30.60	12240.00	3060.00

Table 4-1. Average analytical costs for soil attributes in Australia and the USA. Sample spacing based on 70m grid.

Stratified or Directed Sampling

An improvement on grid sampling or random sampling is to use prior information to guide the determination of sampling points. Any information that allows the sample area to be carved into smaller units along a soil attribute or crop production basis (or a combination) would be usefull. Data such as soil type, texture, colour, landscape elevation and slope, and crop yield could be used (or data from other indirect measurements that may reflect changes in these attributes). This strategy underlies the concept of establishing potential Management Zones within a field.

Figure 4-2 outlines the general strategy for improving soil sampling in Precision Agriculture. At present the interim approach is being developed for field application. However, the economic reality will always restrict the detail in information obtainable from discrete sampling procedures. While the procedures will continue to be employed out of neccessity, it is imperative that more intensive methods of data gathering are developed for Precision Agriculture to develop as an economical and efficient management system.

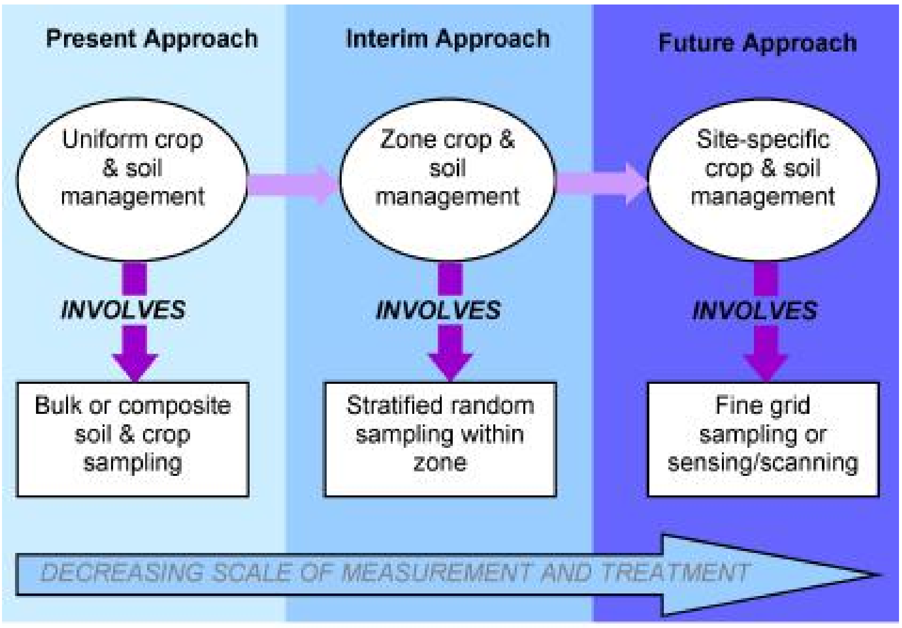


Figure 4-2. Progression of sampling and management scale for Precision Agriculture.

Remote Sensing

Remote sensing encompasses techniques for collecting data on the spatial variation of both soil and crop parameters using aerial or satellite observation platforms. Most techniques rely on the fact that different landcovers have often characteristic ambient reflectance signatures in the visible and/or non-visible electromagnetic (EM) spectrum. Images of this reflectance covering various spatial resolutions may be captured using photographic film, video or digital media. Satellite observed images that are available to civilians have a resolution from $1m_2$ to $100m_2$. Typical resolution is in the $10m_2$ to $30m_2$ range. The resolution of images captured by aerial platforms is generally a function of observation altitude and media composition but is usually around the $1m_2$ to $2m_2$ range

Table 4-2 summarises the remote sensing techniques and the relevant attributes that can be estimated. This form of data appears suitable for quantifying more coarse-scale variation but as the resolution of the technology increases, and ground-truthing is improved, this may become a more useful tool for assessing small-scale variation.

Observation technique	Platform	Attribute estimated	
		soil	crop
Visible/ NIR reflectance	Aircraft/Satellite	Moisture	Leaf area index
		Organic matter	Biomass
		Texture	N status
		Salinity	Photosynthetic activity
			Species identification
			Physical damage
Thermal infrared	Aircraft/Satellite	Moisture	Canopy temperature
			Moisture stress
			Vigour
Radar	Aircraft/Satellite	Moisture	Leaf area index
		Surface roughness	Biomass
			Surface roughness
Gamma emmission	Aircraft	Mineralogy	
		Clay content	

Table 4-2. Relevant remote sensing techniques and the attributes estimated.

Remote Sensing for Precision Agriculture

In general, remote sensing of a fallow field may provide data on soil moisture and texture variability and during the cropping phase vegetative growth may be monitored for variation resulting from nutrient deficiencies, water stress or pest infestation (which may all be related to yield).

Continuous Sampling

Soil Attributes

This refers to the practice of collecting samples for, or directly measuring, variables 'on the go'. Collecting samples or direct data on the variable/s during a pass over the field produces a more fluent data set and obviously enhances the observation resolution. In the case of direct or 'real-time' data collection, there are no sample transport/storage concerns, no laboratory variation to contend with and no delay in accessing the results. Ultimately, the results would also be available in real-time so that farming operations dependent on analysis outcomes may be accomplished in the same pass of the field.

The development of such sensing technology in the area of crop yield measurement has progressed rapidly and will be covered in Chapter 5. The more complex chemical and physical attributes of soil and other crop quality parameters is proving more difficult. Table 4.3 lists the soil attributes and measurement techniques that are under research.

Other Agronomic Attributes

Most other 'on the go' sensing has concentrated on weed mapping and management. The systems developed and studied have usually involved detection of living weeds in fallow fields using optical sensors although height selective spraying equipment employing infrared light beams to detect tall weeds in short crops has be investigated. These are usually integrated detection and treatment systems. Alternatively, many grain yield monitoring systems allow manual operator flagging of weed patch positions observed from the harvester cabin during harvest. Plant density, nitrogen status and grainprotein/oil content is also being investigated.

Soil Attribute	Measurement technique
Texture	Visible and NIR reflectance
	Electromagnetic induction (EMI)
	Ground penetrating radar (GPR)
	Acoustic sensors
	Tillage draft
Moisture	Electromagnetic induction (EMI)
	Ground penetrating radar (GPR)
	Electrical resistance
	Electrical capacitance
	Time-domain reflectivity (TDR)
	NIR reflectance
	Nuclear magnetic resonance (NMR)
Organic matter	Visible and NIR reflectance
Nitrogen	Ion selective electrode
	Ion selective field effect transistor (ISFET)
	Electrical conductivity
pH	Ion selective electrode
	Ion selective field effect transistor (ISFET)
Salinity	Electromagnetic induction (EMI)
Compaction	Penetrometer
Topsoil depth	Electromagnetic induction (EMI)
	Ground penetrating radar (GPR)
Horizon boundaries/ claypans	Electromagnetic induction (EMI)
	Ground penetrating radar (GPR)

Table 4-3. Options for continuous sensing of soil attribute variation.

5

Crop Yield Monitoring

The continuous measurement of crop yield has received much attention in the grains industry. Many other cropping industries are now being presented with the ability to monitor production at the within-field scale. This information technology is crucial to Precision Agriculture. Documenting the spatial variability in the final product provides the major reason for attempting to apply production inputs at variable rates.

Grain, cotton, horticultural, and forage crop yield may now all be monitored in real-time during the harvest process. The grains industry has pioneered the use of these systems, thanks largely to the extensive use of mechanisation around the world and the mechanisation process itself. Like all production systems, information about the quantity, efficiency and reliability of output will become integral to farm management in the future.

Yield Monitoring

Sensors in the Grain Combine

A number of different approaches to monitoring the flow of grain in real-time have progressed to commercialisation (Figure 5-1). These sensors are all harvester mounted and measure the flow of clean grain at some point in the harvest process either directly by using flow impact force or volume, or indirectly through flow density observation using attenuation of signals in the gamma ray, visible, NIR, and radiowave regions of the electromagnetic spectrum. It is apparent that these technologies have driven the development of real-time yield monitoring.

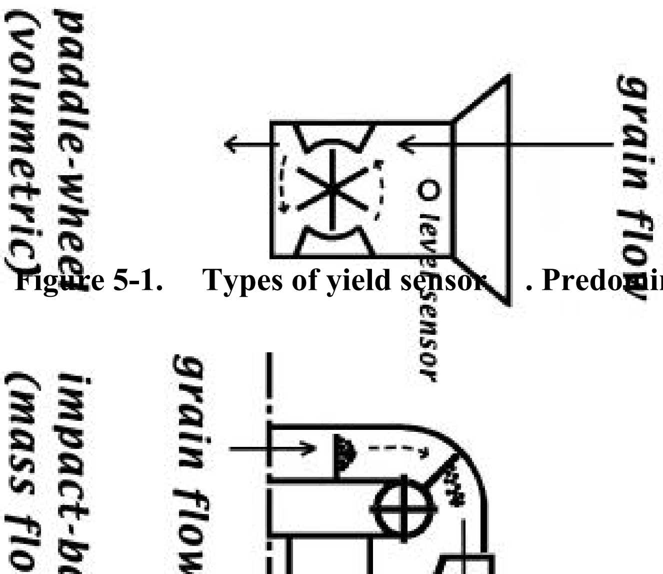


Figure 5-1. Types of yield sensor. Predominantly impact-based available in Australia.

Constructing yield maps from the data generated by these sensors requires that a calibration be determined for the conversion of an electrical signal to a grain mass/ volume and that a harvest area be assigned to the grain quantity at each measurement. Most systems discussed here assume a fixed crop cutting width (commensurate with comb width) or allow some manual adjustment during operation, and monitor ground speed for the purpose of area calculation.

Grain Moisture Content

Grain moisture may also be monitored in the grain flow to improve the estimation of grain mass at a single grain moisture content. Using the correlation between electrical properties of grain and moisture content, capacitance-type measurement systems are more common but alternatives such as microwave attenuation and NIR which requires no grain contact have been examined.

Other Crop Yield Monitors

Tuber & Other Horticultural Crops, Grapes, Peanuts, Sugar cane & Cotton

While grain crop yield has received the most research, other crops have had yield measurement systems investigated or developed. In 1995 a conveyor weighing technology was commercially released to monitor the yield of potatoes during harvest with a reported accuracy of ~ 5%. The same weighing process has been employed to monitor sugarbeet and tomato yield. In effect this technology could be applied to any other harvester that relies on a conveyor system for harvested crop transport e.g. grape harvesters.

Load cells beneath the basket of a peanut harvester have been tested to monitor crop yield by direct weighing. This system is now in commercial release. Sugar cane yield monitoring has been attempted using a correlation between monitored power required to drive the cane elevator and mass cane flow. Silage crop harvesting has also seen the use of power or torque surrogates for mass flow and impact based flow sensors. A load-cell instrumented trailer has been investigated for monitoring the increasing crop weight of non-combinable crops such as sugarbeets as they are loaded in the field. This simple system may also be applied to numerous other agricultural and horticultural crops.

The opportunity for use of Precision Agriculture within the high input/high output cotton industry is now moving forward with the release of a number of commercial cotton yield sensors. The technique uses a plane of light propagated orthogonally to the cotton flow and a light receptive array that responds to the light attenuation caused by the passage of cotton. The transmitter and sensor are mounted in the pneumatic conveyors and the output of the sensor correlates with the volumetric flow rate of cotton.

Table 5-1 summarises the available yield monitoring techniques for combinable and non-combinable crops.

Crop type	Yield measurement: Technique	Yield measurement: Sensor location
Combinable crops	Mass flow by impact force	Clean-grain elevator exit
	Volume flow by light attenuation	Across clean-grain elevator
	Volume flow by mechanical metering	Grain-bin auger exit
	Mass flow by gamma attenuation	Clean-grain elevator exit
	Mass flow by radio freq. attenuation	Clean-grain elevator exit
	Mass flow by mechanical weighing	Cross-auger floor
Potatoes, Beets & Tubers	Mass flow by mechanical weighing	Active conveyor idler wheels
Cotton	Mass flow by light attenuation	Across basket delivery shute
Peanuts	Mass flow by mechanical weighing	Peanut basket
Grapes	Mass flow by mechanical weighing	Active conveyor idler wheels
	Mass flow by mechanical weighing	External weigh-wagon
	Volume flow by ultrasonics	Conveyor belt profile
Sugarcane	Mass flow by impact force	Billet delivery shute
	Mass flow by power requirement	Chopper drive
	Mass flow by power requirement	Elevator drive
Forage crops	Mass flow by impact force	Delivery spout
	Mass flow by mechanical weighing	External weigh-wagon
	Mass flow by power requirement	Chopper drive
Tomatoes & other horticultural	Mass flow by mechanical weighing	Active conveyor idler wheels
	Mass flow by mechanical weighing	External weigh-wagon
	Volume flow by ultrasonics	Conveyor belt profile

Table 5-1. Commercial or well researched crop yield monitoring systems - operational technique and sensor location.

6

Crop Yield Map Production

The yield map is the ultimate score card in Precision Agriculture. It documents the spatial variability in crop yield and provides a check on the performance of any variable-rate treatments. It is the culmination of a whole seasons work and should therefore be constructed with due consideration toward representing the true variability in the field.

Here we shall concentrate on the process of spatial prediction required to produce estimates of yield values at points without an observation. Spatial prediction is required to regularise the spatial distribution of yield values within an area in order to produce an almost continuous surface for mapping.

Spatial Prediction

Any form of spatial prediction is based on the premiss that observations made in close proximity to each other are more likely to be similar than observations separated by larger distances. This is the concept of spatial dependence which has been discussed earlier. The process of spatial prediction requires that a model of the spatial variability (spatial dependence) in a data set be constructed or assumed so that estimates for the prediction points may be made on the basis of their location in space relative to actual observation points. It is the form of these models, and the assumptions underlying the choice of the same, which generally distinguish the major spatial prediction methods. A basic taxonomy of spatial prediction methods has been organised using three categories namely, global or local, interpolating or non-interpolating, and smooth or non-smooth, predictors.

Global Predictors

Global methods use all the data in a data set to determine a model for spatial variation and then apply the one model to the prediction process at all unsampled points. They therefore use all the data for each prediction which may be computationally expensive for large data sets.

Local Predictors

Local predictors use only points 'neighbouring' the prediction point in the prediction operation. A singular form of variance model may be constructed for the entire data set and applied in each neighbourhood, or an individual model may be constructed, and used exclusively for, each neighbourhood. Local methods may therefore be the preferred option, especially on large data sets, and where a single model may be inappropriate.

Interpolators

Spatial prediction methods whose principle requires the prediction to exactly reproduce the data values at sites where data is available are said to act as interpolators.

Smoothers

A smoother is a spatial predictor whose predicted surface and the first partial derivatives thereof are continuous. A non-smooth predictor is one for which the discontinuity of the predictor or its partial derivatives is readily detected by the eye, whereas discontinuity of second and higher derivatives is not usually detected. Despite these definitions, the concept of smoothness of a spatial predictor is somewhat subjective.

Prediction Techniques

Potentially a whole variety of prediction techniques may be used: global means and medians; local moving means; inverse-square distance interpolation; Akima's interpolation, natural neighbour interpolation, quadratic trend; Laplacian smoothing splines and various forms of kriging.

The prediction technique of choice for yield map production in Precision Agriculture will depend on the expected use of the map. However, real-time

Prediction M ethod	C haracteris tic		
Local mov ing means	glob al	non-interp olator	s moother
Inv ers e s quared dis tance	glob al	interp olator	s moother
Local kriging (w ith glob al v ariogram)	local / glob al	non-interp olator	s moother
Local kriging (w ith local v ariogram)	local	non-interp olator	s moother

Table 6-1. Classification of prediction methods.

sensors that intensively sample variables such as crop yield produce large data sets containing a wealth of information on small-scale spatial variability. By definition, Precision Agricultural techniques should aim to preserve and utilise this detail.

The more commonly utilised prediction methods of local moving mean, local inverse distance, and local kriging with a global semivariogram. These will be contrasted with a new technique employing local kriging with a local variogram. Classification of these four methods is shown in Table 6-1.

Neighbourhood

A local neighbourhood is the observations within a chosen radius (d) of each prediction point.

General Model for Prediction

Prediction methods operate on the basis that the yield value Y(x_0) at any unsampled location x_0, (where x denotes a two co-ordinate location descriptor) can be estimated using the values Y(x_i) from the sampled locations x_i, where i = 1,2,3.......n, using the generalised function

$$Y(x_0) = f[w_1, w_2, ...w_n, Y(x_1), Y(x_2), ...Y(x_n)] \quad (6\text{-}1)$$

where:

w_i = the weight assigned to yield value Y(x_i,) at point x_i

The most common prediction techniques applied by agricultural practitioners are linear predictors and use Equation 6-1 such that:

(6-2)

The various prediction techniques do differ in the methods used to calculate the weights. These differences arise from contrasting agronomic assumptions regarding the spatial interdependence of yield estimates and to some extent the degree of certainty placed in the observed data. To ensure that the predictions are unbiased, the weights for each estimate must fulfil the condition of Equation 6-3 by all summing to 1.

$$\sum_{i=1}^{n} w_i = 1 \qquad (6\text{-}3)$$

A Yield Mapping Example

A small portion (~1ha) of a field has been chosen to demonstrate the results of the different prediction methods. The data in 7 metre harvest runs is shown in Figure 6-1. A guide to what the original data may look like if the harvest runs were 1 metre wide and the same variability was maintained is shown in Figure 6-2a.

The prediction procedures all use the closest 100 points as the neighbourhood for each prediction point. The yield values are represented in 0.5 t/ha classes. Figure 6-2b shows that the local moving mean tends to smooth out the data to encompass only 4 yield classes. The inverse distance method (Figure 6-2c) places a lot of varibility in the map by virtue of honouring the very high and low peaks in the harvest data. It is easy to distinguish the harvest lines in the data. Because the inverse distance model is fixed, and its radius of influence is small, the map takes on the characteristic "spottiness" of maps made using inverse distance squared.

Moving to Figure 6-2d, the global variogram has also smoothed out the map to a degree but the harvest lines are not evident because the variogram has a captured a longer spatial dependence in the data set than the fixed inverse distance model. Data points from further out in the neighbourhood have been given some influence on the prediction at each point.

Local variograms have restored some of the local variability in the map (Figure 6-2e) because the changes in spatial dependence between the local neighbourhoods is included. If the prediction is changed from point estimates to estimates representing the yield in a 10 metre block around each prediction point, then some of this variability is removed (Figure 6-2f). This procedure is extremely usefull with data sets where the accuracy in the original data is low or unknown. Yield estimates at the metre resolution should be considered in this class.

Block estimates essentially allow the map to represent each value as an estimate of the yield at a resolution which the error on the original data set is reduced to a satisfactory level. For yield monitoring this should be determined by displacement and flow experiments. At the ACPA, blocks of 20m are used based on experimental results and experience. Figure 6-2g shows the 20 metre block example to include the main spatial structures and gradual changes between the classes. While not fully representing what was seen by the yield monitor, the procedure provides high confidence in that what is being represented is actually distinguishable from the data.

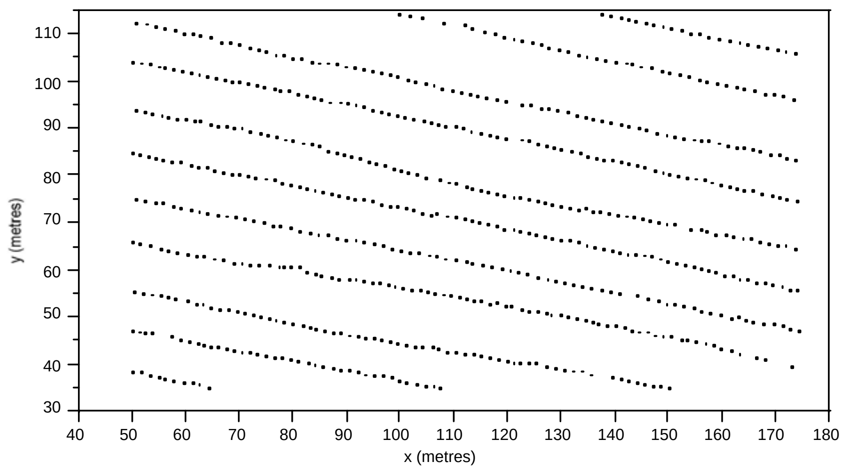
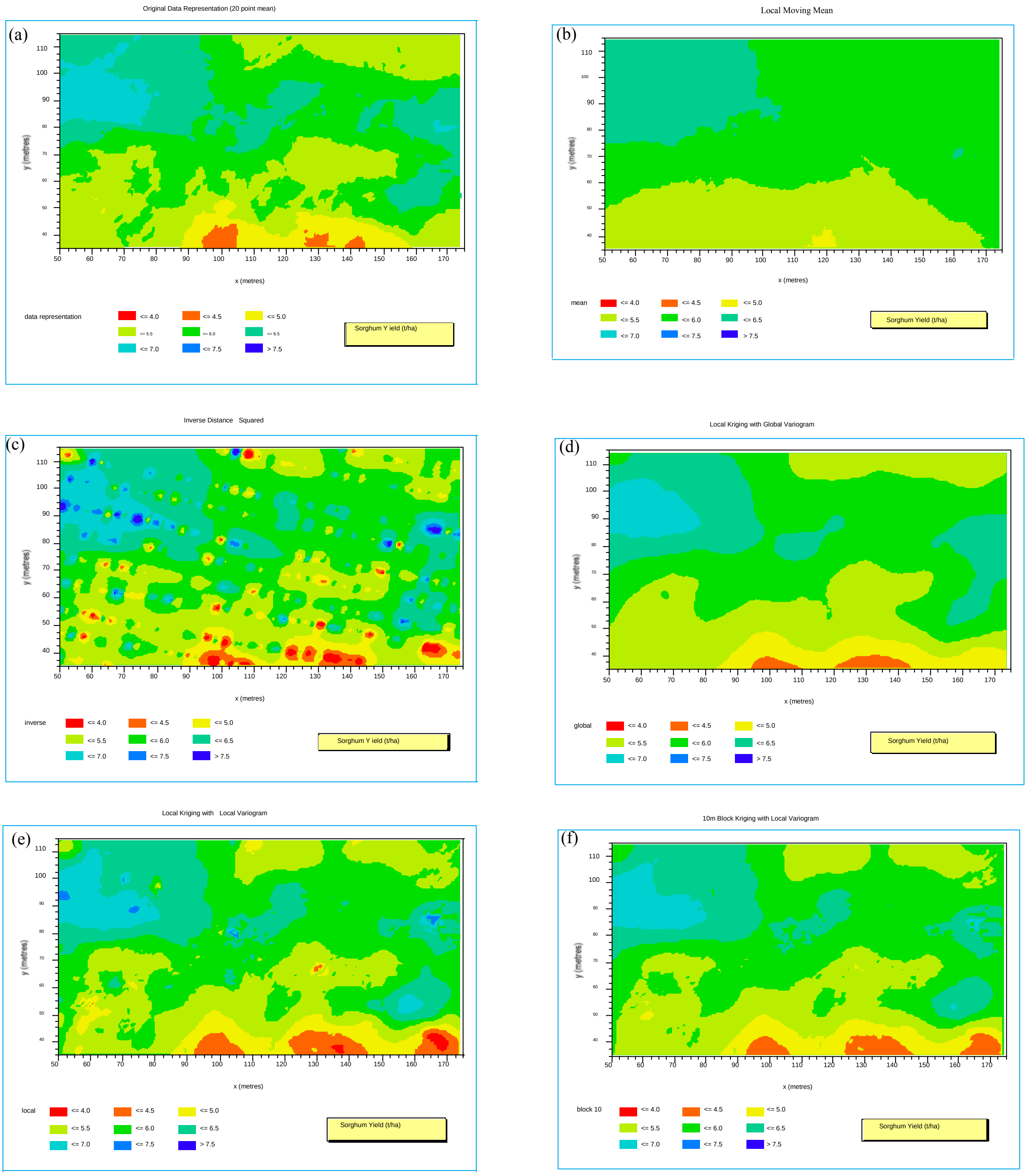


Figure 6-1. Sorghum yield data in 7 metre runs.



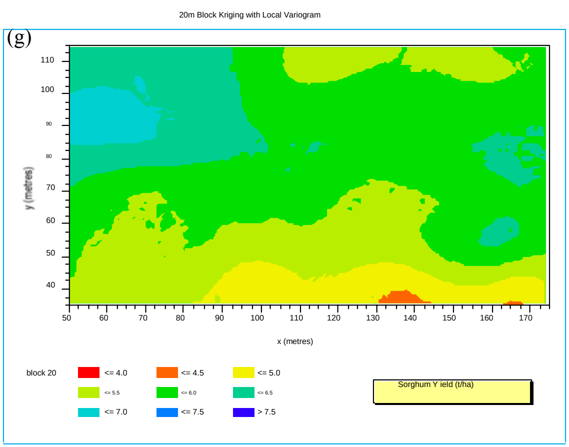


Figure 6-2. Map prediction differences
(a) Surface representation of original data.
(b) Local moving mean prediction.
(c) Inverse distance squared prediction.
(d) Local Kriging with a global variogram.
(e) Local Kriging with a local variogram.
(f) 10 m block kriging with a local variogram.
(g) 20 m block kriging with a local variogram.

7

Variable-Rate Treatment

In implementing this type of management, rate-based operations that influence crop yield can be targeted to achieve desired yield goals with the minimum input of resources. Such governing operations occur at nearly all phases of the crop growth cycle. The array of variable-rate control designs available or proposed range from simple control of flow rate to more complex management of rate, chemical mix and application pattern. The control segment of any variable-rate application should optimise both the economic and environmental product of the field and should ensure that estimates of operational accuracy and dynamics are included in the application process. This is an important point, as incorrect spatial application may be economically and environmentally detrimental.

In all the operations that are under consideration presently, the control commands may be instigated by combining real-time data with the real-time use of a response algorithm or a by accessing a map of application rates and locations. For the majority of cropping industries the important areas of managerial intervention would include:

- Soil tillage implements and depth of operation
- Fertiliser application (quantity and mix)
- Nitrification inhibitor
- Gypsum/lime application
- Sowing rates and depth
- Crop variety
- Pesticide application
- Irrigation water

Table 7.1 lists the methodologies being employed to achieve these operations.

Management prac t ic e	Diierential ac tion As pec t	 Tec hnology
Tillage	Implement ty pe and depth	Ult ras onic range f inders .
		Draught trans duc ers .
	Surfac e c ondit ion	Cone penet rometers .
		Image analy s is .
		Ult ras onic range f inders .
		Draught trans duc ers .
Fertilis er applic at ion	Spreading	Mas t er c ontrolled met ering dev ic e and v ariable dis c height .
	Pneumat ic (v ariable rate and mix)	Mas t er c ontroller gov erning indiv idual bin s lav e c ont rollers .
	Anhy drous ammonia	Flow c ontroller gov erning ac tuat ors .
	Liquid manure	Separate f low c ont roller for t win t ank /boom s y s tem.
Gy ps um/lime applic ation	Spreading	Mas t er c ontrolled met ering dev ic e and v ariable dis c height .
	Slurry injec tion	Flow c ontroller gov erning ac tuat ors .
Sowing	Seed quant it y	Speed independent elec tric or hy draulic mas ter c ont roller.
	Dept h	Sens or f eedbac k loop gov erns ac t uat ors f or dept h c ont rol.
Pes t ic ides	Ins ec t ic ide applic at ion	Map guided pat c h s pray ing.
	Herbic ide applic ation	Map guided pat c h s pray ing.
		Mas t er c ontrol of direc t injec t ion.
		Phot oelec tric real-t ime det ec tion and s pot t reat ment .
		Inf rared height s elec t ion and s pot treatment.
		Real-t ime image analy sis v is ion det ec tion and s pot s pray ing.
I rrigat ion	Trav elling s prink ler	Mas t er c ontrolled z ones with autonomous noz z le array s

Table 7-1. Management options for differential treatment and the available technology.

8 Management Decisions based on Spatial Variability

Techniques for gathering data on spatial variability and the presently available options for differential treatment suggest that the technology for Precision Agriculture is developing well. The criticallinkbetweenthesetwooperationsistheagronomicrationale or decision on which to base spatially variable treatments. This is the most conceptually diverse component in the Precision Agriculture management system, and where the greatest information gap resides.

Initially causal relationships between soil/crop factors and yield must be established at the within-field scale along with the extent to which these relationships vary across the field. This information should be used to determine whether the observed variability warrants differential treatment and if so, direct the decision methodology to be followed.

Decision Methodology

Figure 8-1 provides an example of the decision process that could be employed following a study of field variability. This model begins with the premise that variability in crop yield is the initial signal that variable-rate treatment might be warranted. Another model might begin with the observation of soil variability. However, until the environmental cost of fertiliser wastage is imposed as a grower penalty in Australia, the economic imperative of optimising crop yield will no doubt guide management decisions.

In this model, differential treatment is then examined as an option based on:

- the degree of variation
- the cause/s of variation
- suitability for management intervention

Continuously variable treatment or division of a field into management sub-units is determined based on the spatial dependency observed. Again, this decision marks the point of a conceptual schism. If variability and treatment can be observed and controlled at a fine scale then the question becomes:

Should fields be treated as continuously variable in yield potential or can some classification into management units of 'homogeneous' yield potential be accepted?

If the later is chosen then another question arises:

Should these units be treated with uniform rates of ameliorants if the controlling factor for application was not used to define the management unit?

The answers to such questions are most likely complex and as yet unknown. Options at this point in the model are more than likely governed by limiting factors such as technology, economics and lack of research.

Finally, some form of predictive model must be employed to enable a scientific and agronomically sensible examination of the implications of differential as opposed to uniform treatment, and the interpretation of the results in the form of a spatial management plan. Research relevant to this realm of site-specific management will be examined.

Management Unit Determination

The evidence tends to suggest that the use of more static variables to delineate map units may be supported agronomically. Essentially, the management units should partition the variability within the field so that:

- within-unit variability is reduced below whole field variability.
- mean within-unit variability is significantly different between management units
- the reduction in variability will also be expressed in important attributes that have not been used to make the management zones.

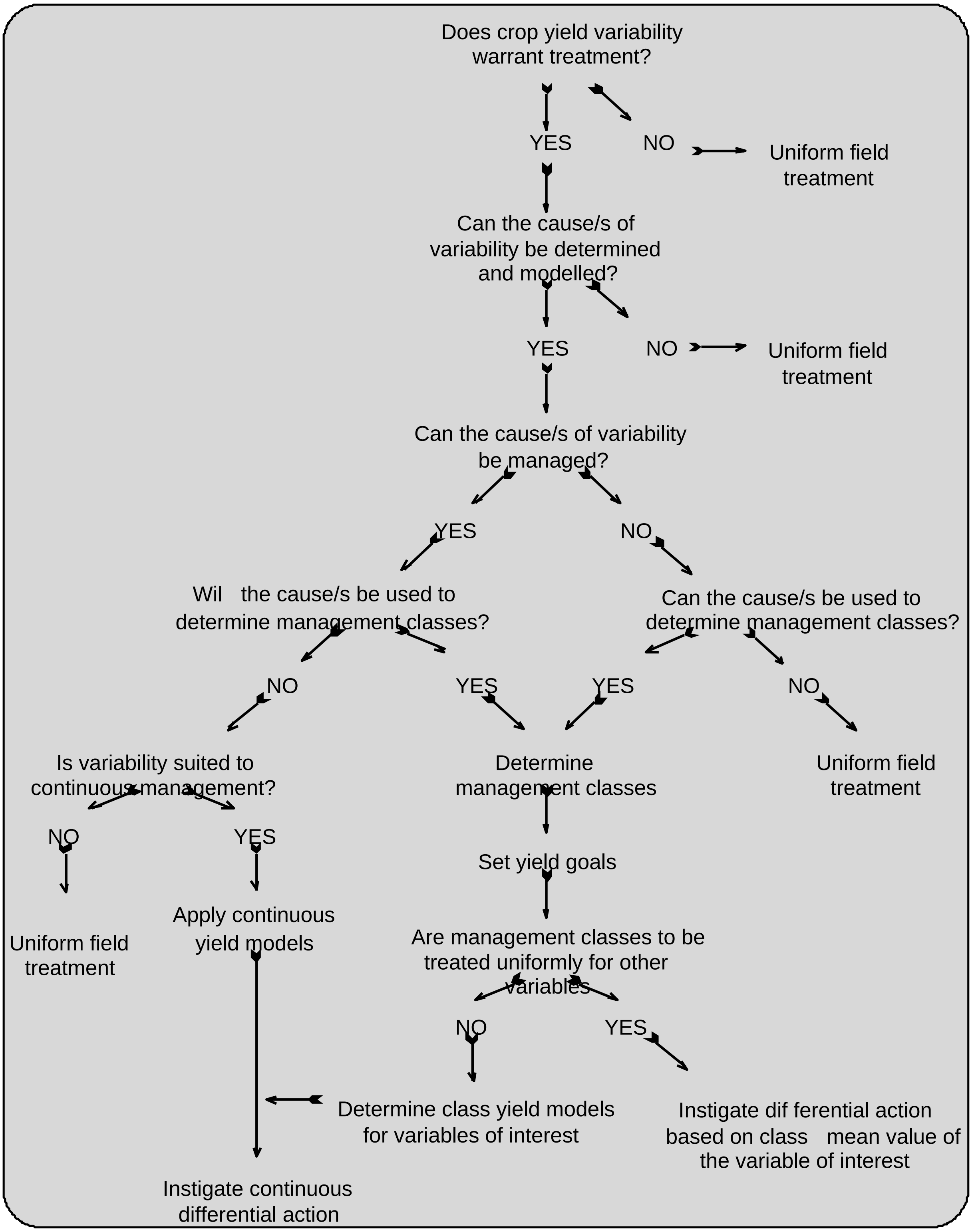


Figure 8-1. Management decision tree for Site-Specific Crop Management – a simple model based on the economic imperative.

A few studies have been undertaken to compare strategies for management unit delineation. Grid sampling at a fine scale (approx 50m) often proves more successful than using existing soil unit maps in delineating units with differing yield potentials but the cost of grid sampling always means that this option was is not the most profitable.

In some instances, aerial imagery of crop reflectance has produced more accurate and precise estimation of soil unit delineations than a final yield maps. Importantly, the aerial photographs must be taken at the correct time of season to truly represent the yield variability induced by soil variability. The period post-anthesis is suggested as the optimum window for cereals.

But most studies suggest that intensive grid sampling of soil attributes is the most accurate method of determining management units (at least for single nutrient fertiliser application). The expense and labouriousness of the sampling regime has fostered the examination of alternative methods. Techniques for the use of multiple year yield maps in management unit delineation are in their infancy. Intuitively, management zones developed on an integrative attribute such as crop yield or vegetative index should be more robust for the application of a range of differential treatments. At the ACPA, research suggests that a number of years yield data in combination with soil ECa and elevation provides a very sound basis for management unit determination when subject to a multivariate clustering process (Figure 8-2).

Summary

Decisions regarding the degree of variability that will be required to justify variable-rate treatment and the best methods for partitioning the variability into potential management zones require much research. As agronomy peers into the crop growth processes at a finer scale, the site-specific nature of causal influences on crop yield variability will be exposed.

This will mean that site-specific experimentation will be important in understanding and managing crop growth at the with-in field scale. Multiple layers of spatial information will be required for each field. The most integrative and influential data layers are yet to be fully revealed. In time gathering data on the important attributes of a field and crop will be undertaken during normal operations. Some, such as elevation and soil texture should only require a single data gathering process. The future for modelling the response of crop yield to inputs at the within-field scale will rely on the cheap and effective gathering of these data layers.

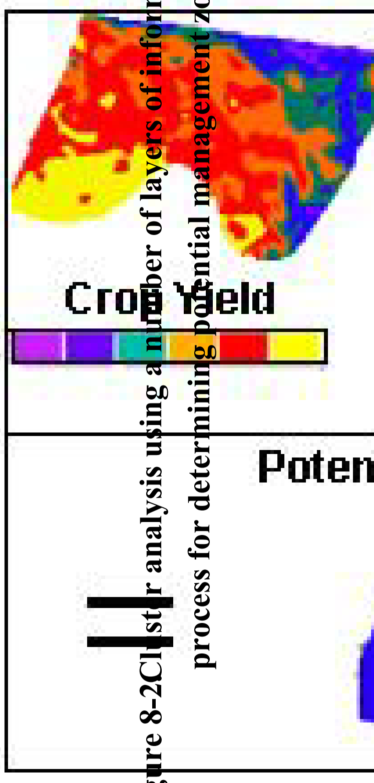


Figure 8-2Cluster analysis using a number of layers of information appears the most promising process for determining potential management zones at present

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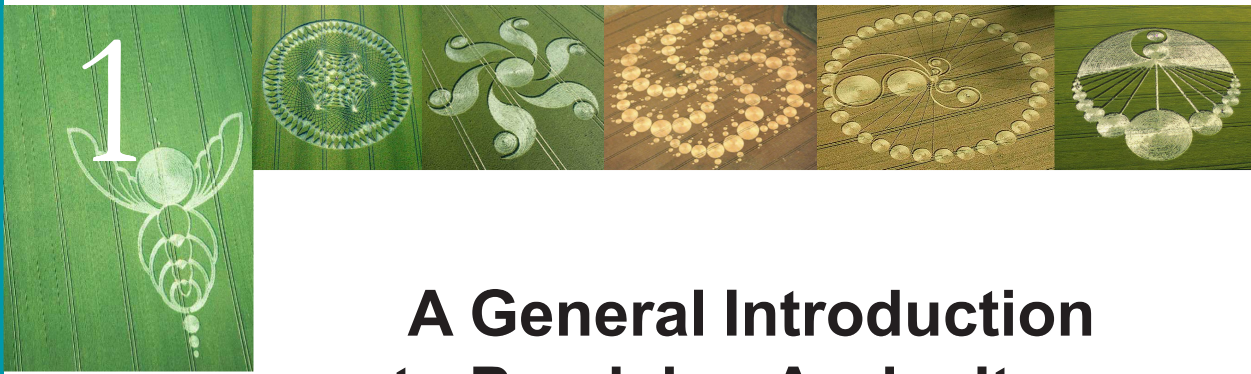
Grains
Research &
Development
Corporation



A General Introduction to Precision Agriculture

Precision Agriculture is a now a term used throughout agricultural systems worldwide. But what do we mean by "Precision Agriculture"? This introductory chapter provides a background to the evolution of Precision Agriculture, the principle philosophy and goals of a Precision Agriculture management strategy and some of the steps required to adopt Precision Agriculture in cropping systems. It provides a stepping stone to subsequent chapters in this series that will investigate the theory, technology and methodology behind the adoption of Precision Agriculture, with particularly emphasis on small grains production in Australia.

A Brief History

Precision Agriculture (PA) is no longer a new term in global agriculture. Since the first substantial PA workshop was held in Minneapolis in 1992, it has become the subject of numerous conferences worldwide. An Australasian symposium on PA has been held annually from 1997. Its acceptance in the United States of America has been formally recognised by the drafting of a bill on PA by the US Congress in 1997. But where did the term and concept of PA come from?

The impetus for the current concept of Precision Agriculture in cropping systems emerged in the late 1980's with the matching of grid-based sampling of soil chemical properties with newly developed variable-rate application (VRA) equipment for fertilisers. Using a compass and dead-reckoning principles, fertilisers were applied at rates designed to complement changes in soil fertility maps that had been created. Crop yield monitoring technologies were still in the research phase at this stage.

Around 1990, the NAVSTAR Global Positioning System (GPS) became available in a limited capacity for civilian use and the opportunity for rapid and 'accurate' vehicle location and navigation sparked a flurry of activity. Electronic controllers for VRA were built to handle this new positioning information and crop yield monitors began to hit the commercial market. By 1993 the GPS was fully operational and a number of crop yield monitoring systems were allowing the fine-scale monitoring and mapping of yield variation within fields. The linking of yield variability data at this scale with maps of soil nutrient changes across a field marked the true beginning of PA in broadacre cropping.

As yield monitoring systems were improved, it became evident that methods other than grid sampling for collaborative information would need to be developed. In many instances, grid sampling at the intensity required to correctly characterise variability in soil and crop parameters proved cost prohibitive and, by the late 1990's, a "zonal" management approach had become a real option for management. This approach subdivides existing fields into zones of similar crop response and helps account for current limitations in data resolution while trying to maximise the benefits of PA for crop management.

New systems for measuring or inferring soil and crop parameters on a more continuous basis continue to be developed using both proximal (i.e. on ground-based platforms) and remote (i.e. aerial and satellite) platforms. Examples of these are soil ECa measuring instruments, crop reflectance imaging and crop quality sensors.

The success, and potential for further success, observed in the grains industry prompted other farming industries, particularly viticultural and horticultural crops, to adopt precision agriculture. Since the late 1990's more and more research has been carried out in non-grain crops. Also, more emphasis is being placed on the environmental auditing capabilities of PA technology and the potential for product traceability. Advances in Global Navigation Satellite System (GNSS) technology since 1999 have also opened the door for machinery guidance, auto-steering and controlled-traffic farming (CTF). CTF has provided sustainability benefits (such as minimisation of soil compaction), economic benefits (by minimising input overlap and improving timeliness of operations) and social benefits (such as reducing driver fatigue). As a result this form of PA technology has been showing swift adoption rates in the first decade of the 21st century.

Defining Precision Agriculture

Many definitions of PA exist and many people have different ideas of what PA should encompass. Here two definitions have been selected to illustrate the concept of PA in general but also specifically its application to broadacre cropping industries. The first definition comes from the US House of Representatives (US House of Representatives, 1997).

> *Precision Agriculture:*
>
> *"an integrated information- and production-based farming system that is designed to increase long term, site-specific and whole farm production efficiency, productivity and profitability while minimizing unintended impacts on wildlife and the environment".*

The key to this definition is that it identifies PA as a "whole-farm" management strategy (not just for individual fields) that utilises information technology and that the aim of management is to improve production and minimise environmental impact. It also refers to the farming system which in modern agriculture may include the supply chain from the farm gate to the consumer. This definition also distinguishes between agriculture and agronomy. Whilst the PA philosophy has been expounded primarily in cropping industries it is important to remember that precision agriculture can relate to any agricultural production system. These may involve animal industries, fisheries and forestry and in many cases PA techniques are being implemented without being identified as such. For example, the tailoring of feed requirements to individual milkers depending on the stage of their lactation in a dairy enterprise.

The second definition narrows the PA philosophy of timely management of variation down to its implementation in cropping systems.

> *Site-Specific Crop Management (SSCM)*
>
> *" A form of PA whereby decisions on resource application and agronomic practices are improved to better match soil and crop requirements as they vary in the field"*

This definition encompasses the idea that PA is an evolving management strategy. The focus here is on decision making with regard to resource-use and not necessarily the adoption of information technology on farm (although many new technologies will aid improved decision making). The decisions can be in regard to changes across a field at a certain time in the season or changes through a season or seasons. The inference is that better decision making will provide a wide range of benefits (economic, environmental and social) that may or may not be known or measurable at present. From an Australian grains perspective this definition provides a defined goal regardless of a growers current adoption of PA or proposed entry level into PA.

To further expand the concept, SSCM can be considered as the application of information technologies, together with production experience, to:

i) optimise production efficiency
ii) optimise quality
iii) minimise environmental impact
iv) minimise risk

- all at the site-specific level.

This is not a particularly new concept in agriculture with essays on this topic dating from the early 18th century. What is new is the scale at which we are able to implement these aims. Prior to the industrial revolution, agriculture was generally conducted on small fields with farmers often having a detailed knowledge of their production system without actually quantifying the variability. The movement towards mechanical agriculture, and the profit margin squeeze, has resulted in the latter half of the 20th century being dominated by large-scale uniform "average" agricultural practices. The advance of technology in the late 20th and early 21st centuries, has allowed agriculture to move back towards site-specific agriculture whilst retaining the economies of scale associated with 'large' operations.

Some Misconceptions

Like many new concepts, PA carries with it some misconceptions.

- PA is often confused with yield mapping. Yield mapping is a tool that is one of the first steps towards implementing a SSCM strategy.
- PA is sometimes misinterpreted as sustainable agriculture. PA is a tool to help make agriculture more sustainable however it is not the total answer. PA aims at maximum production efficiency with minimum environmental impact. Initially it was the potential for improved productivity (and profitability) that drove the development of SSCM as a form of PA. In recent years the potential for this technology as a tool for environmental auditing of production systems has become more obvious. However environmental auditing is not environmental management. The large amount of fine-scale data being collected in a SSCM system can be used for on-farm environmental risk assessment and incorporated into a whole-farm plan to help viability in the long term.
- Finally, machinery guidance and autosteer systems are examples of the successful adoption of new technology on farms. However, these again are tools that help with SSCM. By themselves they are not PA.

Variability And The Production System

SSCM is dependent on the existence of variability and broadly speaking "variability in production = SSCM opportunity". Having said this, the type, magnitude and distribution pattern of variability is also important. There are generally two types of variability to be considered, spatial or temporal. Spatial variability occurs over a measurable distance, temporal variability occurs over a measurable time period. The difference between the low and high values of a measured property define the magnitude in both types of variability. The distribution pattern maps how variability is changing in either the space or time dimension.

The management implications of these aspects of variability are diverse and fundamentally linked to the production property being measured. However there are a few simple generalisations that are worth keeping in mind. The observed magnitude in the variability should be related a benchmark level below which it would be uneconomical to attempt to manage. It is important to note that the costs used to calculate these benchmarks are presently considered from a short-term economic perspective. If we were able to express environmental benefits in a fiscal sense, then in some instances, areas with a small magnitude of variation in production may be viable for SSCM management.

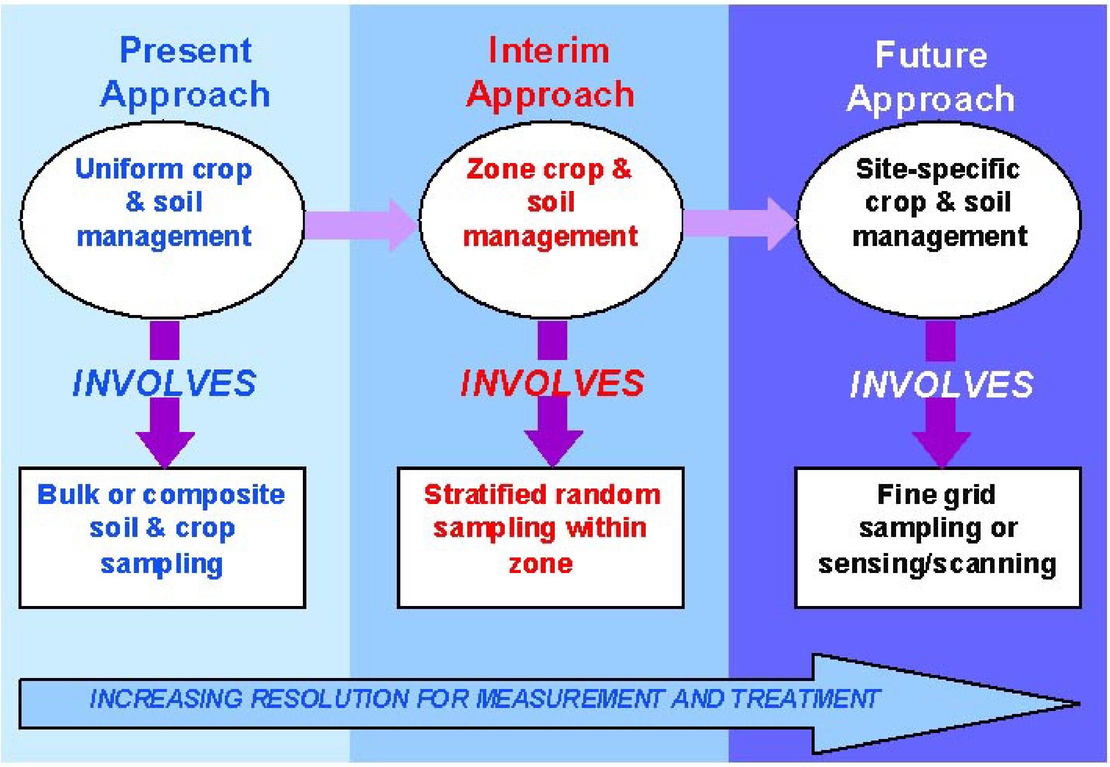


Figure 1. The evolving timeline of SSCM from a uniform to a totally site-specific approach.

The distribution pattern of the variability needs to be considered relative to the options for management intervention. In spatial terms, the pattern should be considered in relation to the smallest unit of treatment applicable (e.g. the size and reaction time of VRA fertilser application gear). In temporal terms, the pattern should be considered in terms of the impact on important management stages of the growing season (or the whole season if relevant).

If spatial variability does not exist then a uniform management system is both the cheapest and most effective management strategy. In cropping situations the magnitude of temporal variability may appear much greater than spatial variability. If the impact of temporal variability on production overwhelms the impact of spatial variability then careful consideration needs to be given to whether a uniform or differential management strategy is the optimal risk aversion strategy.

Based on these considerations, SSCM is at present operating on a zonal rather than a completely site-specific basis (Figure 1). As our ability to measure variability improves, the capital cost of VRA technology decreases and the environmental value is factored in, SSCM will begin to approach a truly site-specific management regime.

Objectives Of SSCM

At the beginning of this introduction SSCM was defined in terms of four main objectives. The success of a SSCM strategy will depend on how each or all of these objectives are met.

Optimising Production Efficiency

In general the aim of SSCM is to optimise returns across a field. Unless a field has a uniform yield potential (and therefore a uniform yield goal), the identification of variability in yield potential may offer possibilities to optimise production quantity at each site or within each "zone" using differential management. The initial emphasis should be on optimising the agronomic response to the manageable input with the most impact on production and costs. In the absence of any clear environmental benefits this will be achieved by differentially applying inputs so that the marginal return = marginal cost at each site or zone in the paddock.

Optimising Quality

In general, production efficiency is measured in terms of a yield (quantity) response, mainly because yield and biomass sensors are the most reliable and commonplace sensors. In the past few years the first attempts to commercialise grain quality sensors have been made and on-the-go grain protein/oil sensors are now commercially available. The ability to site-specifically collect grain quality data will allow growers to consider production efficiency from the perspective of either yield, quality or a yield x quality interaction. Many inputs will impact on quality as well as quantity. In production systems where quality premiums exist this may alter the amount of input required to optimise profitability and agronomic response.

In some product markets, where strong quality premiums/penalties are applied, a uniform approach to quality properties may be optimal. The quality of some agricultural commodities is greatly increased by decreasing the variability in production e.g. winegrapes or malting barley. If quality premiums more than offset yield loss then growers may prefer to vary inputs to achieve uniform production quality (and minimise variability) rather than optimise productivity.

Minimising Environmental Impact

If better management decisions are being made to tailor inputs to meet production needs then by default there must be a decrease in the net loss of any applied input to the environment. This is not to say that there is no actual or potential environmental damage associated with the production system however the risk of environmental damage is reduced.

SSCM, coupled with VRA technology, provides producers with a means to not only quantify the amount and location of any input application but also to record and map applications. This gives producers physical evidence to contest any claims against negligent management or alternatively provide information on 'considerate' practices to gain market advantage. A by-product of improved information collection and flow is a general improvement in the producer's understanding of the production system and the potential implications of different management options.

Apart from avoiding litigation or chasing product segmentation into markets, there is little regulatory incentive for growers to capture and utilise information on the environmental footprint of their production in Australia. Other countries, particularly within the EU, are financially encouraging producers to collect and use this information by linking environmental issues to subsidy payments. Such eco-service payments may well be introduced in Australia.

Minimising Risk

Risk management is a common practice today for most farmers and can be considered from two points of view - income and environmental. In a production system, farmers often practice risk management by erring on the side of extra inputs while the unit cost of a particular input is deemed 'low'. Thus a farmer may put an extra spray on, add extra fertilizer, buy more machinery or hire extra labour to ensure that the produce is produced/harvested/sold on time thereby guaranteeing a return. Generally minimising income risk is seen as more important than minimising environmental risk but SSCM attempts to offer a solution that may allow both positions to be considered in risk management. This improved management strategy will come about through a better understanding of the environment-crop interaction and a more detailed use of emerging and existing information technologies (e.g. short and long term weather predictions and agroeconomic modelling).

The more that is known about a production system the faster a producer can adapt to changes in his own production and in external market forces . For example, accurate mid season yield predictions may give a grower more room to move with forward selling options.

Practical Implementation Of SSCM

The SSCM cycle is illustrated in Figure 2. Each node in the cycle will form the theme for subsequent chapters in this series, however a short introduction is given here. It is important to remember that SSCM is a continuous management strategy. Initially some form of monitoring and data analysis is needed to form a decision. However it is just as important to continue to monitor and analyse the effect of the decision and feed this information into subsequent management decisions.

Geo-referencing

The truly enabling technology of SSCM in its present form. Global Navigation Satellite Systems (GNSS) (of which the GPS is the most widely used at present) are now common place on many farms. Receivers range in accuracy from 10-20m to 2-3cm, in price from $200 to $60,000, and in application from crop monitoring and yield mapping to autosteer systems. The technology continues to improve and the price of receivers to decrease.

The ability to geo-reference activities gives producers the option to map and visually display farm operations. This provides insights into both production variability as well as inefficiencies in crop production and farm operations. In the past few years more advanced systems have become more common on-farm as growers embrace

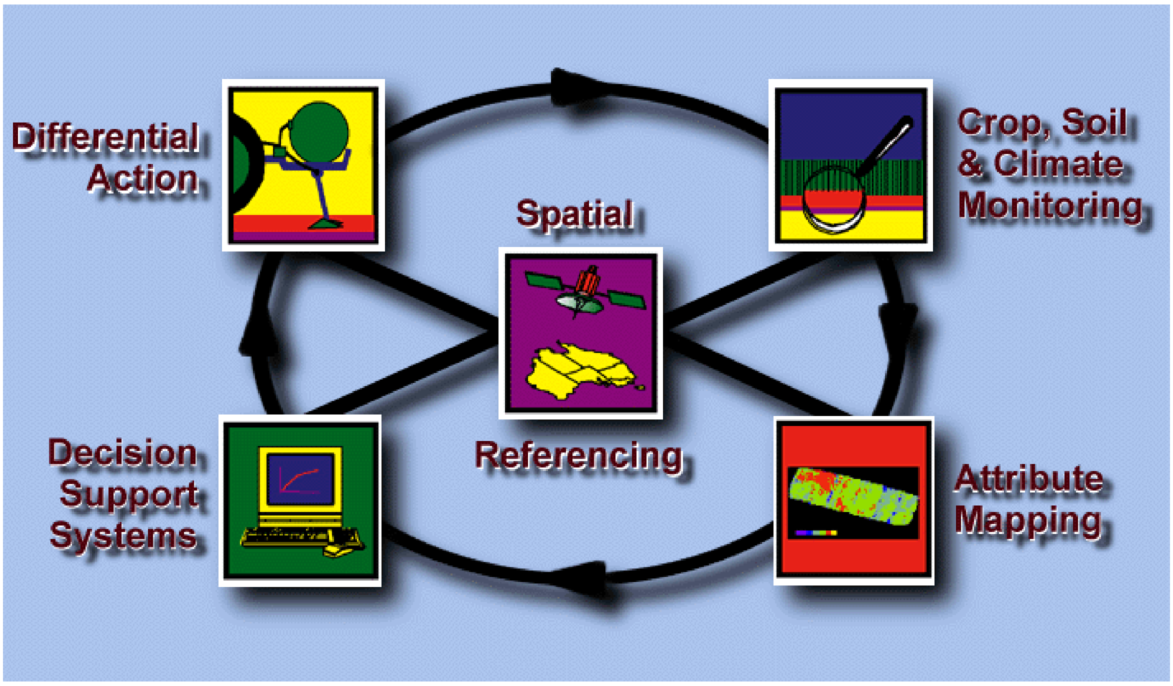


Figure 2: The SSCM cycle indicating spatial referencing as the enabling technology that drives the other parts of the cycle.

guidance and autosteer technologies. These permit machinery to drive along repeatable tracks as well as reduce driver fatigue and permit more timeliness of operations.

Crop, Soil and Climate Monitoring

Many sensors and monitors already exist for *in-situ* and on-the-go measurement for a variety of crop, soil and climatic variables. These include yield sensors, biomass and crop response sensors (aerial and space-borne multi- and hyper-spectral cameras), radio or mobile phone networked weather stations, soil apparent electrical conductivity (ECa) sensors and gamma-radiometric soil sensors to name a few. The majority of SSCM research in Australia is currently being directed at identifying how to utilise the output from these sensors to improve production.

The other challenge for SSCM is to adapt *in-situ* sensors and develop new on-the-go sensors. While the commercial potential of these sensors will mean that private industry will be keen to take up the engineering aspects of research and development, research bodies have an important role to play in the development of the science behind the sensors. Market concerns often lead private industry to sell sensors prematurely to ensure market share. This may lead to substandard sensors and a failure to adequately realise the potential of the sensor. Agricultural scientists also need to continue to assess which and how multiple crop and production indicators can be measured.

Attribute Mapping

Crop, soil and climate sensors often produce large, intensive data sets. The observations are usually irregularly spaced and need to 'cleaned' and interpolated onto a surface to permit analysis. For several decades geostatisticians have been researching ways of describing and representing spatial data that accurately represents the raw data. Historically most of this has been done with sparse datasets. The data sets being generated by SSCM technologies have produced new challenges for mapping, but most of these are now well understood within the PA community although answers are generally poorly disseminated through the wider agricultural community.

Software for mapping and displaying data from different sources on a common platform is improving annually. The development of Geographical Information Systems (GIS) specifically for agriculture is allowing this to occur however the adaptation and adoption of this technology for use in SSCM on individual farms is still in its infancy. The main issues still to be resolved are the development of a user friendly advanced data filtering system and the determination of initial and future sampling schemes to ensure that the variability of the system is properly characterised.

Decision Support Systems

Techniques for data presentation and storage, such as Geographical Information Systems (GIS), developed in other industries should be relatively easily applied, with some modification, to agriculture. However Decision Support Systems (DSS) are not so flexible and it is in this area that much research needs to be done. Decision Support Systems use agronomic and environmental data, combined with information on possible management techniques, to determine the optimum management strategy for production. Most commercial DSS are based on 'average' crop response across a field. The majority of engineering companies currently supplying SSCM technology are currently not producing DSS to support the differential use of their equipment in a production system. Therefore the onus is falling on individual industry bodies, and to a lesser extent government agencies, to fill the gap. Initially it may be sufficient to adapt existing agricultural DSS such as WHEATMAN, COTTONLOGIC or APSIM to site-specific situations. In the long run however a DSS that is able to site-specifically model plant-environment interactions in terms of yield and quality will be needed. This will need to be flexible enough to incorporate a variety of sensor-gathered data, accept feedback from other parts of the SSCM cycle and be able to conform to standards such as ISO 9000/14000.

Differential Action

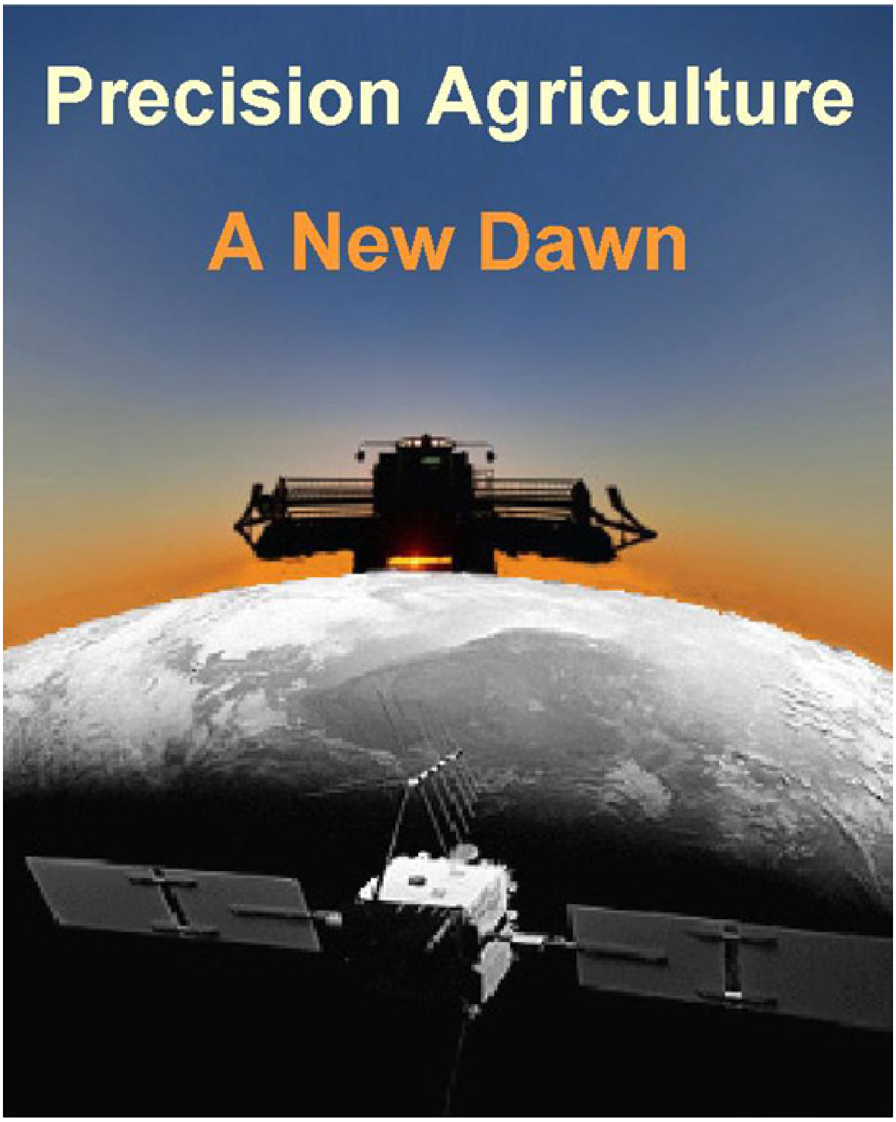
The differential application of inputs using VRA technology is essentially an engineering problem. Due to the commercial potential of VRA technology, much of this engineering development is being driven by the private sector. The main input required for VRA implements is accurate information on required application rates and associated locations or times for the applications. VRA equipment should also record the actual application procedure for quality control. The differential application technology was probably the best developed part of the SSCM cycle in the late 1990's and development of new methods for differential application remains a project of many research and commercial entities around the globe.

Like GPS receivers, VRA equipment is becoming more user friendly, more cost effective and more common especially in broadacre agriculture. The biggest barrier to adoption is the lack of information from a DSS on where, and by how much, inputs should be varied.

Concluding Remarks

Precision Agriculture is a management philosophy, encompassing the use of advances in information technology in agriculture. In 10-15 years time it is likely (and hoped) that SSCM as a form of PA , with its associated technologies and methodologies, will be simply considered as standard cropping practice. But no matter how technology and methodologies change and adapt overtime, SSCM will still be driven by the central philosophies of improved production efficiency, reduced environmental impact and risk minimisation.

James Taylor & Brett Whelan
Australian Centre for Precision Agriculture
www.usyd.edu.au/su/agric/acpa



Cleaning Up Yield Data

with JMP 5

Raw data files from yield monitor software come in a variety of formats and qualities. A cleaning process based on the distribution of the yield data provides a basic way to clean any data set. More sophisticated methods will eventually be available that work with any data set, but for the present, the process described here should help get data ready for further analysis.

Introduction

The ACPA uses the SAS program *JMP* (www.jmp.com) to calculate crop yield in tons per hectare and trim erroneous data points from yield monitor data files. The full procedure is usually applied to *.txt* files in the AgLeader 'advanced' format but can be adapted to any *.txt* yield file that contains 'mass flow', 'distance travelled', 'cutting width' and 'grain moisture' data columns. The data trimming procedure can also be adapted to *.txt* files where the yield values have already been calculated. In the Procedure section the task is listed in Green followed by the JMP commands in Red. The result and any other requirements for each step are also discussed.

Associated Files

Files used in conjunction with *yield.txt* files:

YieldCalcB.jmp :	for data recorded in metric units (mass flow units = kg/s; length units = mm)
YieldCalcImperial.jmp:	for data recorded in imperial units (mass flow units = lb/s; length units = inches)
JDYieldCalcB.jmp:	for data exported from John Deere Office software (mass flow units = decagrams/s; length units = mm)
DisTrim.jmp:	for data that has an already calculated yield column (yield units = t/ha)

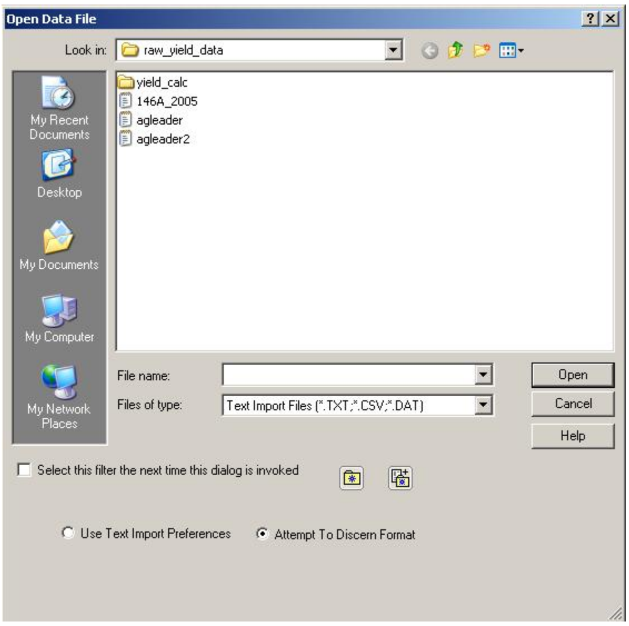
Procedure in JMP

Calculate Crop Yield and Trim Data

1. Open yield.txt file: *File/Open/Open Data File*

Ensure the 'Files of Type' field reads 'Text Import Files (*.TXT;*.CSV;*.DAT) and the 'Attempt To Discern Format' button is checked. Then navigate to where the yield file is stored and select the desired '.txt' file and press OPEN. This will open a 16 or 17 column data file depending on whether elevation has been recorded.

Column 3 = mass flow
Column 5 = measurement time span
Column 6 = distance travelled
Column 7 = cutting width
Column 8 = grain moisture



Open Data File window: ensure that the correct 'File of Type' is selected and the 'Attempt to Discern Format' button is checked

2. Open YieldCalc file: File/Open/Open Data File

Navigate to the folder where the YieldCalc.JMP files have been stored. If the yield file is from JDOffice choose the JDYieldCalcB.JMP file. If the file is from another harvester and the meaurement units (imperial or metric) are not known then examine column 7 (cutting width). It should be easy to tell what units are being utilised. Numbers such as 10000 indicate metric measurement of a 10 metre front while 393 indicates imperial measurement of a 10 metre front. Choose the appropriate file and press OPEN.

You will now have 2 spreadsheet files open and the last file opened will be 'active'. Ensure the yield file that you wish to work on is made active by clicking on the file spreadsheet. An 'active' file or window is denoted by a blue strip along the top.

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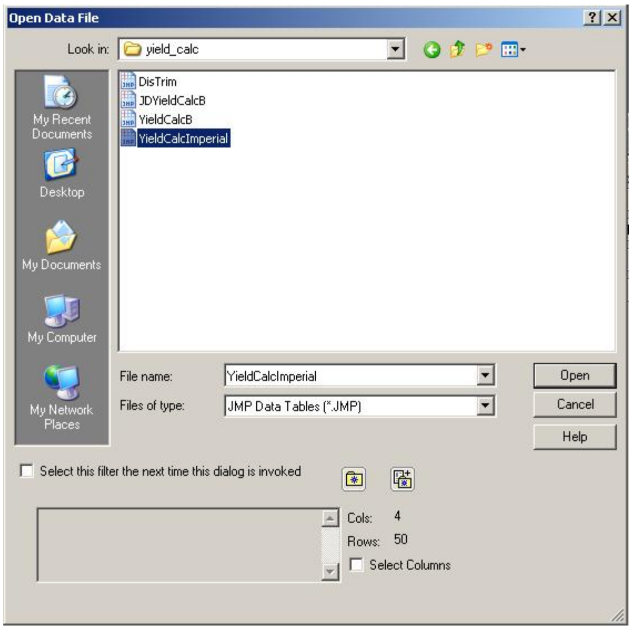

Open Data File window: ensure that the 'File of Type' field reads 'JMP Data Tables (*.JMP)

3. Join the Yield.txt file with the YieldCalc file: Tables/Join

Select the appropriate YieldCalc file from the list, ensue the 'Suppress Formula Evaluation' box is UNTICKED and press JOIN.

This will produce a new spreadsheet file where the columns of the YiledCalc file will be added onto the end of the Yield file and the last 4 columns will be 'yield, trim1, yield_t_ha, trim2'.

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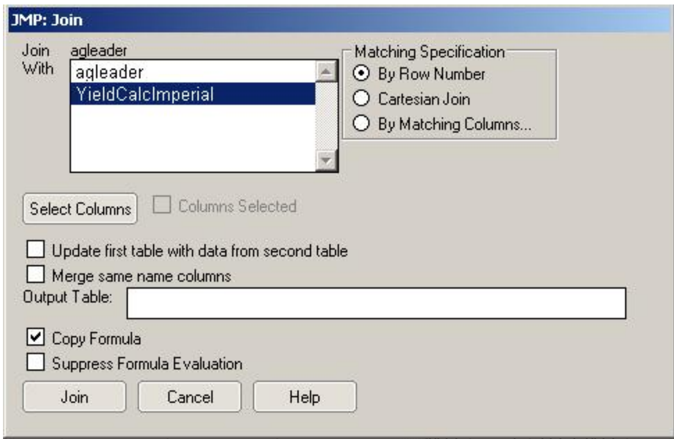


Join JMP files window: highlight the file to join with the yield file and ensure the 'Suppress Formula Evaluation is unticked

umn10	Column11	Column12	Column13	Column14	Column15	Column16	Column17	yield	trim1	yield_t_ha	trim2
1	960446	F5:COMETB	L0:44 012911	WHEAT	7	0	1011.4	8.91660275	5	8.91660275	0
1	960446	F5:COMETB	L0:44 012911	WHEAT	7	0	1011.1	7.50215454	5	7.50215454	5
1	960446	F5:COMETB	L0:44 012911	WHEAT	7	0	1011.4	7.10019052	5	7.10019052	5
1	960446	F5:COMETB	L0:44 012911	WHEAT	7	0	1011.8	5.52338244	5	5.52338244	5
1	960446	F5:COMETB	L0:44 012911	WHEAT	7	0	1012.1	5.42670455	5	5.42670455	5
1	960446	F5:COMETB	L0:44 012911	WHEAT	7	0	1012.1	5.66147932	5	5.66147932	5
1	960446	F5:COMETB	L0:44 012911	WHEAT	7	0	1012.8	5.48553787	5	5.48553787	5
1	960446	F5:COMETB	L0:44 012911	WHEAT	7	0	1011.8	5.9195876	5	5.9195876	5
1	960446	F5:COMETB	L0:44 012911	WHEAT	7	0	1011.4	5.8504535	5	5.8504535	5
1	960446	F5:COMETB	L0:44 012911	WHEAT	7	0	1009.8	5.49686105	5	5.49686105	5
1	960446	F5:COMETB	L0:44 012911	WHEAT	7	0	1009.5	5.43745582	5	5.43745582	5
1	960446	F5:COMETB	L0:44 012911	WHEAT	7	0	1009.5	5.33353441	5	5.33353441	5
1	960446	F5:COMETB	L0:44 012911	WHEAT	7	0	1008.5	5.58973439	5	5.58973439	5
1	960446	F5:COMETB	L0:44 012911	WHEAT	7	0	1008.5	5.49999533	5	5.49999533	5

Joined data file showing the four added columns

The four added columns are:

‘yield’: has the yield in t/ha calculated from the data in Columns 3,5,6,7 and 8.

‘trim1’: is an indicator column that identifies values in the ‘yield’ column that are either 0 or >10. Such values are shown as 0 in this column and all others are shown as 5.

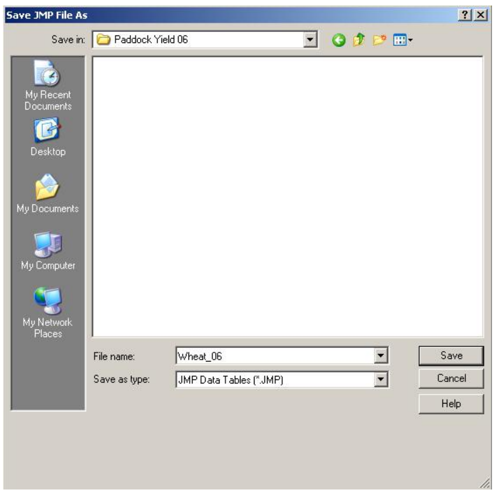
‘yield_t_ha’ yield values identified by ‘5’ in the previous column are carried across to this column. Those identified by 0 in ‘trim 1’ are left blank.

‘trim2’ uses the identifier concept again, but here the 0 represents ‘yield_t_ha’ values that are either greater or less then the mean ‘yield_t_ha’ value +/- 2.5 standard deviations. An indicator 5 identifies yield values that fall within these distribution limits.

In effect the process calculates the yield values from the data, identifies where the yield is 0 t/ha or greater than 10 t/ha and discards them, then identifies where the remaining yield values fall outside the data limits of the mean yield +/- 2.5 standard deviations.

4. Save the file: File/SaveAs

Navigate to the appropriate storage location for the yield data, give it a relevant name and press SAVE

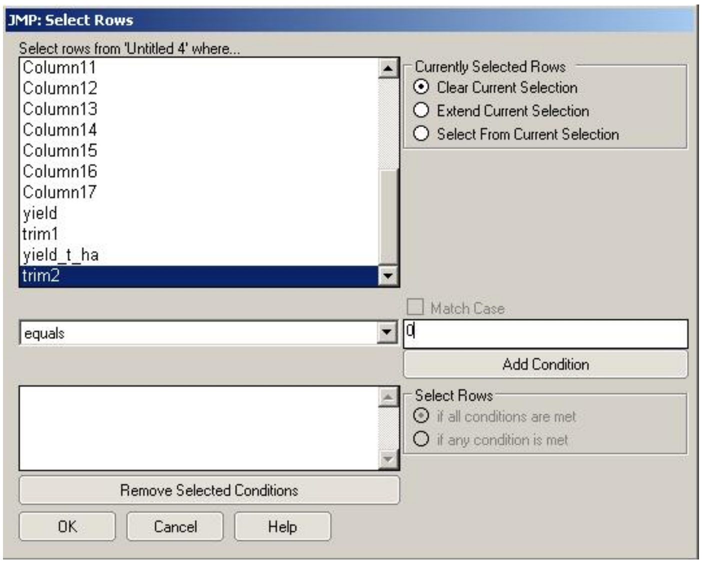


Save the joined file as a JMP file in the appropraite location

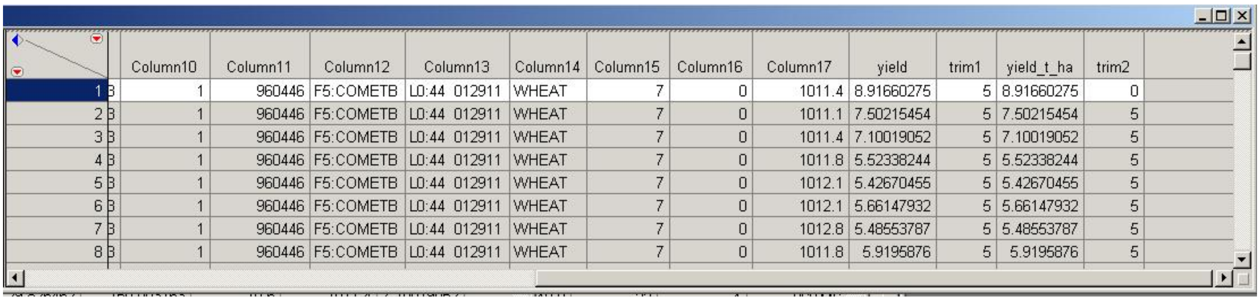
5. Examine which points will be trimmed — Rows/Row Selection/Select Where

Highlight the ‘trim2’ column from the list offered, select ‘equals’ from the pull down menu and type ‘0’ into the vacant box next to the pull-down menu arrow. Press OK.

This will highlight all the rows in the spreadsheet that fulfill this criteria. These are the data points that will be trimmed.



Select the points in the ‘trim2’ column that equal ‘0’



		Column10	Column11	Column12	Column13	Column14	Column15	Column16	Column17	yield	trim1	yield_t_ha	trim2
1	B	1	960446	F5:COMETB	L0:44 012911	WHEAT	7	0	1011.4	8.91660275	5	8.91660275	0
2	B	1	960446	F5:COMETB	L0:44 012911	WHEAT	7	0	1011.1	7.50215454	5	7.50215454	5
3	B	1	960446	F5:COMETB	L0:44 012911	WHEAT	7	0	1011.4	7.10019052	5	7.10019052	5
4	B	1	960446	F5:COMETB	L0:44 012911	WHEAT	7	0	1011.8	5.52338244	5	5.52338244	5
5	B	1	960446	F5:COMETB	L0:44 012911	WHEAT	7	0	1012.1	5.42670455	5	5.42670455	5
6	B	1	960446	F5:COMETB	L0:44 012911	WHEAT	7	0	1012.1	5.66147932	5	5.66147932	5
7	B	1	960446	F5:COMETB	L0:44 012911	WHEAT	7	0	1012.8	5.48553787	5	5.48553787	5
8	B	1	960446	F5:COMETB	L0:44 012911	WHEAT	7	0	1011.8	5.9195876	5	5.9195876	5

The rows where ‘trim2’ equal ‘0’ are highlighted blue in the spreadsheet

To see where these data points fit in the distribution: Rows/Colours/Select a colour. This will highlight the points with a coloured dot in the far left column. To see the distribution histogram, the commands are: Analyse/Distribution. Then scroll down and with a single click select the column name ‘yield_t_ha’ and press the ‘Y,Columns’ button to cast the ‘yield_t_ha’ column into the adjacent box.

Then press OK. A histogram displaying the data distribution will be displayed and the upper and lower trim points will be highlighted in red.

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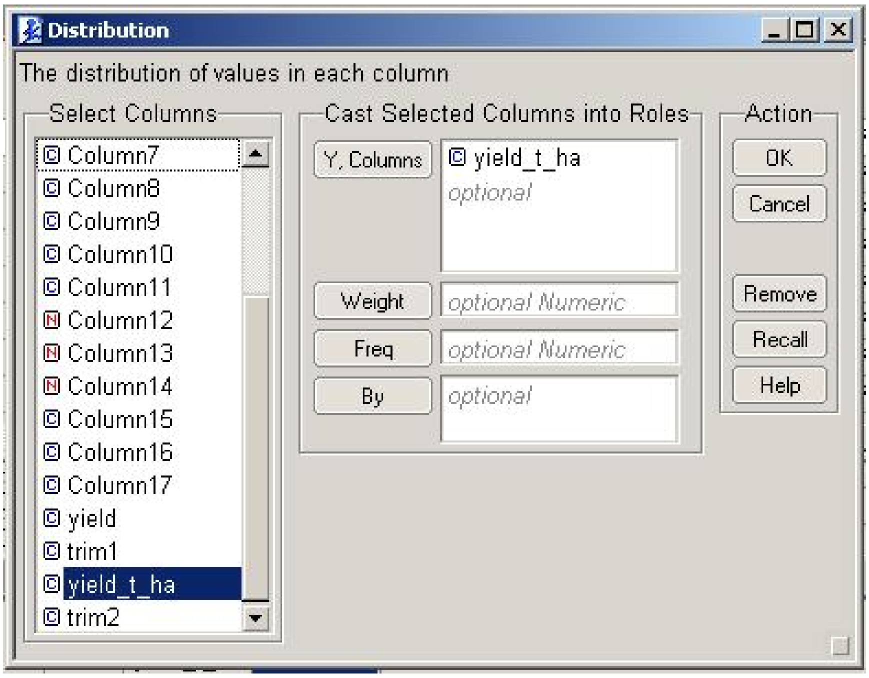
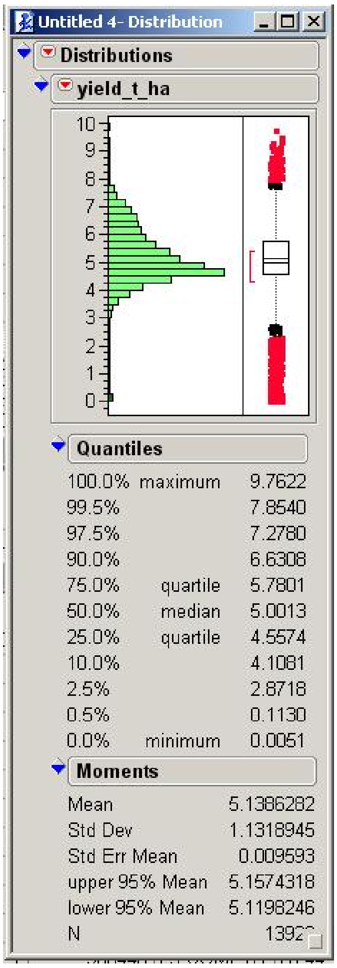
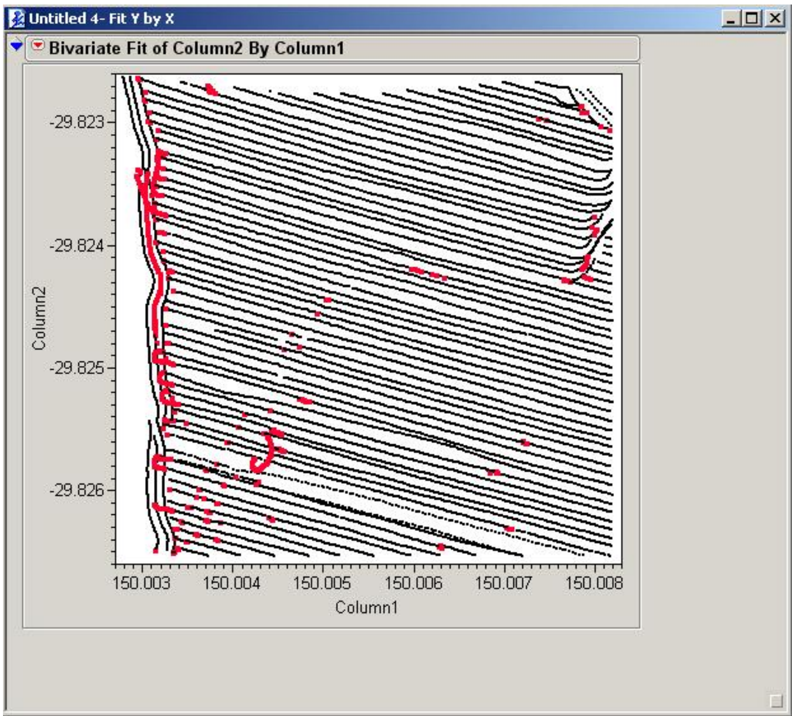


Examine the distribution of the 'yield_t_ha' data in a histogram

It is also possible to see where these points are in the paddock using a biplot. Choose Analyse/Fit Y by X. Then with a single click select 'Column 1' and cast it as an 'X,Factor' by pressing the 'X,Factor' box. Select 'Column2' and cast it as a 'Y,Factor' in the same way. Press OK.

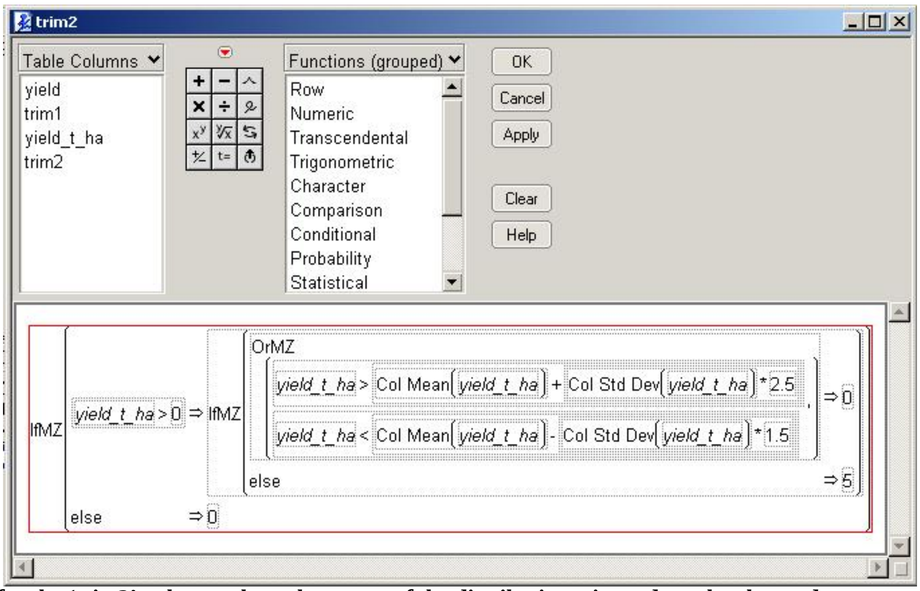


The data histogram with the points to be trimmed identified in red



The points to be trimmed are concentrated at the end of runs and where the comb may have been left down without harvesting.

The trimming procedure is the same for all 3 YieldCalc files. The different files just use different formulas for the yield calculation to account for different recorded units of measure. The JDYieldCalcB file also has a different formula for trimming the distribution (trim2). The JD yield monitor files usually have a longer tail at the low end of the distribution. If you find this is truncating too much data from your JD files, the formula in the trim2 column can be accessed by RIGHT CLICKING in the box containing the column name in the spreadsheet and then LEFT CLICKING on ‘Formula’. This opens the box below and you can change the value 1.5 to 2 or 2.5 to gradually include more of the data at the lower end of the range. Press APPLY and OK .



The formula box for the ‘trim2’ column where the extent of the distribution trimmed can be changed

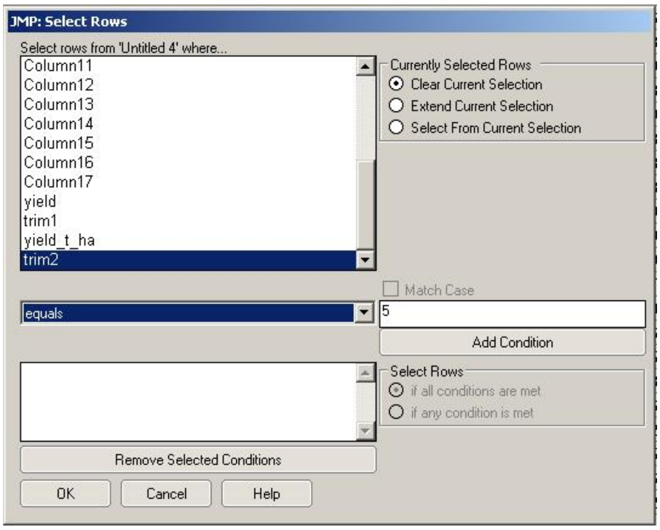
This will recalculate the trimming so it is necessary to then go back and clear the row colours before beginning Step 5 again. Clear the row colours in the spreadsheet by clicking on the top of the spreadsheet to Activate it, then Rows/Clear Row States.

Step 5 is optional but is a good way to initially check that the trimming is working for your data sets. Before continuing, Rows/Clear Row States will set the spreadsheet back to the correct state.

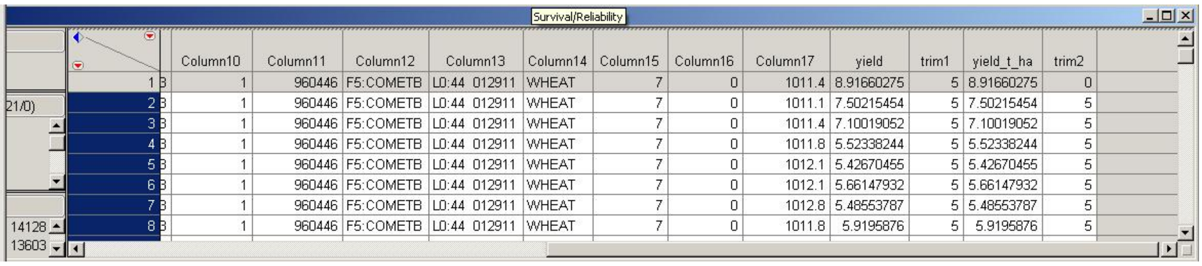
6. Trim the data set: Rows/Row Selection/Select Where

Highlight the ‘trim2’ column from the list offered, select ‘equals’ from the pull down menu and type 5 into the vacant box next to the pull-down menu arrow. Press OK.

This will highlight all the rows in the spreadsheet that we want to retain for mapping. For further processing it is not necessary to keep all the columns so we will select and save those that are important. This is achieved by holding the curser over the box with the column name in it and clicking once. The column will be highlighted and the top rectangle will be blue. Hold down the Control Key (Ctrl) and select the next column to save. Save columns 1,2,8, and yield_t_ha. If elevation has been recorded it is good to save that as well. It should be in Column 17.

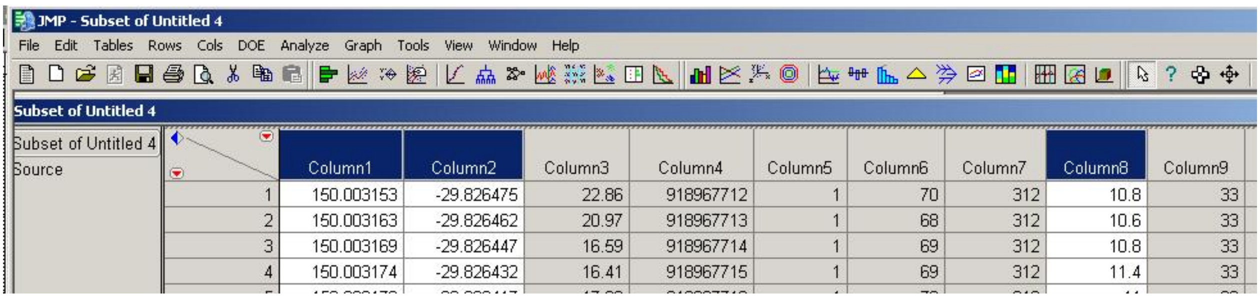


Select the points where 'trim2' equals '5'



	Column10	Column11	Column12	Column13	Column14	Column15	Column16	Column17	yield	trim1	yield_t_ha	trim2
1	1	960446	F5:COMETB	L0:44 012911	WHEAT	7	0	1011.4	8.91660275	5	8.91660275	0
2	1	960446	F5:COMETB	L0:44 012911	WHEAT	7	0	1011.1	7.50215454	5	7.50215454	5
3	1	960446	F5:COMETB	L0:44 012911	WHEAT	7	0	1011.4	7.10019052	5	7.10019052	5
4	1	960446	F5:COMETB	L0:44 012911	WHEAT	7	0	1011.8	5.52338244	5	5.52338244	5
5	1	960446	F5:COMETB	L0:44 012911	WHEAT	7	0	1012.1	5.42670455	5	5.42670455	5
6	1	960446	F5:COMETB	L0:44 012911	WHEAT	7	0	1012.1	5.66147932	5	5.66147932	5
7	1	960446	F5:COMETB	L0:44 012911	WHEAT	7	0	1012.8	5.48553787	5	5.48553787	5
8	1	960446	F5:COMETB	L0:44 012911	WHEAT	7	0	1011.8	5.9195876	5	5.9195876	5

The points that are selected are highlighted in the spreadsheet

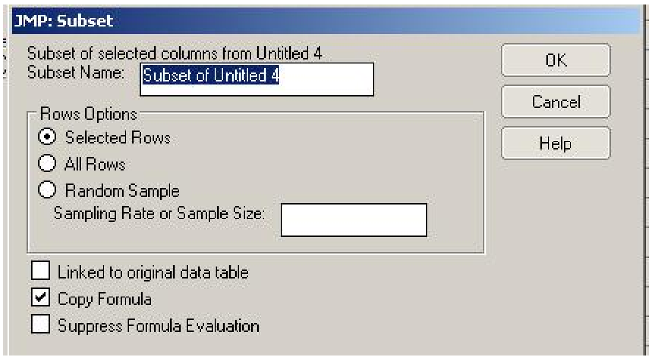


	Column1	Column2	Column3	Column4	Column5	Column6	Column7	Column8	Column9
1	150.003153	-29.826475	22.86	918967712	1	70	312	10.8	33
2	150.003163	-29.826462	20.97	918967713	1	68	312	10.6	33
3	150.003169	-29.826447	16.59	918967714	1	69	312	10.8	33
4	150.003174	-29.826432	16.41	918967715	1	69	312	11.4	33

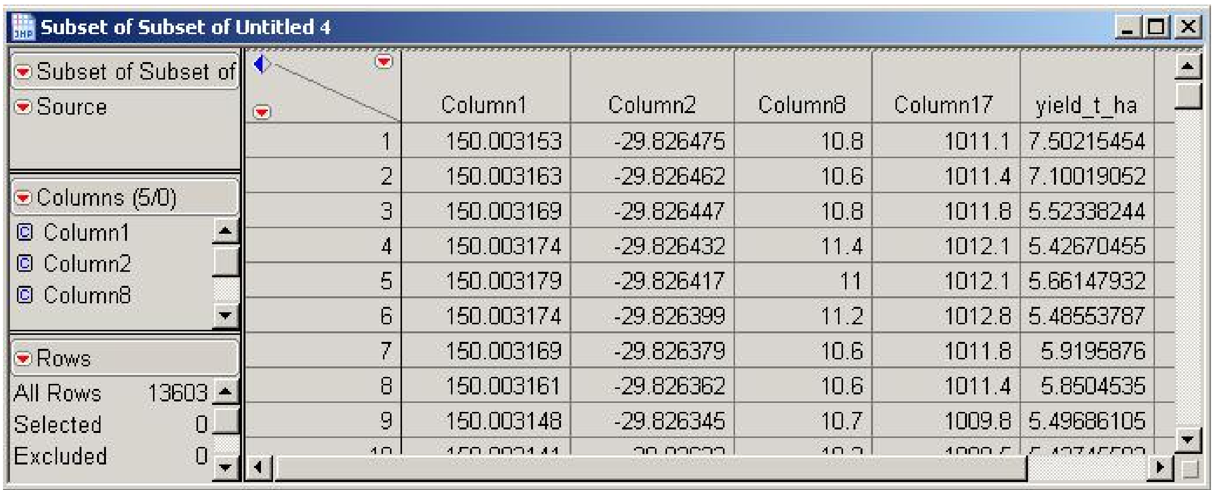
Clicking once in the top of the box that contains the column name will select a column

7. Subset the Spreadsheet: Tables/Subset

Ensure that the ‘Selected Rows’ button is ON and the ‘Copy Formula’ box is ticked.Press OK.



Make a new spreadsheet with only the data selected

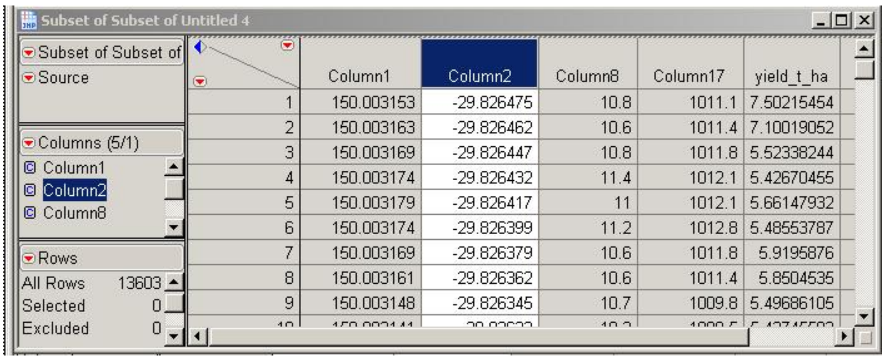


	Column1	Column2	Column8	Column17	yield_t_ha
1	150.003153	-29.826475	10.8	1011.1	7.50215454
2	150.003163	-29.826462	10.6	1011.4	7.10019052
3	150.003169	-29.826447	10.8	1011.8	5.52338244
4	150.003174	-29.826432	11.4	1012.1	5.42670455
5	150.003179	-29.826417	11	1012.1	5.66147932
6	150.003174	-29.826399	11.2	1012.8	5.48553787
7	150.003169	-29.826379	10.6	1011.8	5.9195876
8	150.003161	-29.826362	10.6	1011.4	5.8504535
9	150.003148	-29.826345	10.7	1009.8	5.49686105

The new spreadsheet contains only the columns and rows that were selected

Move ‘Column 2’ to the beginning of the Spreadsheet by first highlighting the column by placing the cursor in the box containing the column name and clicking once.

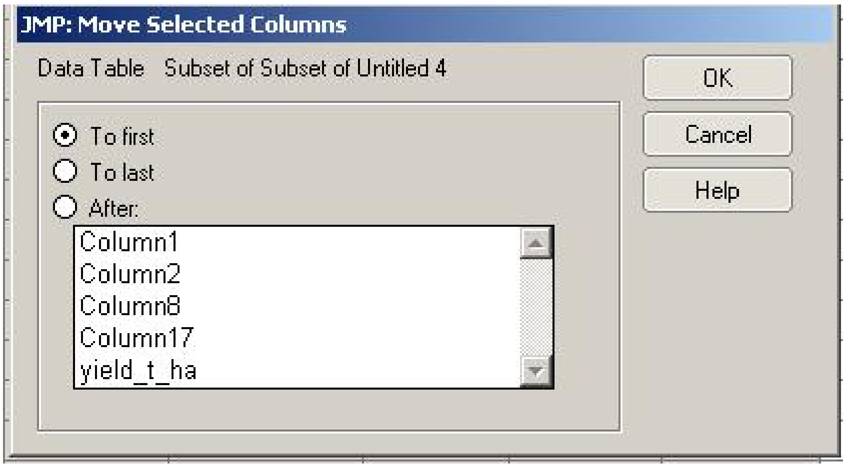
Then: Cols/Reorder Columns/Move Selected Columns...



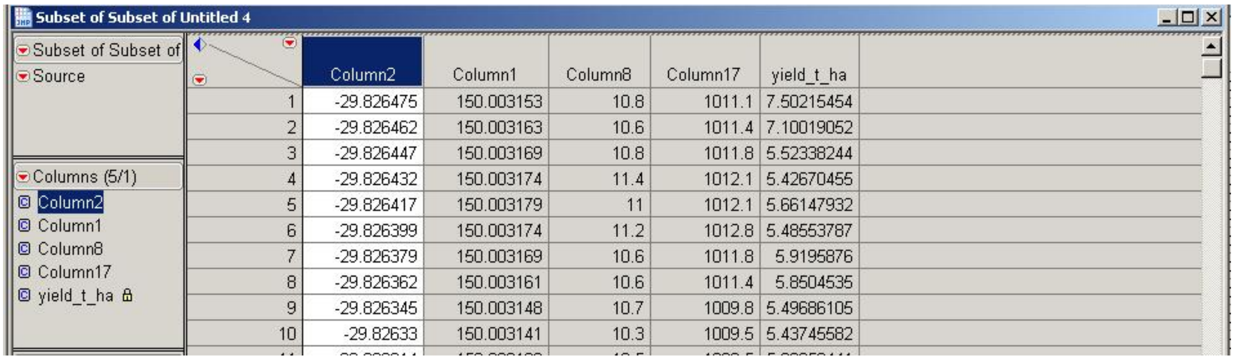
	Column1	Column2	Column8	Column17	yield_t_ha
1	150.003153	-29.826475	10.8	1011.1	7.50215454
2	150.003163	-29.826462	10.6	1011.4	7.10019052
3	150.003169	-29.826447	10.8	1011.8	5.52338244
4	150.003174	-29.826432	11.4	1012.1	5.42670455
5	150.003179	-29.826417	11	1012.1	5.66147932
6	150.003174	-29.826399	11.2	1012.8	5.48553787
7	150.003169	-29.826379	10.6	1011.8	5.9195876
8	150.003161	-29.826362	10.6	1011.4	5.8504535
9	150.003148	-29.826345	10.7	1009.8	5.49686105

Column 2 is selected

Ensure that the 'To First' button is ON and press OK.



Highlight column 2 and move it to the beginning of the spreadsheet



	Column2	Column1	Column8	Column17	yield_t_ha
1	-29.826475	150.003153	10.8	1011.1	7.50215454
2	-29.826462	150.003163	10.6	1011.4	7.10019052
3	-29.826447	150.003169	10.8	1011.8	5.52338244
4	-29.826432	150.003174	11.4	1012.1	5.42670455
5	-29.826417	150.003179	11	1012.1	5.66147932
6	-29.826399	150.003174	11.2	1012.8	5.48553787
7	-29.826379	150.003169	10.6	1011.8	5.9195876
8	-29.826362	150.003161	10.6	1011.4	5.8504535
9	-29.826345	150.003148	10.7	1009.8	5.49686105
10	-29.82633	150.003141	10.3	1009.5	5.43745582

Column 2 has been moved to the beginning of the spreadsheet

Name the columns with more appropriate descriptors by placing the cursor directly on the name and clicking TWICE. The name will be highlighted and can be edited. A shortcut here is that once you have edited the first column name, pressing the TAB key will move the cursor directly to the next column name and it will be ready to edit.

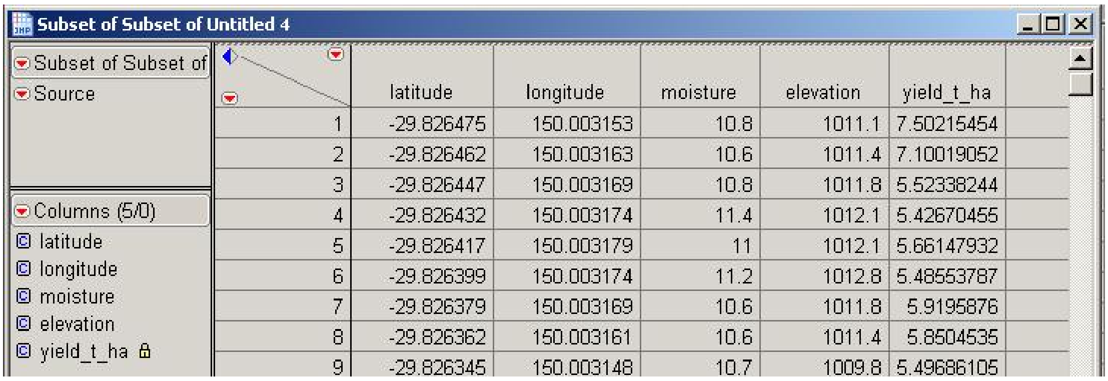
The names will be:

Rename Column2 with:*latitude*

Rename Column1 with: *longitude*

Rename Column8 with: *moisture*

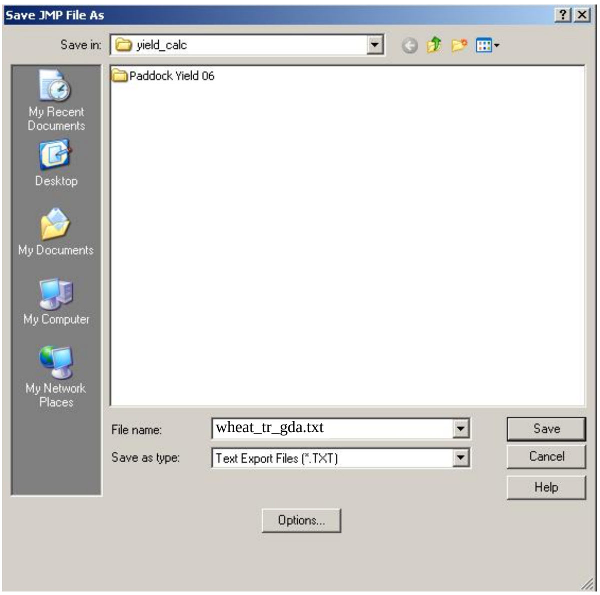
Rename Column17 with: *elevation*



	latitude	longitude	moisture	elevation	yield_t_ha
1	-29.826475	150.003153	10.8	1011.1	7.50215454
2	-29.826462	150.003163	10.6	1011.4	7.10019052
3	-29.826447	150.003169	10.8	1011.8	5.52338244
4	-29.826432	150.003174	11.4	1012.1	5.42670455
5	-29.826417	150.003179	11	1012.1	5.66147932
6	-29.826399	150.003174	11.2	1012.8	5.48553787
7	-29.826379	150.003169	10.6	1011.8	5.9195876
8	-29.826362	150.003161	10.6	1011.4	5.8504535
9	-29.826345	150.003148	10.7	1009.8	5.49686105

The columns have been labelled with suitable names

8. Save the data as a .txt file: File/Save As



Save the data as a .txt file with a meaningful name

Locate the appropriate storage location and give the file a suitable name. The name should reflect the fact that the data has been trimmed or cleaned and that it contains GPS location in latititude and longitude. An example is: wheat_tr_gda.txt.

For the 'Save as Type' window, select 'Text Export Files (*.TXT) from the drop-down menu and then press SAVE. A trimmed yeld file in .txt format has been created and can be used in further mapping and analysis.

NOTE: If the original yield data file has an already calculated yield value that is to be used but the file still has erroneous points, the DisTrim.jmp file can be used from Step 2. The column with the yield values from the original file must be labelled 'yield' prior to joining in Step 3. All other steps remain the same.

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last updated January 2007
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Grains Research & Development Corporation

Clustering Field Data

with JMP to create Management Classes

The production of 'pretty' maps of various production variables is satisfying, however maps can only be used to visually assess relationships. Consequently the quality of the cartography may have a large impact on the quality of decisions made. The analysis of multiple layers of field data using some statistical justification will help us overcome these problems. Cluster algorithms are one (of numerous) statistical methods that can be used to 'fuse' data from different sensors and/or times together into a single useful data layer - a management class map.

Introduction

Clustering is a process that allows multiple layers of information to be compressed into a single layer. It is a statistical technique with a wide range of applications. In Precision Agriculture one of the most common uses of clustering algorithms is for delineating managment classes using various layers of crop and/or environmental information on a paddock. This short manual provides step-by-step instructions for performing a cluster analysis using JMP™ 5 (or higher) software (SAS Institute, Cary, NC, USA).

The manual assumes that the input (predicted) data files have been created with VESPER®, a shareware spatial prediction program available from the Australian Centre for Precision Agriculture (www.usyd.edu.au/su/agric/acpa). However data from other programs can also be used provided that the data has been transformed onto a standard grid. The clustering process requires all data to be co-located therefore it is incompatible with raw field data.

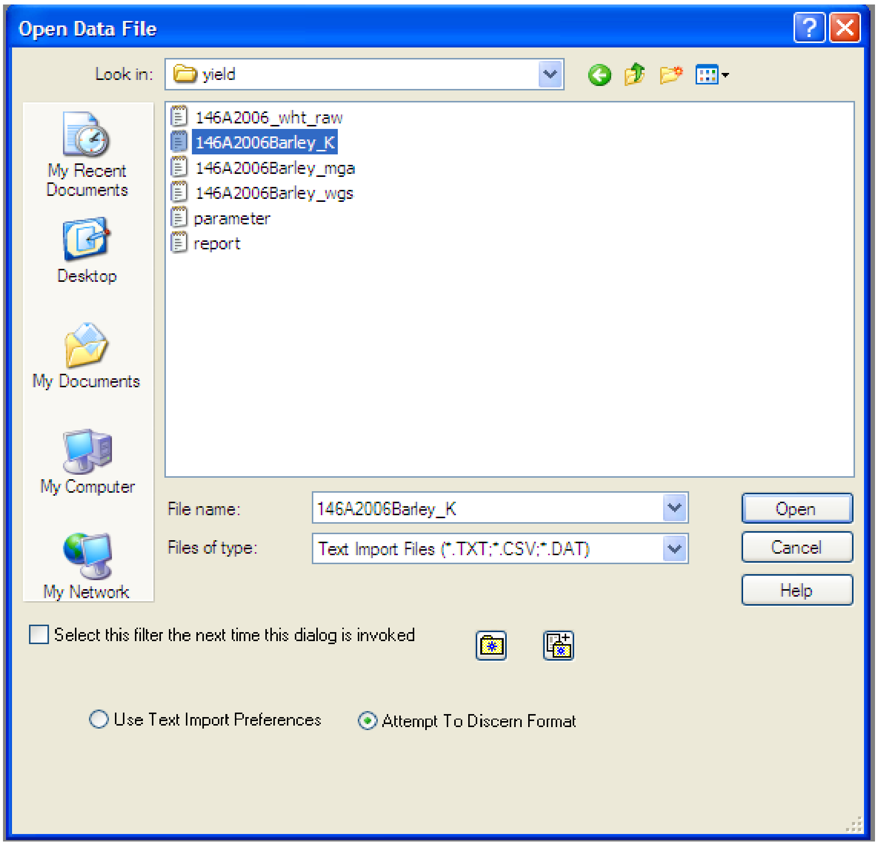
Procedure in JMP

In this section the task is listed in Green followed by the JMP commands in Red.

Import the data and establish a JMP spreadsheet

1. Open files containing the predicted field variables: File/Open/Open Data File

Ensure that the 'Files of Type' field reads 'Text Import Files (*.TXT, *.CSV, *.DAT) and the 'Attempt To Discern Format' button is checked. Navigate to the desired folder using the Windows features and select the desired .txt file and press OPEN. Repeat this for all the interpolated variables for the field. NB. All files should have the same number of rows which corresponds to the field grid size.

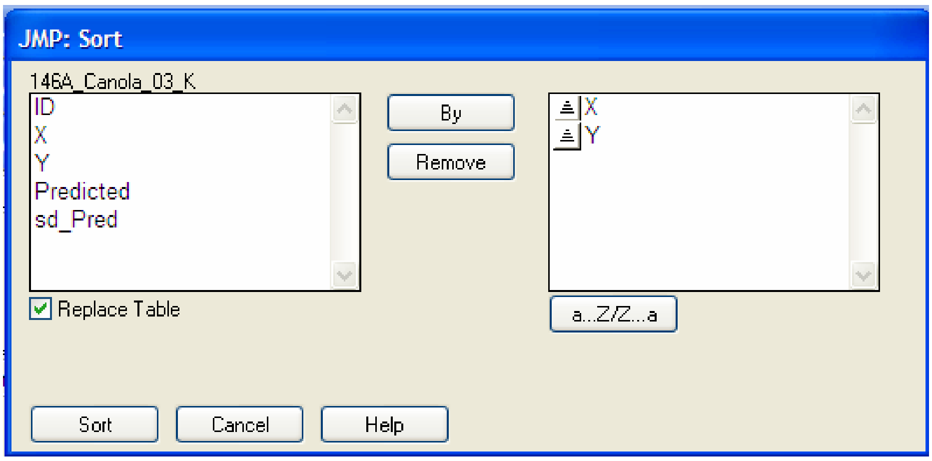


Open Data File window: Ensure that the correct 'Files of Type' is selected and the 'Attempt To Discern Format' button is checked

2. Sort columns: Tables/Sort

Sorting the columns by the Easting and Northing coordinates ensures that all the rows of data in the separate files will align correctly. Occasionally the interpolation process will reorder rows (without changing the values in the rows). If different files have a different row order then the data will not correspond and cannot be analysed successfully.

Place the X and Y (Easting and Northing) columns in the right-hand box, always keeping them in the same order (X on top). Ensure that the 'Replace Table' box is checked before clicking sort. Each spreadsheet needs to be sorted independently.



Sort window: Each data set needs to be independently sorted by X and Y. Check the 'Replace Table' box to update the existing spreadsheet.

3. Join the interpolated files into a single spreadsheet

Select one file as the master file and 'Save As' under a new name as a JMP file. It is recommended to use the earliest dataset for this. (File/Save As/ then navigate to the correct storage directory)

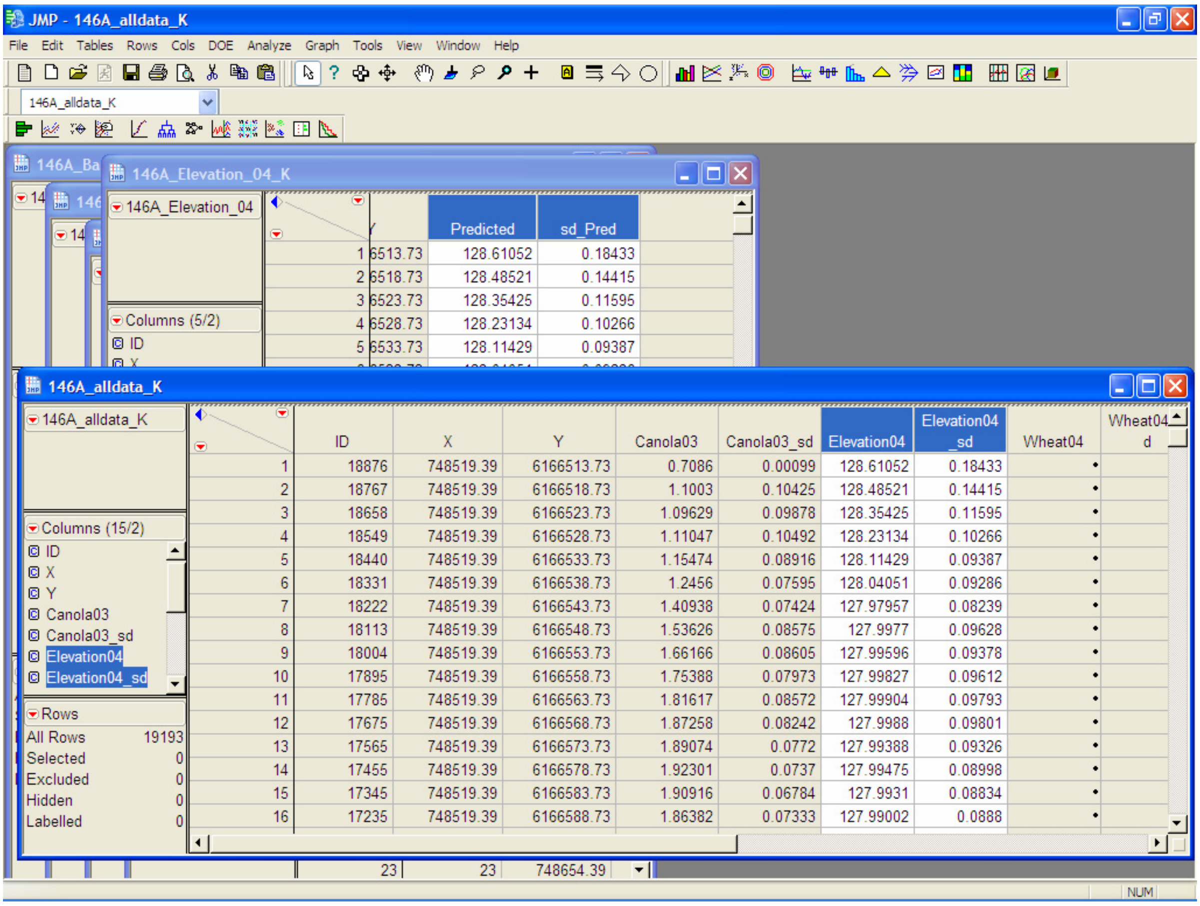
Rename the 'Predicted' and the 'sd_Pred' columns in the master file with an ID corresponding to the data (Select a column by clicking on its header and then Cols/Column Info to enter a new name). For example Barley data from 1999 may be renamed 'Barley99, and 'Barley99_sd' respectively. The '_sd' suffix refers to the standard deviation of the predicted data and helps to distinguish between this data and the 'Predicted' values.

Create new columns in the master spreadsheet (Cols/Add Multiple Columns.../). The number of columns needed will be twice the number of other interpolated files for the field.

Rename the new columns with appropriate IDs. Again the variable name and a year is recommended. Create labels for both the 'Predicted' and 'sd_Pred' values.

In the original predicted files select the two columns containing the 'Predicted' and 'sd_Pred' data. Copy the two columns ensuring that all the rows are selected. (Select columns then Edit/Copy)

Select the desired destination columns in the master spreadsheet then paste (Edit/Paste) the columns. Repeat for all available data.



Example of the master spreadsheet being setup and the naming protocol recommended. NB. the master spreadsheet has been saved under a new name (as a .JMP file)

4. Perform Cluster Analysis: Analyze/Multivariate Methods/Cluster

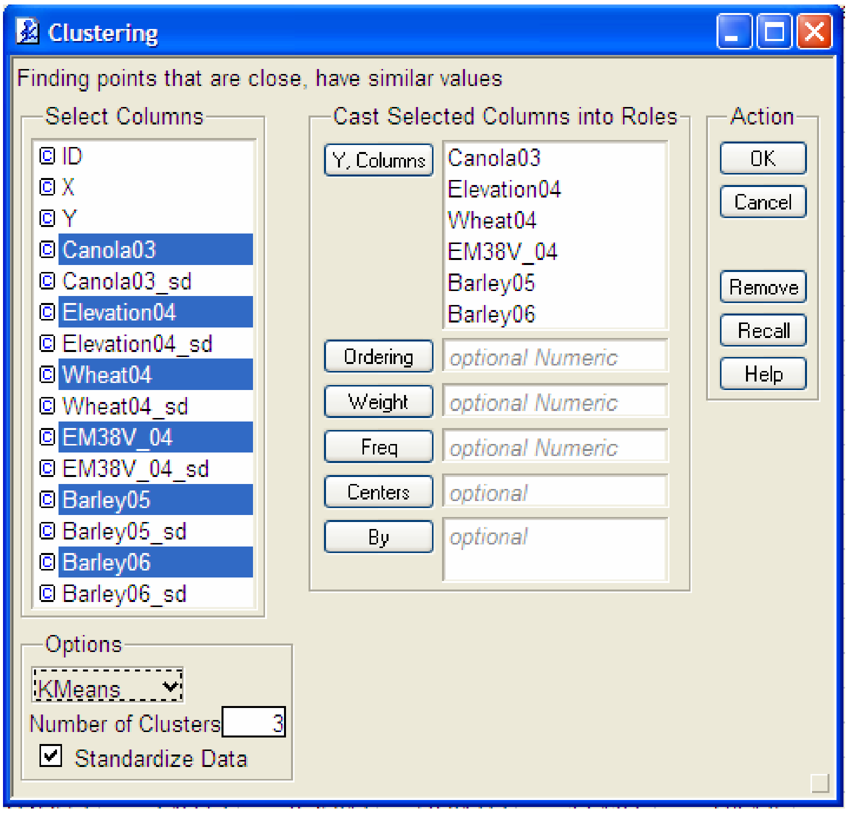
This opens the 'Clustering' window. On the lefthand side in the 'Select Columns' frame click on the name of the column (variable) to be included in the analysis. Then click the 'Y, Columns' button to add the variable to the righthand side frame. Do this for all variables that are to be clustered together. Only 'Predicted' values should be used. The 'sd_Pred' values should not be used in the cluster process. Ignore the options for 'Ordering', 'Weight', 'Freq', 'Contains' and 'By'. In the drop down menu for 'Options' change the default 'Hierachical' to 'KMeans'. 'Method' shold be left at the default ('Ward') and the 'Standardize Data' box should be checked. Click 'OK'

The 'K Means Cluster' window (next page) will be launched.

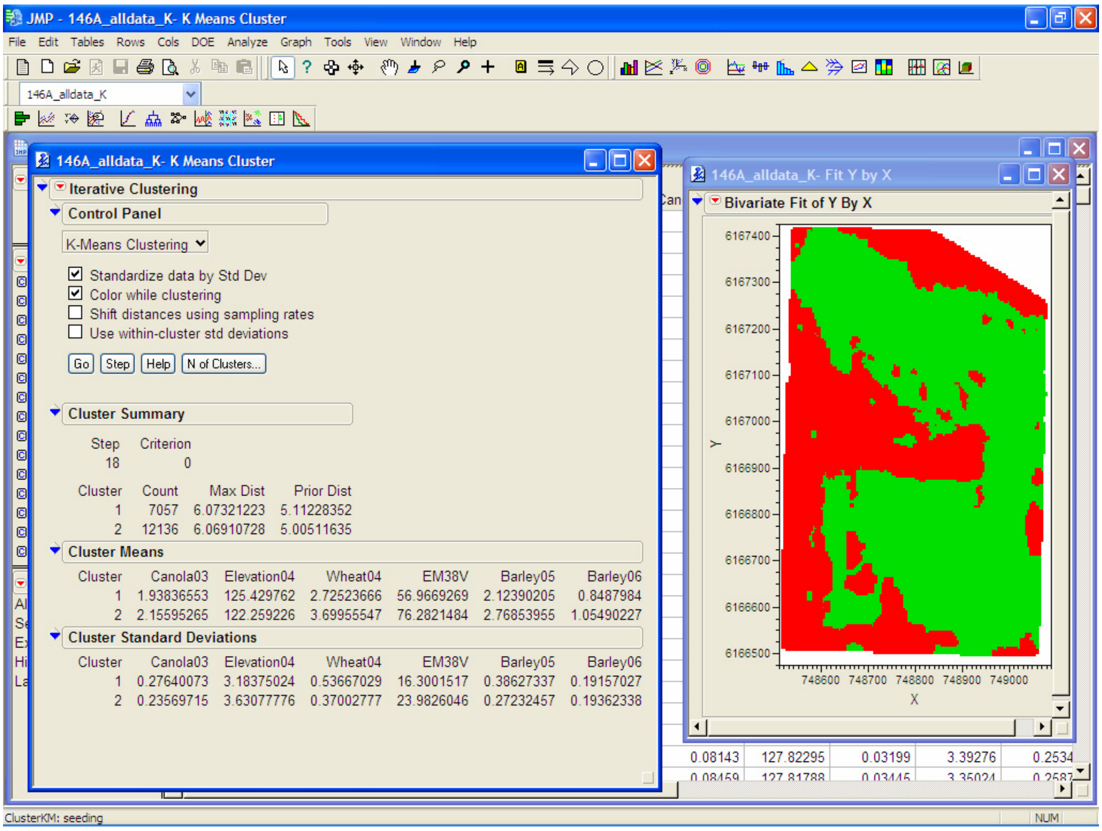
Before proceeding with this window, viewing the cluster pattern as the process proceeds is possible by making a plot of the paddock in another window (Analyze/Fit Y by X/X into X/Y into Y). The 'K Means Cluster' and 'Fit Y by X' windows can be rearranged to allow both to be simultaneously viewed (see figure next page for an example).

In the 'K Measns Cluster' window :ensure that the 'Standardize data by Std Dev' and 'Color while clustering' boxes are checked. Click 'GO'. The software will iterate until it finds a solution.

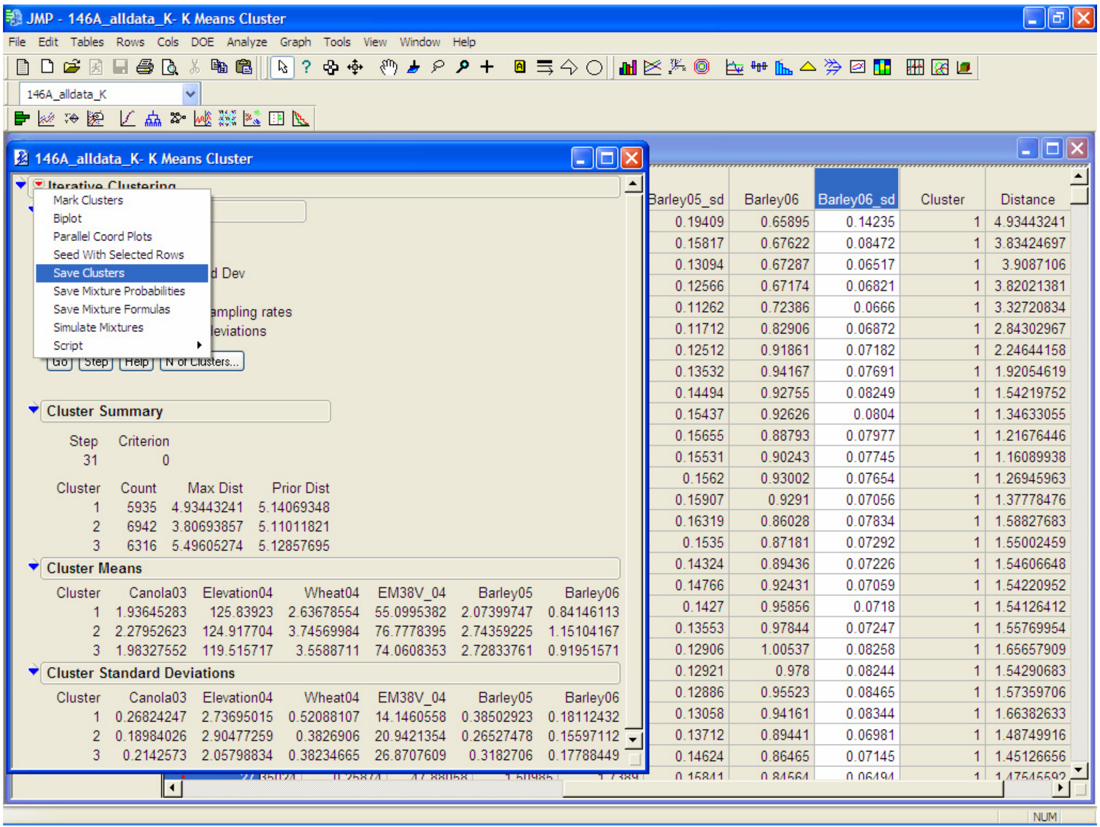
To try different numbers of clusters click the 'N of Clusters...' button and redefine the number of clusters desired. To change the variables used in the cluster process the entire cluster process must be restarted (Analyze/Multivariate Methods/Cluster/) and the new combination of variables selected.



Clustering window: Showing the variables (columns) being selected for the cluster analysis, the 'Options' set at KMeans and the 'Standardize Data' box checked.



The set-up of the K Means Cluster window and a X by Y plot is also dislayed with the results of the cluster analysis which is equivalent to a 2 class management map



The process for saving cluster results and on the lefthand-side in the master spreadsheet the saved Cluster vaues and Distance scores.

To save the results of the cluster analysis, select the small red dropdown menu next to 'Iterative Clustering' in the 'K Means Cluster' window, then select 'Save Clusters'. This saves a column of cluster IDs and a Distance measurement into the master spreadsheet.

Once the clusters have been saved it is advisable to make a note of the variables that were used in the analysis. This can be done by selecting the Cluster column then selecting Cols/Col info/. In the 'Column Info' window chose the drop down menu labelled '*New Property*' and select '*Notes*'. Enter the variables used into the 'Notes' frame then click 'OK". This process is useful when updating managment zone maps as new information, particularly subsequent years yield maps, are added to the master spreadsheet. It also creates the option for multiple cluster approaches to be stored and compared in the one spreadsheet without creating confusion.

Using the Output

5. Exporting the results:

The results of the cluster analysis can be exported through a two step process

1) Select the X, Y and Cluster columns in the master spreadsheet. Subset the three columns (Tables/Subset/). Provide a new name for the new spreadsheet, ensure 'All rows' are selected and uncheck the 'Linked to original data table' box.

2) Export the new spreadsheet as a '.txt', '.csv' or relevant data format for use in other PA software/hardware (File/Save As.../). The desired file type can be selected from the 'Save as type' drop down menu.

The cluster results (classes) can be used for a wide range of purposes, including targeted sampling, variable rate application, analysis of yield results, on-farm experiments etc. that are beyond the scope of this manual. Further information on applications of Management Classes can be found in the educational resources section of the ACPA website.

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Last updated January 2007
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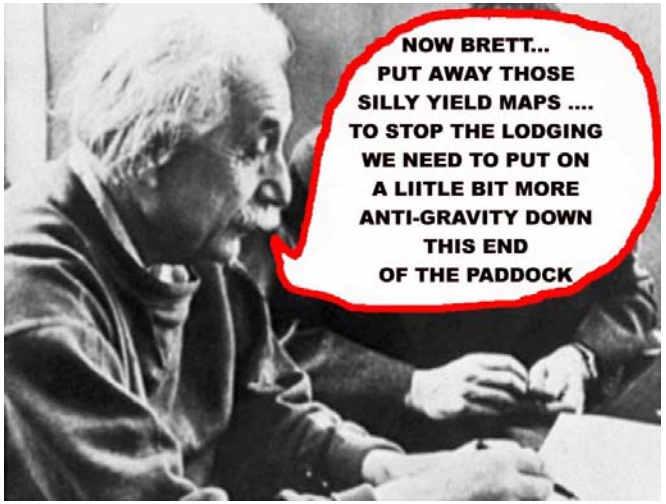
Einstein and Precision Agriculture

Alex. McBratney *Australian Centre for Precision Agriculture*

In the earlier part of this decade I was asked to give a talk one evening. I had fairly tough opposition as somewhere else in the university a fairly recent Nobel Laureate in physics was giving a talk on how through astrophyical measurements he had confirmed one apsect of Einstein's relativity theory. A brilliant new theory published in 1905. So I told my audience that given the opposition I'd talk on the application of relativity theory to agriculture. If I'd been serious it would have been a very short talk _ because I couldn't think of any. Things are not massive enough or fast enough in farming to warrant the relativity theory. Good old Newton will do the trick. At least that's what I thought at the time. Now, the incredible new technology that is GPS has been made possible by a combination of scientific and engineering advances, particularly development of the world's most accurate timepieces: atomic clocks that are precise to within a thousandth of a millionth of a second. The clocks were created by physicists seeking answers to questions about the nature of the universe, questions raised by Einstein, with no conception that their technology would some day lead to a global system of positioning and navigation.

For centuries, the only way to navigate was to look at the position of the sun and stars and use dead reckoning. Even after modern clocks were developed for the Royal Navy by Harrison in England, making it possible to find one's longitude, the most accurate chronometers could yield a position that was accurate only to within a few miles. So until the late 1920s, the most accurate timepieces depended on the regular swing of a pendulum. They were superseded by more accurate clocks based on the regular vibrations of a quartz crystal, which could keep time to within less than one-thousandth of a second per day. Even that kind of precision, however, would not suffice for scientists who wanted to study Einstein's theory of gravity and ***here is the link between Einstein and Precision Agriculture***.

According to Einstein, a gravitational field would distort both space and time. Thus, a pendulum clock on top of Mount Everest, for instance, was predicted to run 30 millionths of a second per day faster than an identical clock at sea level. For light travelling 300 million metres per second this is equivalnent to ...... The only way to make measurements this accurate was to control a clock by the infinitesimal oscillations of the atom itself. Additionally, an atomic clock travelling at high speed in a satellite ticks slightly more slowly than its counterpart on the ground.



The difference is extremely small when we're dealing with jets and cars and such, but at velocities approaching the speed of light, the effect is enormous. In 1938 I.I. Rabi's research on the fundamental properties of atoms and nuclei led to his invention of a technique called magnetic resonance (the basis for the medical imaging of soft tissue) on which the first atomic clock was based. Rabi's student, Norman Ramsey, laid the groundwork for the development of the caesium-beam "fountain" clock and invented the hydrogen maser, devices that redefined timekeeping.

In addition to the clock, when the Soviet Union launched Sputnik on October 4, 1957, it was immediately recognized that this "artificial star" could be used as a navigational tool. The very next evening, researchers at the Lincoln Laboratory of the Massachusetts Institute of Technology (MIT) were able to determine the satellite's orbit precisely by observing how the apparent frequency of its radio signal increased as it approached and decreased as it departed--an effect known as the Doppler shift. The proof that a satellite's orbit could be precisely determined from the ground was the first step in establishing that positions on the ground could be determined by homing in on the signals broadcast by satellites.

In the years that followed, the U.S. Navy experimented with a series of satellite navigation systems, beginning with the Transit system in 1965, which was developed to meet the navigational needs of submarines carrying Polaris nuclear missiles. These submarines needed to remain hidden and submerged for months at a time, but gyroscope-based or inertial navigation, could not sustain its accuracy over such long periods. The Transit system comprised half a dozen satellites that would circle the earth continuously in polar orbits. By analyzing the radio signals transmitted by the satellites--in essence, measuring the Doppler shifts of the signals--a submarine could accurately determine its location in 10 or 15 minutes. In 1973, the US Department of Defence was looking for a foolproof method of satellite navigation. A brainstorming session at the Pentagon over the Labour Day weekend produced the concept of GPS on the basis of the department's experience with all its satellite predecessors. The essential components of GPS are the 24 Navstar satellites built by Rockwell International, each the size of a large automobile and weighing some 850 kg. Each satellite orbits the earth every 12 hours in a formation thatensures that every point on the planet will always be in radio contact with at least four satellites. The first operational GPS satellite was launched in 1978, and the system reached full 24-satellite capability in 1993.

A Chronology of Some Key Developments leading to GPS

1905-1915 Einstein develops his Special and general theories of relativity

1938-1940 I.I. Rabi invents and applies magnetic resonance at Columbia University in 1938. Possibility of atomic clock is discussed.

1954-1956 Zacharias and National Company develop the first self-contained portable atomic clock, the Atomichron.

1957 Sputnik is launched in October by the Soviet Union. Satellite Doppler tracking is inaugurated at MIT Lincoln Laboratory and Johns Hopkins Applied Physics Laboratory (APL) Navy Transit program is started at APL in December.

1960-1965 Rubidium optically pumped clock is introduced. Caesium frequency standards are installed in most international time-standard laboratories.

1964-1965 First position fix from a Transit satellite is computed aboard Polaris submarine.

1967 Transit system is made available to civilian community.

1968 Standards of a Defence Navigation Satellite System are defined.

1973 Development of Navstar GPS is approved by the US Department of Defense.

1974 First GPS test satellite, from Timation program, is launched to test rubidium clocks and time-dissemination techniques.

1977 Test satellite incorporating principal features of later GPS satellites, including first caesium clocks in space, is launched.

1978-1985 Ten prototype GPS satellites are launched, built by Rockwell International.

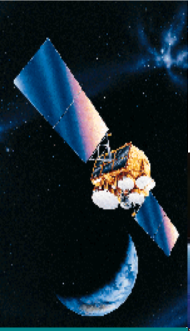
1989-1993 Series of 24 satellites are launched at about 6 per year. Final satellite is launched on June 26, 1993.
The current worldwide market for GPS receivers and technology is estimated at more than A$3 billion and is expected to grow to more than A$45 billion during the next 10 years.

It is often forgotten that GPS is still a military device built by the Department of Defense at a cost of $12 billion and intended primarily for military use. That fact has led to one of the few controversies surrounding the remarkably successful system. As with any new technology, progress brings risk, and GPS potentially could be used to aid smugglers, terrorists, or hostile forces. The Pentagon made the GPS system available for commercial use only after being pressured by the companies that built the equipment and saw the enormous potential market for it. As a compromise, however, the Pentagon initiated a policy known as selective availability, whereby the most accurate signals broadcast by GPS satellites would be reserved strictly for military and other authorized users. GPS satellites now broadcast two signals: a civilian signal that is accurate to within 30m and a second signal that only the military can decode that is accurate to within 10m. The Pentagon has also reserved the ability to introduce errors at any time into the civilian signal to reduce its accuracy to about 100m.

In March 1996, the White House announced that a higher level of GPS accuracy will be made available to everyone, and the practice of degrading civil GPS signals will be phased out within a decade. The White House also reaffirmed the federal government's commitment to providing GPS services for peaceful civil, commercial, and scientific use on a worldwide basis and free of charge.

The future of GPS appears to be virtually unlimited; technological fantasies abound. The system provides a novel, unique, and instantly available address for every square metre on the surface of the planet--a new international standard for locations and distances. To the computers of the world, at least, our locations may be defined not by a street address, a city, and a state, but by a longitude and a latitude. With the GPS location of services stored with phone numbers in computerized "yellow pages," the search for a local restaurant or the nearest petrol station in any city, town, or suburb will be completed in an instant. With GPS, the world has been given a technology of unbounded promise, born in the laboratories of scientists who were motivated by their own curiosity to probe the nature of the universe and our world, and built on the fruits of publically supported basic research.

The moral of this story that governments, economists and the community should remember is that all basic research will turn out to be useful in the long run. It's just a question of how long is long?



Global Navigation Satellite Systems

Satellite based navigation systems are truly the enabling technology of Precision Agriculture. They provide a relatively simple and robust technique for identifying any location on the earth's surface, or, in the case of aircraft, relative to the surface. This permits any agricultural and environmental operations to be geo-referenced and spatially analysed. A wide range of satellite-based navigation and geo-location tools are available to suit different agronomic situations from point crop/soil sampling to autonomous vehicle guidance.

Introduction

Satellite navigation systems utilise a constellation of satellites orbiting the earth to geo-locate a receivers position on or near the earths surface. Two systems are currently in operation, the NAVSTAR Global Positioning System (GPS), owned by the government of the United States of America, and the Global Navigation Satellite System (GLONASS), which is controlled by a consortium headed by the Russian Government. Two more systems are being planned. The European Space Agency intends to have their network, Gallileo, fully operational in 2008. A Japanese consortium is also planning to launch a satellite navigation system designed for satellite navigation and communication for automobiles. All four existing and proposed systems are basically similar however far more receivers have been developed by commercial enterprises to utilise the information from the GPS satellites so its operation will form the basis of the following review.

How Satellite Based Navigation Systems Work

The GPS, GLONASS and proposed Gallileo and Japanese systems are all designed with three core segments, Space, Control and User.

Space Segment

This consists of the satellite constellation that is orbiting the earth and the Delta rockets used to launch the satellites. In the GPS constellation there are 24 satellites that orbit the earth every 12 hours at an altitude of 20,200km. The satellites are organised into 6 equally spaced orbital planes (60 degrees apart), with 4 satellites per plane. Each satellite is inclined at 55 degrees to the equatorial plane to ensure

coverage of the polar regions. A visible explanation of the satellite constellation is provided in Figure 1. This combination is designed to provide a user anywhere on the earths surface with 5-8 visible satellites. The satellites are powered by solar cells, programmed to follow the sun, and have 4 on-board atomic clocks that are accurate to a nanosecond (a billionth of a second). The satellites also have a variety of antennas to generate, send and receive signals. On-board the satellite signals are generated by a radio transmitter and sent to land-based receivers by L-band antennas

Control Segment

The control segment of the GPS Navigation Systems consists of a Master Control Station which is supported by Monitor Stations and Ground Antennas. The Monitor Stations check the exact altitude, position, speed and overall health of the GPS satellite. A Monitor Station can track up to 11 satellites simultaneously and each satellite is checked twice a day by each Monitor Station. The information collected by the Monitoring Stations is relayed to the Master Control Station to assess the behaviour of each satellites orbit and clock. If any errors are noted then the Master Control Station directs the relevant Ground Antenna to relay the required corrective information to the relevant satellite. The global locations of the Control Segments are shown in Figure 2.

User Segment

The User Segment refers to the civilian and military personnel who use the signals generated by the GPS satellites. There are a wide range of receivers available for civilian use, ranging in price from a few hundred dollars to over fifty thousand dollars per receiver. The price is usually strongly related to the precision and accuracy of the receivers.

How Geo-Location Is Determined

Geo-location using satellite navigation systems is based on the ability to measure the time taken for a signal to travel from a satellite to the receiver. Radio signals travel at the speed of light, which is constant, so if the time of travel is known then the distance between the satellite and the receiver can be determined. Since the position of the satellites is always known, thanks to the work by the Control Segment of the system, an unknown point (the users receiver) can be calculated if the receiver is obtaining signals from at least four satellites.

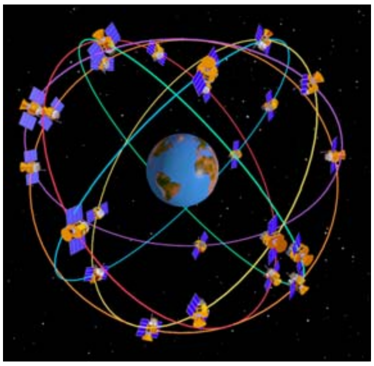


Figure 1: Schematic view of the orbit paths of the GPS satellites. There are 6 orbits with 4 satellites per orbit. (Courtesy of www.aero.org).

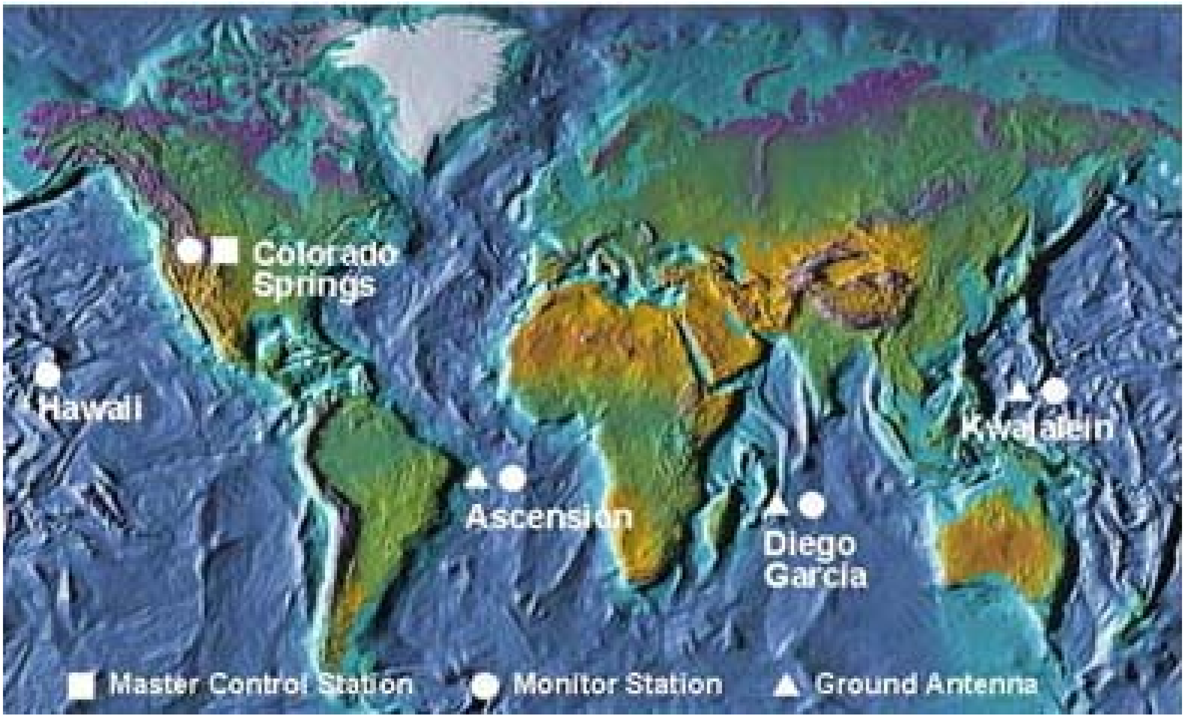


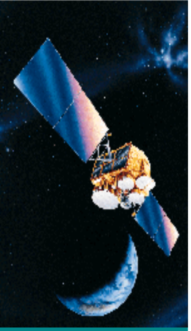
Figure 2: Locations of the Control Segment of the GPS Satellite Navigation System (Courtesy of gps.faa.gov)

Measuring Distance

Each GPS navigation satellite continuously broadcasts its position along with timing data on two frequencies (L1 and L2). The L1 band carries two codes, Coarse Acquisition (C/A) code and Precision (P) code. The L2-band only carries the P code. The C/A signal is also termed "code phase" or Standard Positioning Service (SPS) and is the main signal used in civilian activity. The P signal is also referred to as "Precise Positioning Service" and was designed for US government and military use only. It requires special cryptographic equipment to decode. The C/A and P signals take ~6 milliseconds (6/100ths of a second) to travel from satellite to receiver. The signals require a direct line of sight so receivers will not work indoors or under vegetation canopies/trees. This is a major problem in the use of GPS in horticultural tree crops.

Both the C/A and P signals have a time reference digital code referred to as a pseudo random code. Receivers contain an almanac of the pseudo random codes generated by the satellites and the time they are generated. When a receiver intercepts the digital code from a satellite it can compare the digital signal to its almanac to determine when the signal was generated. The time of travel is simply the difference between the time the signal was intercepted and the time it was generated (Figure 3). The difference between the C/A and P code is in the resolution of the code and thus the accuracy of timing and distance determination.

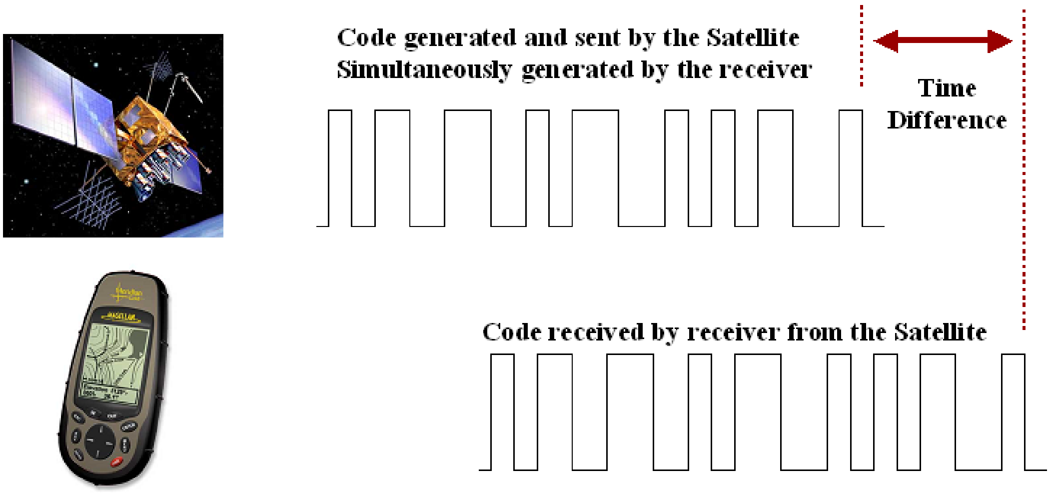
As well as transmitting in "code phase", satellites also transmit general satellite information in "carrier phase". Carrier phase signals are broadcast on both the L1 and L2-band and at a much higher frequency than the code phase. The higher



frequency permits a more accurate measurement of the range between the satellite and receiver. However the carrier phase is not time referenced like the code phase. This makes the interpretation of the signal susceptible to “cycle slip”. To minimise this effect, carrier phase receivers use the C/A code to provide a rough estimation and the carrier phase signal to improve the estimation. The frequency of the different code and carrier signals is illustrated in Figure 4 and a further explanation the difference between code and carrier phase is given in Appendix 1)

Calculating Position

If the distance (d_1) from the receiver to a satellite is known then the receiver must be somewhere on a sphere with a radius of d_1 that is centred on the satellite. If the distance (d_2) to a second satellite is determined then the receiver must also lie somewhere on a sphere of radius d_2 centred on the second satellite. Given this knowledge, the receiver must lie on the ellipse that forms the intersection of the spheres. If a third satellite is located then the receiver position is narrowed down to two points where the spheres of the three satellites intersect. Usually one of these positions can be discarded as it is not near the earth’s surface. Thus by locating three satellites, the three unknowns in the receiver’s location (latitude, longitude and altitude or X, Y, Z) can be determined.



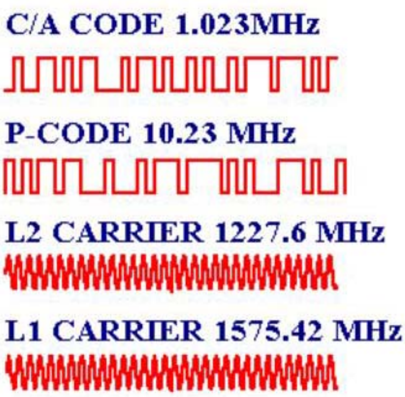
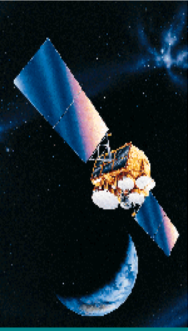


Figure 3 (above): Diagrammatic representation of the C/A code and how it is used to determine time and distance between the satellite and the receiver. (Adapted from of Paul Bolstad, http://bolstad.gis.umn.edu/chapt5figs.)

Figure 4 (left): A comparison of the waveforms and frequency of the different signals emitted by the L1 and L2-band antennas from a GPS satellite. (adapted from www.go.ednet.ns.ca)



However, the determination of the distance between the receiver and satellite relies on very accurate timing. Satellites have very accurate timing due to the use of atomic clocks on-board and constant monitoring by the Control Segment. Unfortunately atomic clocks are too heavy (~20kg) and expensive (US$50,000) to mount into GPS receivers. Therefore GPS receivers need to use inferior clocks. This creates a problem as errors in the receiver clock will degrade the estimation of distance by ~300,000m per millisecond. This problem can be overcome by assuming that the receiver clock error is a fourth unknown in the system. By connecting to a fourth satellite the receiver is able to solve the four simultaneous equations to resolve the four variables (X, Y, Z and clock error). In this case there is a trade off between the number of satellites required to calculate the receiver position and the cost of the receiver. Aschematic illustration of positioning is shown in FIgure 5.

Geo-Location Error Sources

Any error source will affect the ability of a GPS receiver to accurately determine the range to satellites which creates uncertainty in geo-location (Figure 6). Apart from the quality of the signal (C/A vs. P vs Carrier) the error in geo-location calculation by a receiver may be affected by a one or more of the following error sources.

Satellite Errors - These may be due to either errors in the timing of the on-board atomic clocks or an error in the transmitted location of the satellite (ephemeris error). Regular monitoring by the Control segment is aimed at minimising these errors. A special error associated with the Satellite clock time is Selective Availability (SA). This was a man-made error introduced into the satellite time to limit the accuracy of a GPS receiver to ±*100m* so that it could not confidently be used by other military organisations outside the USA.. In 2000, the President of the USA (and Commander-in-Chief of the US Armed Forces) turned off the SA error to promote the use of the GPS system over other Satellite-based Navigation Systems. By 2000 the development of differential correction techniques to compensate for the SA error had effectively removed any benefits derived by the military having the SA error turned on.

Receiver Errors - The ability of the GPS receiver and associated software to cope with thermal and electronic noise will affect how accurately the receiver can geo-locate itself.

Atmospheric Errors - To reach a GPS receiver, the satellite signal needs to pass through the Earths atmosphere and, in particular, the Ionosphere and Troposphere which affect the signals.

The Ionosphere contains charged particles that have the effect of slowing the code phase signal and speeding up the carrier phase signal. The speed of a signal through the Ionosphere is related to its frequency thus, by using a receiver's dual frequency capabilities, the Ionospheric errors can be corrected. This is the primary reason why satellites broadcast both L1 and L2-bands. Traditionally only the military have been able to access the L2-band and utilise it for Ionospheric error correction. However some GPS receivers have been developed with sophisticated techniques to take

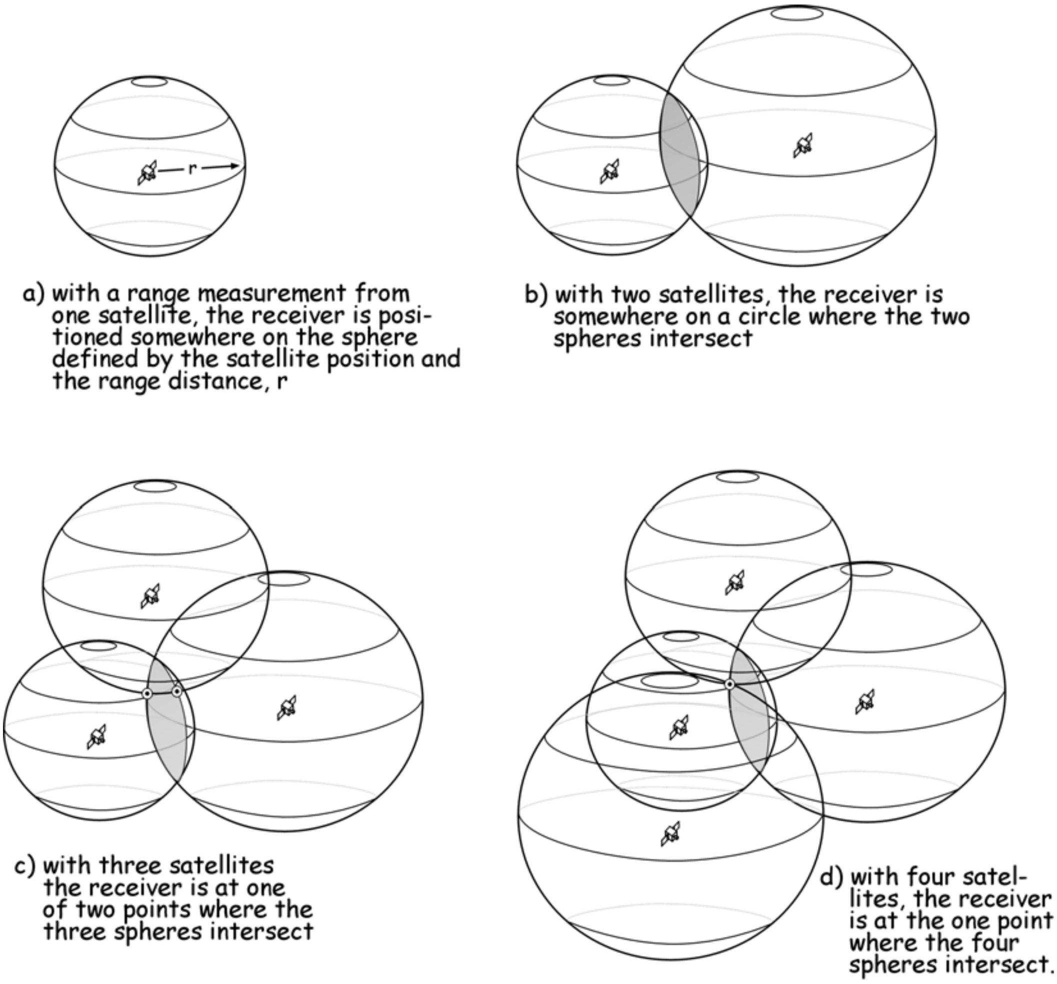


Figure 5: A schematic illustration of how ranging from a receiver to three or more satellites can be used to pinpoint an exact location. (Courtesy of Paul Bolstad, http://bolstad.gis.umn.edu/chapt5figs.)

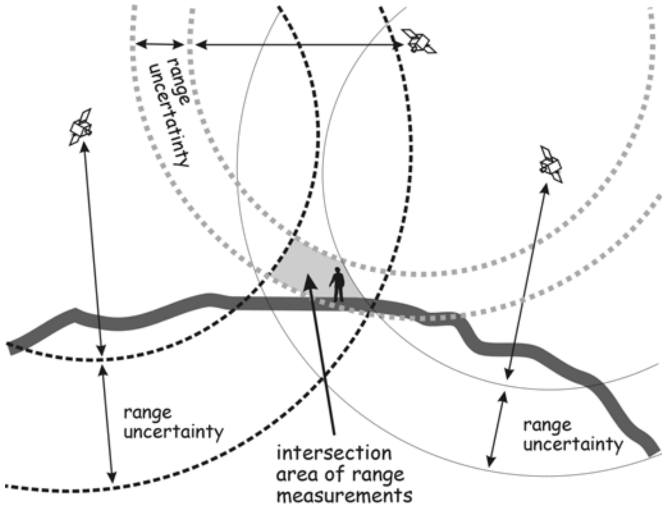


Figure 6: An graphical description of how the inaccuracies in ranging can create some uncertainty in the estimation of actual location. (Courtesy of Paul Bolstad, http://bolstad.gis.umn.edu/chapt5figs.)

advantage of the L2-band without contravening the security objectives of the US Department of Defense. For single frequency receivers mathematical models to reduce the error have been developed however these only remove ~50% of the error.

The troposphere, the lower level of the atmosphere, contains water vapour that slows both the code and carrier phase signals. Dual frequency systems cannot compensate for this error and it must be modeled using measurements of atmospheric moisture, pressure and temperature.

The amount of error introduced into the system by atmospheric effects will be related to the distance that the signal has to travel through the atmosphere. Signals from satellites low on the horizon will travel further through the atmosphere than satellites positioned directly above the receiver. This is illustrated in Figure 7.

Multipath Errors - These are errors caused when the GPS antenna receives signals that have been reflected from a secondary source. This lengthens the travel time and thus creates error in the distance determination.

Satellite Geometry - Apart from errors in determining the distance between the satellites and receiver, the accuracy of geo-location is also a function of the geometry of the satellites used for geo-location. Satellite geometry is measured by the Dilution of Precision (DOP) statistics. The dilution of precision can be determined horizontal (HDOP), vertical (VDOP) or as a timing factor (TDOP). Alternatively the individual DOP statistics can be joined to produce more general estimations of the positional DOP (PDOP = $\sqrt{(\text{HDOP})^2 + (\text{VDOP})^2}$) or geometric DOP (GDOP = $\sqrt{(\text{HDOP})^2 + (\text{VDOP})^2 + (\text{TDOP})^2}$. The DOP statistics are unitless and the lower the value the better the positional accuracy.

In general to have confidence in your GPS receiver GDOP should be < 5 and PDOP < 4.

Geometrically, PDOP is proportional to 1 divided by the volume of the pyramid formed by lines running from the receiver to four observed satellites. Four widely separated satellites reduce the DOP error compared with satellites clustered in one sector of the sky (Figure 8). The optimum geometry is for one satellite to be directly overhead and the other three spread out evenly. As satellites orbit the earth, their geometry relative to a receiver varies and the DOP errors will vary and this is the main cause of daily variation in the accuracy of geo-location. However, since

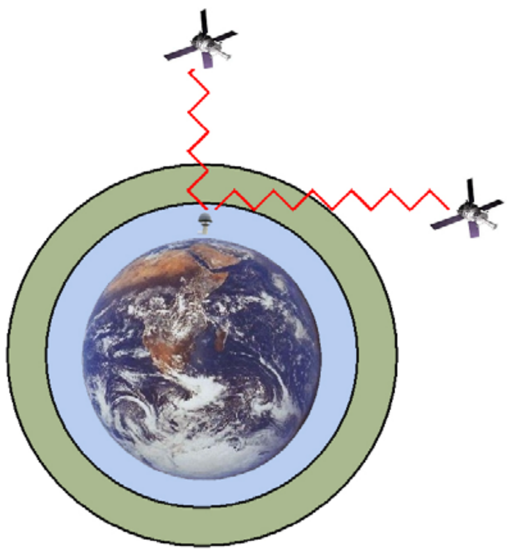


Figure 7: An illustration of the extra atmospheric distance that satellites low on the horizon must travel through.

the path of the satellites is fixed and known, mission planning software is available to determine when these errors can be minimised. Unfortunately, in agricultural situations, it is usually impractical to delay or alter farm management to take advantage of these windows. (Further information on Dilution of Precision errors is provided in Appendix 2).

Types Of Receivers

Code Phase Receivers

Stand Alone GPS receivers

Also known as Standard Position System (SPS) receivers, these receivers operate using only the basic C/A code on the L1-band from the navigation satellites. They are the cheapest GPS receivers available as there is no additional correction signal or complex circuitry to utilise the P code or carrier phase. However SPS receivers have the worst geo-location accuracy (usually ±5m but may be greater) of all the GPS receivers on the market. Most SPS receivers contain filtering algorithms designed to smooth the signal noise when the GPS is moving. This makes SPS receivers more accurate when moving and suitable for wide swathing, low resolution applications.

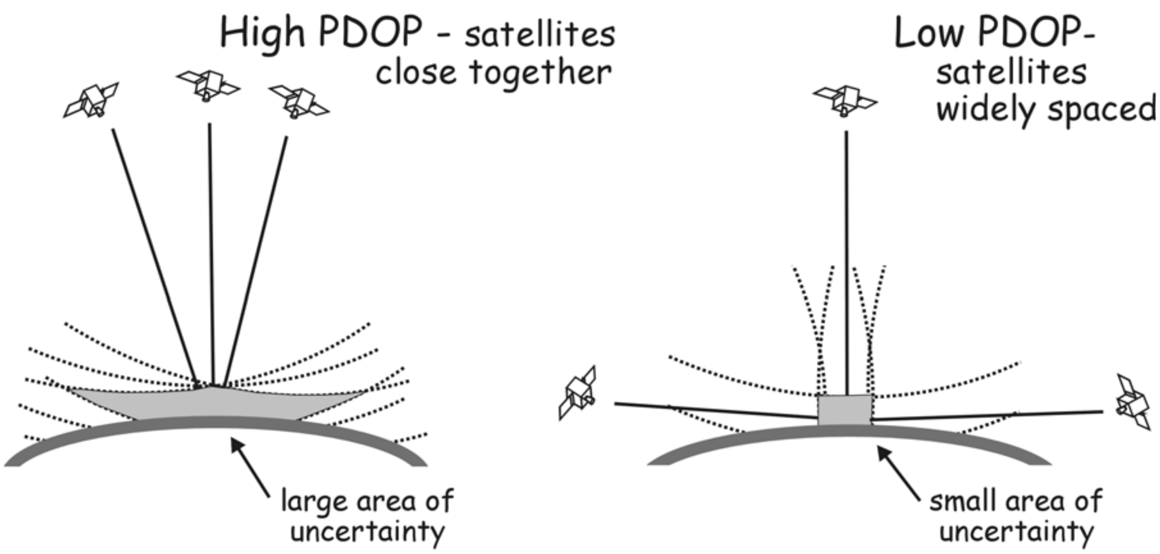


Figure 8: A Diagrammatic representation of how satellite geometry (relative to receiver) can influence the uncertainty and Dilution of Precision (DOP) of a geo-location estimation. The diagram on the left represents poor geometry and an high DOP while the diagram on the left represents good geometry and a low DOP. (Courtesy of Paul Bolstad, http://bolstad.gis.umn.edu/chapt5figs.)

Differential Correction

The error in a GPS signal can be determined by recording the GPS signal at a fixed surveyed location. By comparing the GPS receiver position to the surveyed position the physical error can be determined. Differential GPS (DGPS) take advantage of this known error to correct the SPS geo-location. The correction can be recorded independently and the SPS geo-location corrected later (post processing) or the correction can be applied in real-time. Real-time DGPS systems require two antennas: one to collect the C/A code and determine a geo-location and a second to receiver a correction factor to improve the accuracy of the geo-location. There are a variety of different sources available for the correction signal. These GPS receivers tend to be more expensive then the stand-alone GPS receivers, as they require extra componentry to accept the correction signal and update the geo-location.

Local Base Station

Any user can establish a local base station using a second GPS receiver and a pair of radios to transmit and receive the correction signal. A typical local base station set-up is shown in Figure 9.

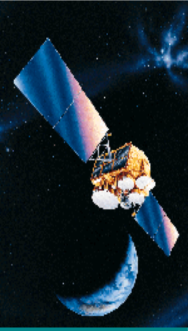
Using a single fixed base-station for correction assumes that all errors applying at the reference station apply equally to the mobile receiver. Therefore the effects of ionospheric delay can be compensated for to a degree. As the distance between the two receivers increases, the receivers begin to observe different satellite information errors and receive the satellite signals via different travel paths through the atmosphere.

Initial studies on civilian use of DGPS, with user-controlled base stations and selective availability turned on, suggested an accuracy between 2-4m was attainable if the two receivers were positioned close together. This accuracy would degrade at approximately 1cm per km until the separation distance reached 100 - 200km. Further separation would subject the user to position error up to approximately 15m at 500km. Such degradation limits the usefulness of operating DGPS with a single base station to short-range operation.

Generally a single fixed local base stations are limited to ranges less than 30km by the strength of the radio signals used and the possibly of terrain interference. To overcome this and make the signal more accessible some alternative approaches to signal delivery have been used however issues with correction signal degradation need to be understood when using these wider area signals.

FM Frequency

If the differential signal is broadcast on a FM frequency sideband the system can accommodate multiple users within the effective range. Such differential correction signal coverage was available for many of the major cropping regions in Australia though it is now indefinitely out of service.



Coast Guard Beacon

It possible for some farming areas in Victoria, South Australia and Queensland to receive a free correction signal from a maritime navigation "beacon" system. There are plans for more of these maritime beacons to be installed along the east coast of Australia in the coming years, but their effective range will be dependent on a users location, intervening terrain and the signal strength of each beacon.

WADGPS and WAAS

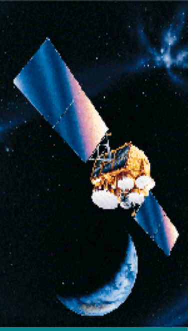
Problems with radio signal limitations and loss of accuracy by moving away from the base station can be overcome by using two or more base stations. The corrections from numerous base-stations can be combined into a correction algorithm that is optimised for any user located within the base station network (Figure 10). This form of correction is term Wide Area DGPS (WADGPS). Two competing companies, OmniSTAR and Thales Geosolutions Australia, offer WADGPS services with submetre accuracy across Australia.

A similar network, Wide Area Augmentation Service or WAAS, has been established in North America to aid flight navigation. The WAAS correction is free and improves the accuracy of a stand alone SPS receiver to ±3m (with a 95% Confidence).

Carrier Phase Receivers

More accurate modes of operation are available whereby the distance to satellites is determined in a codeless manner. This approach uses the phase shift of the information carrier signal between propagation at the satellite and reception by the user. This method offers potentially greater accuracy (centimetre level) but also requires more expensive receivers. Carrier phase systems may be either single frequency, i.e. accessing only the L1-band signals, or dual frequency, i.e. accessing both L1 and L2-band signals. Dual frequency receivers have the advantage of faster acquisition time. Many receivers are also capable of accessing the GLONASS as well as GPS satellites if required. Similar to code phase receivers, carrier phase receivers can be improved by using a local base station or a WADGPS correction.

OmniSTAR (OmniSTAR HP) and John Deere (Starfire) have both produced WADGPS dual frequency carrier phase networks offering sub decimetre accuracy in Europe, North America and Australia. The use of the WADGPS correction negates the need for a local base station. However the trade off is a loss of accuracy. Dual frequency carrier phase GPS receivers, with a local base station, are able to provide sub 2cm accuracy. These systems are often referred to as Real-Time Kinematic GPS (RTK-GPS). The on-farm use of carrier phase receivers is rapidly increasing with the adoption of auto-steer farm machinery.



Basic Approach to Differential Correction (DC).

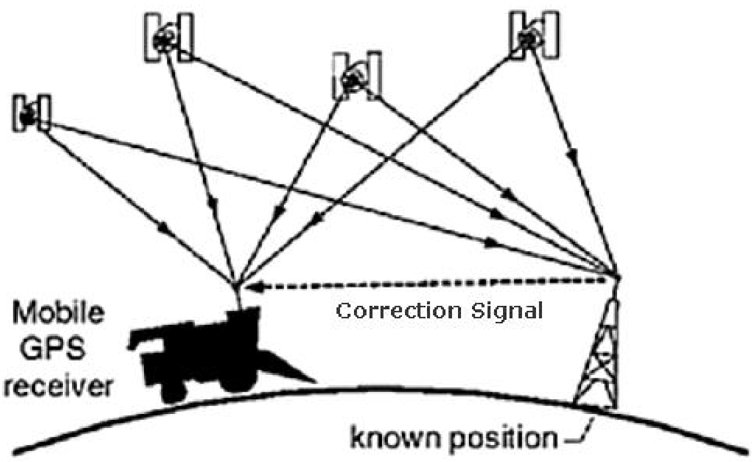


Figure 9: Operation of a DGPS network from a single fixed base station. Both the mobile receiver and the fixed point receive satellite signals. The error at the fixed point is calculated and transmitted to the mobile receiver for correction. (Adapted from http://pasture.ecn.purdue.edu/~abegps/)

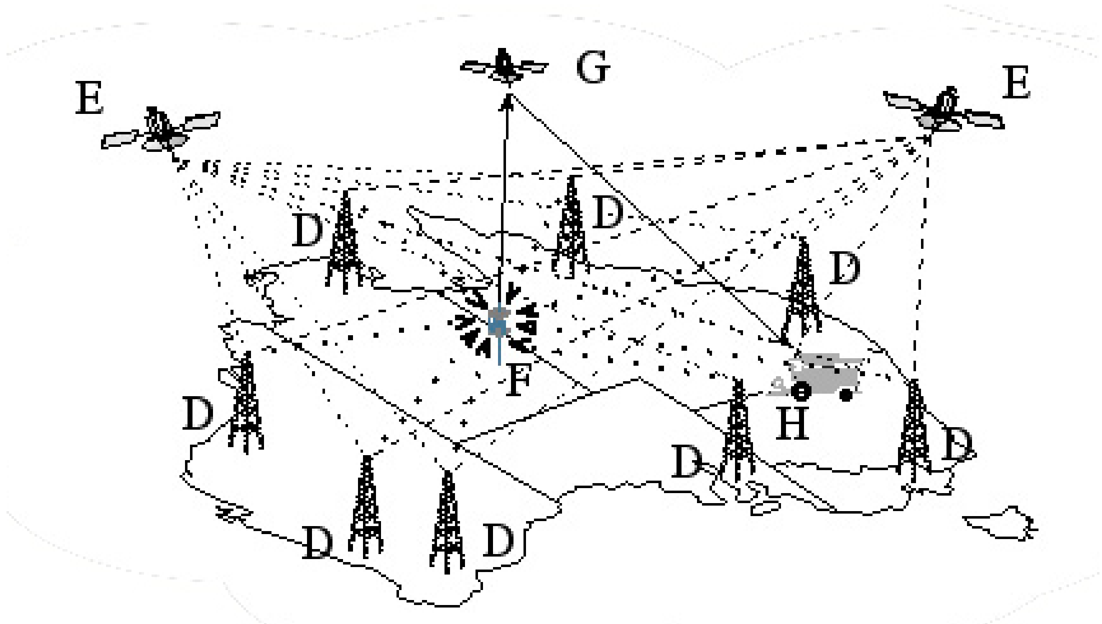


Figure 10: The network of fixed position receivers (D) communicate with the GPS satellites (E) and calculate an individual correction algorithm which is then passed to a master station (F). The master station computes a system-wide correction from all the individual stations and relays this to a general communications satellite (G) that increases the broadcast range to remote users (H). The correction transmission is supplied in a standard format (RTCM-104) defined by the Radio Technical Commission for Maritime Services. (Courtesy of Australian Centre for Precision Agriculture, University of Sydney)

Measuring Precision And Accuracy

Precision and accuracy are two terms that tend to be confused when discussing GPS (or any navigating/targeting system) performance. Precision is most simply defined as repeatability i.e. how close are the data points while accuracy is defined as how close the data points are to the actual point i.e. an estimation of the bias in the system (see Figure 11 for a graphical explanation of this concept).

Accuracy is a measure of how well the logged point approximates the actual point. It is usually determined by finding the radial error of the logged position from the actual point. The mean radial error can be determined if the logged position is averaged over a certain time period.

There are various methods of representing the precision of data. The most common approaches in GPS specifications are the 95% confidence interval (2s) and the Circular Probable Error (CEP). The 95% C.I. describes the radius of the circle within which 95% (i.e. 2 standard deviations) of the data lies. The CEP describes the radius of the circle within which 50% of the dataset resides. The CEP is equivalent to the median radial error of the data. The CEP statistic must always be smaller, or in extreme cases equal to, the 2s statistic thus the precision of the GPS system appears improved when quoting the CEP. For 3D descriptions the Spherical Error Probable (SEP) statistic is used. This is the same as the CEP except the SEP describes the radius of a sphere not a circle. Another useful alternative if multiple measurements are taken is the root mean squared radial error ($RMSE_r$). The difference between the RMSE of accuracy and RMSE of precision is that for accuracy the absolute location of the point is used as a reference while for precision the reference point is the mean location of the logged points.

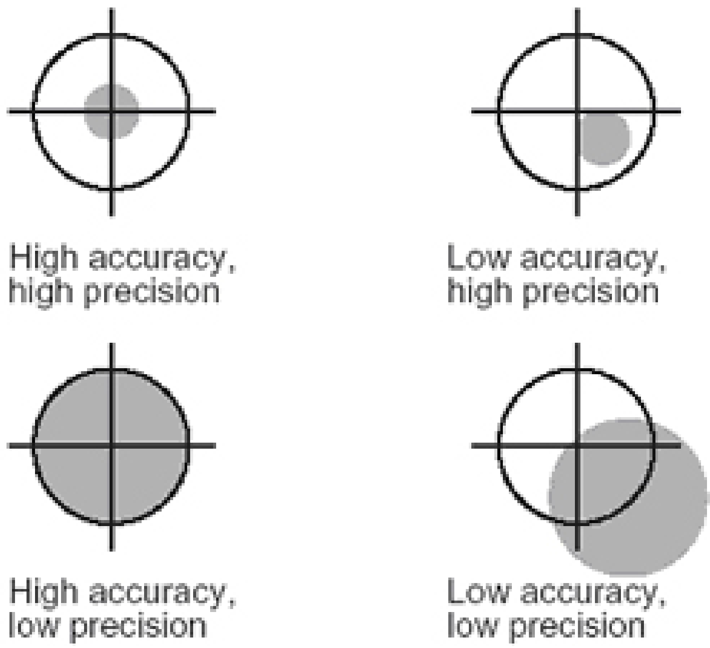
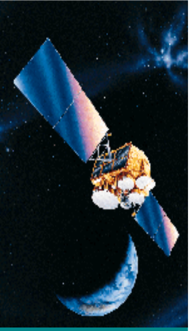


Figure 11: Comparison of the concepts of Precision and Accuracy in geo-location (after Environment Canada, 1993, Guideline for the Application of GPS Positioning)



Choosing a GPS

In an agricultural context, the required location accuracy and precision will depend on the operation being undertaken. As a guide, Table 1 presents some of the common usages of GPS in agricultural and the type of GPS required for each operation. There are many retailers of GPS equipment in Australia. Growers are advised to talk to various manufacturers and distributors to determine which GPS system is right for them and usages for different types of GPS receivers.

	Pegs $50	Standalone GPS ~$500	DGPS (C/A) ~$5000	DGPS High Quality ~$15-25000	DGPS Own Base Station ~$40-60000
Soil tests	*	*	*	*	*
Fertiliser Strips	*	*	*	*	*
Strategic Trials		*	*	*	*
Yield Maps		*	*	*	*
Guidance			*	*	*
AutoSteer				*	*

Table 1: Types of GPS currently commercially available and their potential uses on-farm.

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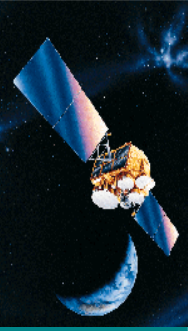

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Satellite Navigation Product Team. (http://gps.faa.gov/gpsbasics/spacesegment-text.htm)

Other Useful Resources

All About GPS
http://www.trimble.com/gps/

US Navel Observatory
http://tycho.usno.navy.mil/gps.html

US Coast Guard Navigation Centre
http://www.navcen.uscg.gov/

European Space Agency
http://www.esa.int/esaNA/index.html

James Taylor & Brett Whelan
Australian Centre for Precision Agriculture
www.usyd.edu.au/su/agric/acpa

APPENDIX 1: MEASURING DISTANCES TO SATELLITES

Time Is Distance

Have you noticed that during a thunderstorm, you hear the sound sometime after you see the light? The reason is that sound waves travel much slower than light waves. We can estimate our distance to the storm by measuring the delay between the time that we see the thunder and the time that we hear it. Multiplying this time delay by the speed of sound gives us our distance to the storm (assuming that the light reaches us almost instantaneously compared to sound). Sound travels about 344 meters (1,130 feet) per second in air. So if it takes 2 seconds between the time that we see the lightning and the time that we hear it, our distance to the storm is 2 x 344 = 688 meters. We are calculating the distance to an object by measuring the time that it takes for its signal to reach us.

In the above example, the time that we see the lightning is the time that the sound waves are generated in the storm. Then we start to measure the delay until the time that we hear the sound. In this example, the light is our start signal. What about the cases for which we don't have a start signal? Consider the next example.

Codes and Patterns

Assume that your friend at the end of a large field repeatedly shouts numbers from 1 to 10 at the rate of one count per second (10 seconds for a full cycle of 1 to 10 count). And assume that you are doing the exact same thing, synchronized with him, at the other end of the field. Synchronization between you and him could have been achieved by both starting at an exact second and observing your watches to count 1 number per second. We assume that you both have very accurate watches. Because of the sound travel time, you will hear the number patterns of your friend with a delay relative to your patterns. If you hear your friend's count with a delay of one count relative to yours then your friend must be 344 meters away from you (1 sec x 344 meters/sec = 344 m). This is because the counts are one second apart.

Now assume that you and your friend count twice as fast, two counts in one second. Then at the same distance between you and your friend you will hear a two-count delay. This is because now each count takes 0.5 seconds and each count delay measures 172 meters. If you could count 100 times faster then each count would take 0.01 seconds and each count delay between you and your friend would measure the distance of 3.44 meter. Counting faster is like having a ruler with finer graduation. Of course in real world, you need appropriate devices and instruments to generate and receive very fast counts.

Next assume that you and your friend are far apart and counting very fast, say each count in 0.01 second (each delay count is 3.44 meters), and, as before, both are repeatedly counting from 1 to 10. Assume when you say 7 you hear your friend's voice say 5. You hear a delay count of 2 but you know your distance is more than 6.88 meters. This is because the delay is not just only 2 counts, but rather 2 counts plus some multiples of 10 counts (i.e. some multiples of the pattern cycle). This is as if your measuring tape is not long enough and there are some multiples of the full length of measuring tape plus some fraction. We refer to this unknown number of full pattern delays as *unknown integer*. If you and your friend were to count repeatedly from 1 to 1000 (instead of 1 to 10) then you could hear 212 count delays between the numbers that you hear and your numbers, which would produce the distance of 212 count delays x 3.44 meters = 729.28 meters. This is 21 full cycles of the 1-to-10 pattern, plus 2 counts. The number of full cycles, 21, that we were not able to observe with our short pattern is our *unknown integer.*

What we demonstrated above are the concepts of *pattern granularity* (fineness of tape marks) and *pattern length* (tape length).

The concept of measuring distances to satellites is much like what we discussed above, but satellites transmit electronic patterns rather than voice counts. Likewise, our receiver generates similar electronic patterns for comparison with the received patterns from satellites in order to measure the distances to them.

Satellites generate two types of patterns: One has a granularity of about 1-millimeter and a length of about 20 centimeters. The other has a granularity of about 1 meter and effectively an unlimited length. In satellite terminology, the first pattern is called *"carrier"* and the second is called *"code"*. The distance measured by carrier is called *"carrier phase"* and the distance measured by code is called *"code phase"***.** Because code pattern is long, the code phase measurements are complete and do not have any unknown integer. We can measure our distance to a satellite as 19,234,763 meters, for example. In contrast, the carrier pattern is short and carrier phase has a large unknown integer. You may think that it is useless to say, for example, that our distance to satellite is 13.2 centimeters plus an unknown number of carrier cycles. The unknown integer is in the order of several tens of millions. You may ask what good will it do to measure the fractional part so accurate when millions of full cycles are missing? We will explain more.

Initial Unknown Integer (Integer Ambiguity)

In the previous counting example with a short pattern, assume that you and your friend are standing next to each other and synchronized together counting fast from 1 to 10. You hear no delay because you are standing next to each other. Then your friend starts to move away. The count delays start to grow from 0 (no delay) to 9. After it reaches 9 it will drop back to 0. This is actually 10 and not zero. You know that this is the case (that the zero count delay actually represents one full cycle count) because you have been following the count delays continuously. You will keep in mind, as your friend moves away, to count the whole number of cycles that are being added to your distance. In this case, there is no unknown integer as long as you keep track of him continuously.

If, instead of starting next to each other, you start at some unknown distance, then you are starting from an unknown integer of cycles. However, if after starting your friend moves away from or towards you, you can account for the number of full cycles that must be added to or subtracted from the *initial unknown integer*. All the distances that you measure every second contains the same initial unknown integer. This is true as long as you keep track of him continuously. If you don't hear him for some period of time, then you don't know how many full cycles he moved and you will have to start with another unknown number of cycles. The point is that as long as you keep track of him you have only one initial unknown integer.

The concepts of code and carrier are very important. Let us use another analogy for better understanding. You may consider that code phase is like a watch that only has an "hours" hand (call it code watch). At any time you can look at this watch and know the time of the day approximately. You may consider carrier phase like a watch that only has a "seconds" hand (call it carrier watch). You can keep track of the elapsed time with this watch with the accuracy of one second as long as you monitor the watch continuously to keep track of the elapsed full minutes. If you somehow can determine the number of full minutes initially (the initial unknown integer when you started looking at this watch) then you can keep track of time very accurately. If you get distracted and lose track of the number of minutes, then you have a new "initial unknown integer" that you somehow must determine again. With code phase watch you always get the time of the day instantly but with the accuracy of not better than 10 minutes by estimating the location of the hour hand. The code watch can narrow the estimate of unknown minutes (integers) of the carrier watch to plus or minus few minutes. You see that there is a gap between the seconds hand and the hours hand. We are missing the minutes hand. GPS manufacturers have developed techniques to narrow the gap such that code phase and carrier phase can make unambiguous and accurate distance measurements as fast as possible. We will explain the reason for the gap later.

The good news is that the integer ambiguity of carrier phase can be determined by tracking satellites for some period of time. This is the fundamental concept in precision applications like geodesy.

With carrier phase, tracking the correct number of full cycles that the distance to satellite is changing is very critical. You will miscalculate this number if you miss a cycle or add an extra cycle. In GPS terminology, this is called a *"cycle slip"*. In our previous example, cycle slips can happen if you don't hear your friend's voice correctly due to noise or other effects, or if he suddenly jumps a very long distance. Cycle slips is like missing the meter marks while you are concentrating on reading the millimeter ticks. It can create large errors. Most GPS systems are able to detect and repair cycle slips.

Note that not all receivers can measure carrier phase. Carrier phases are typically used in high precision receivers.

We can measure the distances to the satellites with the accuracy of 1 meter with code phase and 1 millimeter with carrier phase. This does not mean that we can determine our position with a GPS receiver with the accuracy of one meter or one millimeter. There are several sources that introduce inaccuracies into the GPS measurement

Appendix 2: Dilution of Precision

If you use this material polease reference the original source

www.gps-practice-and-fun.com/gps-tests.html

Here we will describe some practical tests about GPS satellite reception. These tests should not be considered scientific and all exclusive. However, the results will have practical value in the field.

A GPS receiver determines its *Position* (horizontal and vertical), its *Velocity* and the *Time* from the signals of at least four satellites by means of triangulation. The precision of the computations by triangulation depends on the constellation of all satellites of which the signals are taken into account (four or more). As the number and position of satellites will seldom be ideal, the maximum obtainable precision will be *diluted* in practice. Here we present the different terms of dilution of precision.

Dilution of precision (DOP) is a measure of the quality of the GPS data being received from the satellites. DOP is a mathematical representation for the quality of the GPS position solution. The main factors affecting DOP are the number of satellites being tracked and where these satellites are positioned in the sky. The effect of DOP can be resolved into HDOP, VDOP, PDOP and TDOP.

HDOP (Horizontal Dilution Of Precision) is a measure of how well the positions of the satellites, used to generate the Latitude and Longitude solutions, are arranged. PDOP less than 4 gives the best accuracy, between 4 and 8 gives acceptable accuracy and greater than 8 gives unacceptable poor accuracy. Higher HDOP values can be caused if the satellites are at high elevations.

VDOP (Vertical Dilution Of Precision) is a measure of how well the positions of the satellites, used to generate the vertical component of a solution, are arranged. Higher VDOP values mean less certainty in the solutions and can be caused if the satellites are at low elevations.

TDOP (Time Dilution Of Precision) is a measure of how the satellite geometry is affecting the ability of the GPS receiver to determine time.

PDOP (Positional Dilution OF Precision) is a measure of overall uncertainty in a GPS position solution with TDOP not included in the estimated uncertainty. The best PDOP (lowest value) would occur with one satellite directly overhead and three others evenly spaced about the horizon.

The **Position Accuracy = Dilution Of Precision (DOP) X Measurement Precision**. So, if the Measurement Precision = 1m and the DOP = 5, then the best position accuracy will be 5m.

www.usyd.edu.au/su/agric/acpa

Australian Centre for Precision Agriculture

The Impact of Precision Agriculture

Brett Whelan, Alex McBratney & Broughton Boydell

Through the ages agricultural production systems have benefited from the incorporation of technological advances primarily developed for other industries. The industrial age brought mechanisation and synthesised fertilisers, the technological age offered genetic engineering and now the information age brings the potential for Precision Agriculture.

With the advent of tools such as the differential Global Positioning System (dGPS), Geographical Information Systems (GIS), and miniaturised computer components, agricultural enterprises are now capable of gathering more comprehensive data on production variability in both space and time. The desire (and ability) to monitor and respond to such variation on a fine-scale is the goal of Precision Agriculture.

This desire has both an economical and environmental basis. Matching inputs to crop and soil requirements as they vary within a field should improve the efficiency of resource use and minimise adverse environmental impact.

At present, monitoring and mapping the spatial variation in small-grain crop yields is receiving much publicity in Australia. Yield mapping is only one component of a Precision Agriculture system and small-grains is not the only enterprise to embrace the ideas. Crop yield monitors are also available for potato, peanut and forage harvesters and are under development for cotton, sugarcane and a range of horticultural crops.

The Precision Agriculture philosophy may be eventually applied to the spectrum of agricultural industries, for both quantity and quality control.

A Precision Agriculture System

There are 5 components to consider in the development of a Precision Agriculture system.

Spatial referencing

Gathering data on the pattern of variation in crop and soil parameters across a field requires an accurate knowledge of the position at which samples are taken. The dGPS network enables this information to be swiftly obtained with an accuracy here in Australia of approximately +/- 1 metre.

Crop & soil monitoring

Influential factors effecting crop yield, along with the crop yield itself, must be monitored at a fine-scale. Measuring soil factors such as texture, nutrient concentrations, pH etc. at present remains reliant on systematic manual soil sampling and analysis in the laboratory. Research is underway worldwide into real-time analytical soil sensors that will eventually automate the sampling and analysis procedures in the field.

Pest and disease dispersal along with crop growth indicators such as water stress can be successfully monitored using aerial or satellite photography in conjunction with crop scouting. In Australia two types of real-time small-grain yield sensor, measuring either volumetric or mass flow, are available from five manufacturers. This number will possibly double by 1998.

The total number of grain yield monitors operating in the country is below 200 at present. In the USA it is estimated by the manufacturers that between 5,000 and 10,000 units are operating, half with dGPS capability.

Spatial prediction & mapping

To produce a map of variation in soil, crop or disease factors that represents an entire field it is necessary to estimate values for unsampled locations. Various methods may be used for these predictions based on the values at the sampled locations. The most suitable methods for the various factors continues to be debated and the techniques refined.

Decision support

The degree of spatial variability found in a field will determine whether unique treatment is warranted in certain parts. Correlation analysis between the variation in crop yield and the measured factors influencing crop yield can be used to formulate agronomically suitable treatment strategies.

Differential action

To deal with spatial variability, operations such as fertiliser, lime and pesticide application, tillage, sowing rate etc. may be varied in real-time across a field. A treatment map can be constructed to guide rate control mechanisms in the field. Here in Australia there are presently three systems on the market that can integrate these operations and the number will continue to rise. The controller hardware is also available.

System Development

These components are at different stages of development and implementation. The technology required to gather detailed data leads the agricultural science of deciphering and applying the information it contains.

Technology

Ground positioning using dGPS receivers is well advanced and continues to increase in precision. Competition among an expanding number of GPS companies in Australia should also begin to reduce unit costs.

Crop yield monitors are considered very accurate at measuring the bulk yield of an entire field however less is known about the accuracy of the monitoring systems at the 1-2 metre level where individual yield measurements are matched with dGPS position. This contributes to uncertainty in the industry over the detail yield maps should attempt to display

Variable-rate controlling equipment is also well advanced with feed-forward times being reduced and rate changes becoming much smoother. Technological answers are less abundant in the search for information on what may be causing the observed yield variation. Data is required on the same scale as yield data (i.e. every 1-2m). This will eventually require sensors that either externally scan or invasively measure soil attributes as they pass in the field.

Agronomic Research

Here lies the greatest information gap. Scientists and commercial entities both in Australia and internationally are actively researching the causes of, and treatments for, the observed yield variation.

It is evident that grain yield can vary widely within a field and that the spatial pattern of this variation may change over time (Figure 1). This reflects interactions between influential field attributes and also between these attributes and the environment.

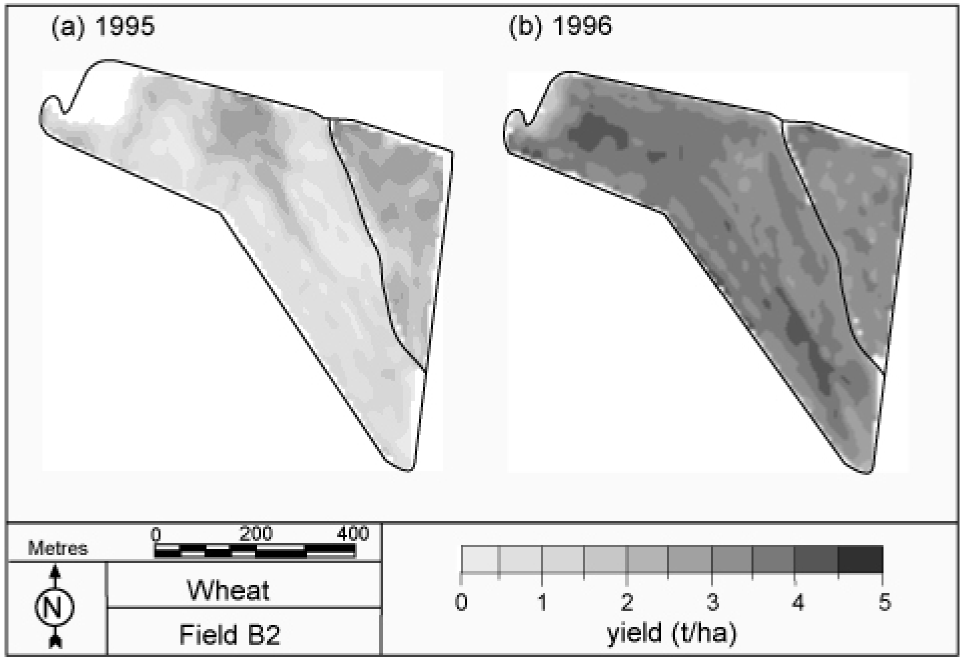

Figure 1. Wheat yield maps for 1995 and 1996, ‘Marinya’, Biniguy, NSW.

Figure 2 shows that spatial variability is also evident in a 1997 season cotton crop where irrigation usually mediates the significant environmental parameter of soil moisture.

Identifying a significantly yield limiting factor in one year may have limited bearing on the next growing season if its influence is considered singularly. Yield, soil, pest and environment variability data will have to be collected for a number of years (possibly up to 10 in highly variable environments) to adequately characterise and model this interaction.

In this manner a map of yield potential for a field may be constructed and then used each year in conjunction with early season environmental indicators and crop response models to guide differential actions.

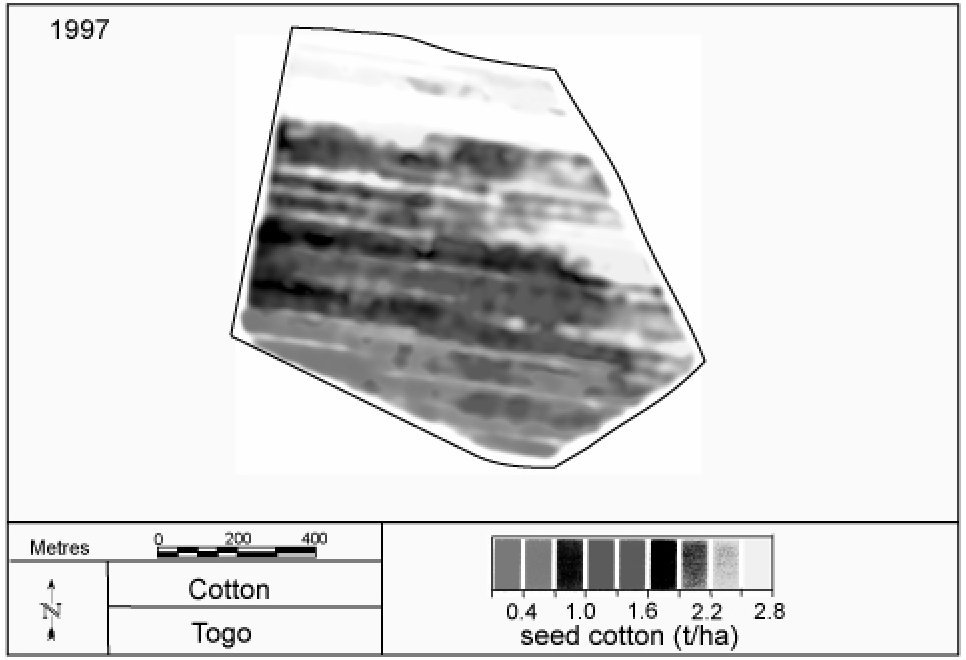

Figure 2. Cotton yield for 1997, ‘Togo’, Narrabri.

Establishing a baseline understanding of the variability in yield potential within a field becomes essential if the most significant soil-based contributors to variability are shown to be difficult to manipulate.

Soil factors such as clay content and organic matter levels are known to contribute to nutrient availability and moisture storage capacity of the soil. They are also extremely difficult or impractical to amend in the short-term.

Our research has shown that the spatial variability in these two factors overwhelmingly affects the variation in sorghum yield in one northern NSW field. Intuitively, factors contributing to variability in the soil moisture regime will be important in the majority of cereal growing regions in Australia.

The more easily adjusted soil factors such as available nutrient levels and pH will also be important in many areas. However if the more rigid factors are going to limit yield then it would seem prudent to allow these to govern the application rates of any ameliorants in the field.

Precision Agriculture is not about treating a field to produce a uniform yield unless the potential is uniform. Its potential will be only be realised by acknowledging diversity in yield potential and environmental conditions when formulating field management operations.

Economics

The potential value of Precision Agriculture can best be displayed in a gross margin map (Figure 2). Uniform field treatment costs have been deducted from variable gross profit (yield x price). The 1996 wheat harvest produced a gross profit range between $A0/ha and $A560/ha at a mean of $A295/ha. Mean gross profit could have been increased with some form of differential treatment.

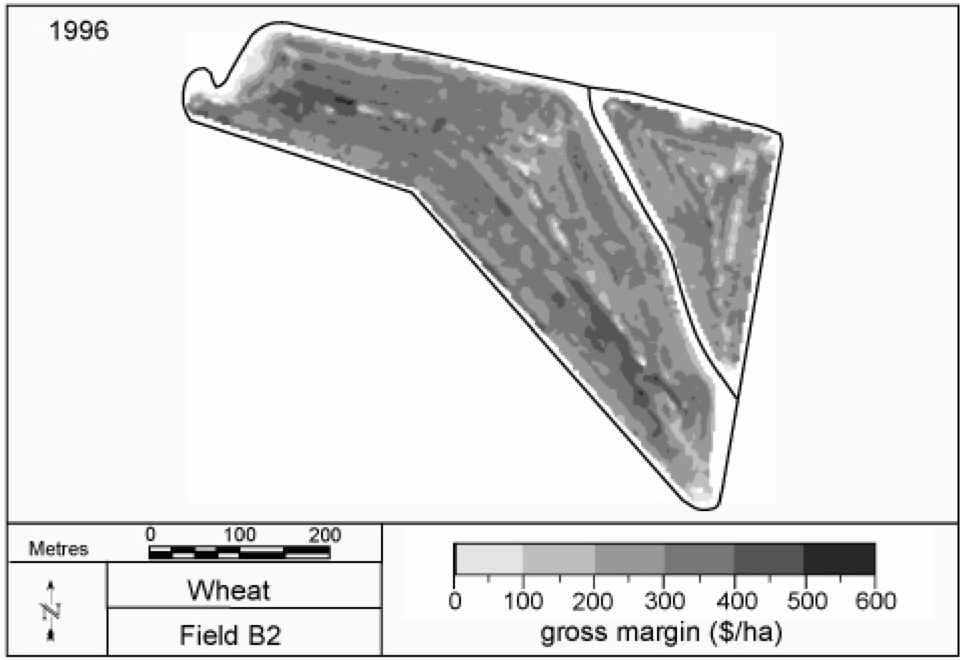

Figure 3. Gross margin map for 1996, ‘Marinya’, Biniguy, NSW.

Determining and attempting to manage variability in yield potentials will obviously raise the variable costs associated with sampling and amelioration. Estimates from the USA place this figure between $A12/ha and $A21/ha depending on the sampling detail. In Australia the projected cost would be between $A12/ha and $A63/ha due to greater unit sampling and analysis costs.

However, the economics of improved environmental stewardship does not easily fit the standard accounting paradigm. The allocation of monetary value to environmental gain is a fledgling science. Payments for positive actions or fines for deleterious actions could be accommodated, but at present Australia has no such remunerative or punitive legislation in place. It is apparent that Europe and the USA are moving in this direction.

Risk Assessment

The improved production information gathered using Precision Agriculture techniques also provides an ideal tool for risk assessment in potentially poor growing seasons. For example, well documented areas of low yield potential may be removed from production or have their inputs reduced to minimise potential financial losses. Such assessments would form part of the decision-support system, so that management actions may be used to disperse or lower production or capital risks across a whole farm.

Education

As with the introduction of all new approaches to crop production, education plays a pivotal role in its widespread adoption. Within the farming community, the main source of Precision Agriculture information has been the marketers of technology, and not agricultural systems managers or recognised educational bodies. The main reason for this being the as yet mimimal agronomic research being performed here in Australia. It is vital that the technology is utilised in an efficient systems approach that is suitable for the Australian environment.

This type of ‘high tech’ approach will probably see the advent of skilled consultants catering for a number of enterprises. Tertiary education will be required to train such people.

Politics

There is still not as yet a strong Precision Agriculture movement in Australia, driven by the economic-environmental imperative, as in the US and Europe. We anticipate legislation such as the 1996 US Farm Bill to expedite research and development.

Conclusions

Information is an economic necessity in any productive industry. The technology is now becoming available to monitor agricultural input/output at an increasingly detailed level. At present, it is necessary to gather data on output to characterise the variability that may be expected over space and time. Understanding the causes will be more difficult at this scale and require committed research from the agricultural industry and improvements in soil sampling and analysis technology. Ultimately these will be available but the impact of Precision Agriculture in Australia will depend on ensuring only suitable techniques are adopted within a fertile research, educational and political framework.

Acknowledgements

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Australian Centre for Precision Agriculture

Within Block Variability in Grapes - An Example

James Taylor *Australian Centre for Precision Agriculture*

Over the last 5-10 years there has been much talk and interest in the potential applications of "Site-specific" farming especially in regards to crop management. In the past few years this has spilt over from the broadacre industries into horticulture. In viticulture the research and application of site-specific crop management (SSCM) is still in its infancy. However the potential of SSCM in a high value crop is making people sit up and take notice. This document is aimed at illustrating the amount of variability inherent in winegrape blocks and the potential that exists for SSCM in Viticulture.

"Does variability exist?" is the key question. If variability does not exist or cannot be managed then SSCM is not applicable to the production system. Variability in production systems is often a function of size. The larger the production area the more likely that there is variation, either environmental or managerial. The small nature of many winegrape blocks, often only 1-10 hectares in size, may help to minimise variability and preclude the need for SSCM. An analysis of two years yield data in the Cowra region does not confirm this suspicion. The highly sensitive nature of the vines interaction with the local environment (terroir) counters the smaller area. A survey of grain and pulse crops revealed similar co-efficients of variation to winegrapes. The larger mean of winegrapes compared with grains/pulses results in a larger range of yield values. In Figure 1a the yield of a 3 hectare block of Merlot varies threefold from 6 to 17 ton/ha. When this is coupled with the higher value of the crop there is a large profit gradient within even small blocks of grapes (Figure 1b). (NB. Data used for this analysis is hypothetical however ball park figures are used. Winegrapes are valued at $1000/ton and cost of production $5000/ha)

Figure 1a: Yield Map - Merlot, 2000

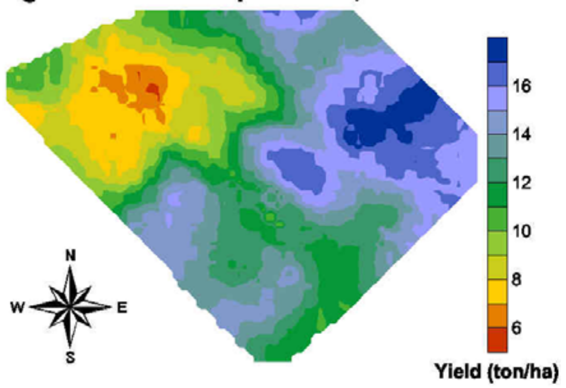
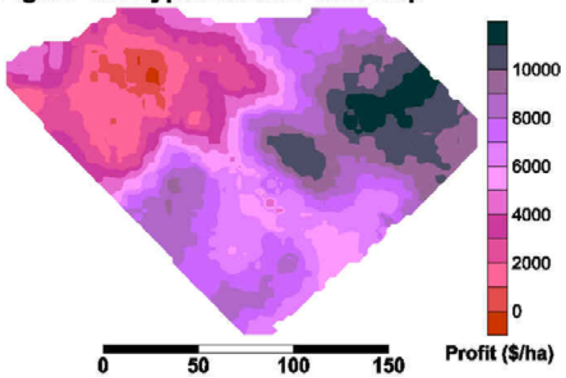


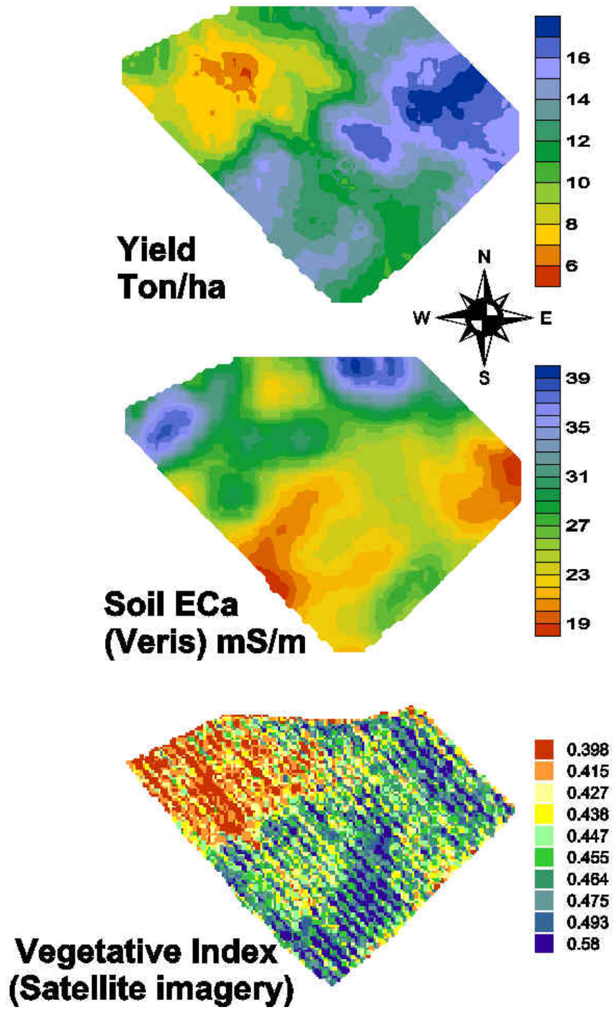
Figure 1b: Hypothetical Profit Map



From the analysis the value of the crop across the block grades from $0/ha, or operating at a loss, to a profit of over $10,000/ha. So having seen this variability and its cost, the next key question is can we minimise this variability and maximise productivity? There are two ways to approach this problem, either treat the cause or remedy the symptoms. The cause is predominantly environmental variation. By designing vineyards based on our knowledge of the local environmental variation it is possible to minimise this effect. Remedying the symptoms refers to the scenario with existing vines where environmental variation is now inherent in the blocks and differential management is needed to minimise the variation. Ultimately SSCM of vines will encompass both facets. Improved vineyard design will decrease the inherent environmental/terroir variability then differential or site-specific management will help maximise production across the block. While researchers within the CRC for Viticulture and the Australian Centre for Precision Agriculture are investigating the remedy there is no concerted effort yet to treat the cause.

We have already seen that production is variable, so is it possible to predict this variation prior to planting and use the information in vineyard design? Figure 2 shows a preliminary investigation into this question.

Figure 2: Comparision of methods of describing production variability



Shown together with the yield is a mid season aerial image of the Normalised differences Vegetative Index (NDVI) and a subsoil apparent electrical conductivity (ECa) map produced using the Veris 3100 EC cart. From the images the strong correlation ($r^2 = 0.75$) between yield and NDVI is apparent. Areas of low yield have a low NDVI and vice versa for areas of high yield and NDVI. This is not unexpected as vegetation is often a good indicator of yield. However for vineyard design taking imagery of planted vines is too late and a pre-planting indicator is needed. The Subsoil map shows a similar spatial pattern to the yield map however it is negatively correlated i.e. areas of low yield tend to have a higher ECa value and vice versa for areas of high yield and low ECa. The subsoil conductivity map explains ~56% of the variation in the yield map. The reason for the yield-ECa relationship has yet to be established but may stem from water logging, if irrigation scheduling is based on the lighter textured soil, or a heavier clay subsoil retarding root growth and penetration. What is apparent is the discrete area within which the lower yield occurs. Identification of this area pre-planting may have prompted the grower to use an alternative variety or rootstock in this area. This may negate the depressed yields observed. This plan of action however is not yet plausible as no methodology or guidelines have been established for the correct use of ECa data, either Veris or EM, in vineyard layout. Also there are other sources of production system information available that have yet to be investigated e.g. ground penetrating radar is capable of plotting soil thickness. When these alternative data sources are combined with the ECa data we may be able to explain a lot more of the yield variation.

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Australian Centre for Precision Agriculture

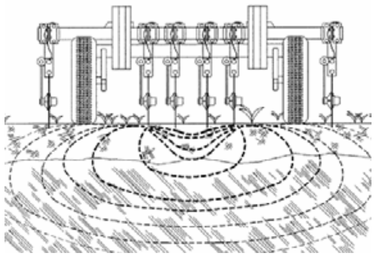
Preliminary results with the VERIS soil electrical conductivity instrument

Broughton Boydell, Alex McBratney, Brett Whelan & Budiman

- **Note this work is in Progress**
- **This version 9th April 1999***

1. Introduction

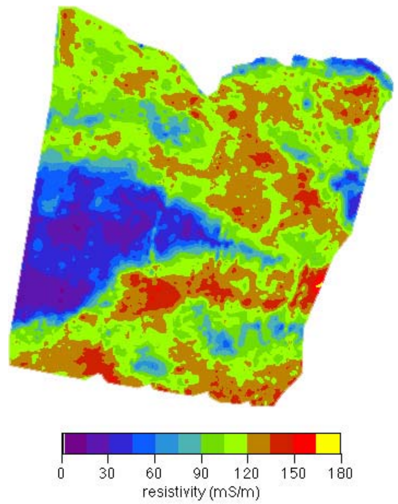
1a. Figure 1 How does it work?



1b. What do the numbers mean?

2. Preliminary surveys

2a Creek Field



3. Future Work

3a. Practical

3b. Research

4. Conclusion

Introduction

ACPA recently purchased a VERIS. Here we report on its use in a couple of Australian conditions. The VERIS is a continuously recording version of the old 4-electrode resistivity probe long used in archaeology for finding buried structures.

How does it work?

We think it works like this. Veris 3100 Soil EC Mapping System

A resistivity meter involves applying a voltage into the ground through metal electrodes and measuring the resistance to the flow of the electric current.

A typical system of resistivity survey consists of four equally spaced metal electrodes [a so-called Wenner array] inserted into the soil. An AC-power source supplies current flow (I) between the two outer electrodes and the resultant voltage difference (V) between the two inner electrodes is measured. The resistance of the soil is given by R = V / I. This needs to be standardised over a unit length. The resistance times the length (of the resistor in this case the soil) is called the resistivity (ρ) which is measured in ohm m. The equation is,

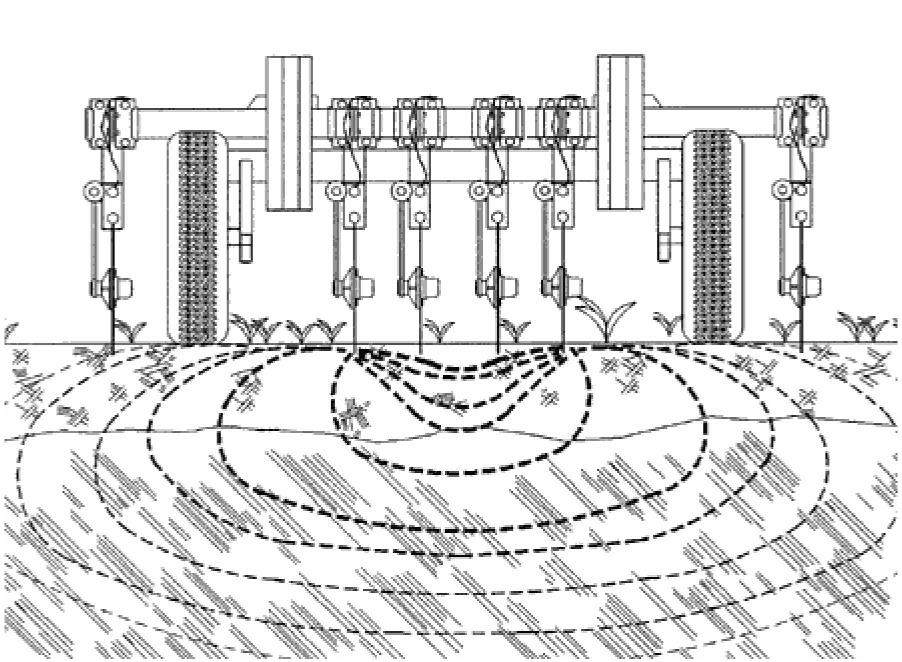
$$\rho = 2\pi d\ R = 2\pi d\ V/I, \text{ unit: } [\omega \text{ m}],$$

where d is the spacing between the electrodes (in m).

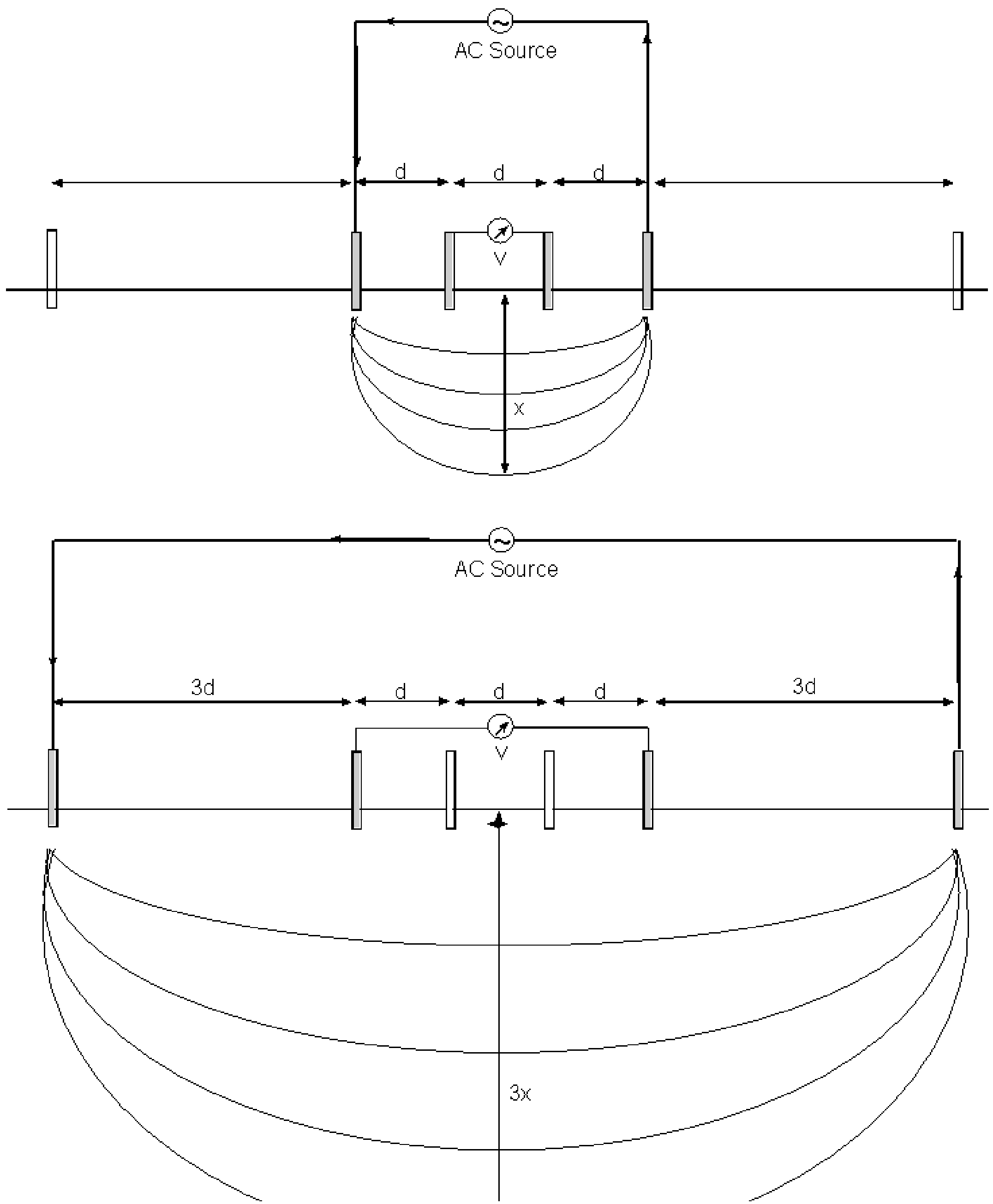
Alternatively, this can be expressed in terms of conductance (C = 1/ R, unit ohm^{-1} = siemens) and conductivity ($\chi = 1/\rho$, unit $\text{ohm}^{-1}\ \text{m}^{-1}$ = siemens m^{-1}). The equation for the (soil electrical) conductivity (EC) is given by,

$$\chi = 1/(2\pi d\ R) = I / (2\pi d\ V) \text{ unit: } [\text{S m}^{-1}]$$

In the Veris 3100 Soil EC Mapping System the electrodes have been replaced by rotating discs which are placed 6cm into the soil. As the cart is pulled through the field, one pair of electrodes passes electrical current into the soil, while two other pairs of electrodes measures the voltage drop.

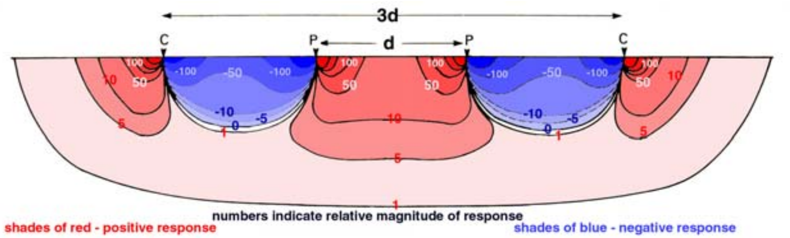


The system is set up to switch between two configurations, let’s call them configuration (A shallow) and (B deep)


AC Source
d
d
d
V
x
AC Source
3d
d
d
d
3d
V
3x

As you can see Configuration A uses the four inner discs (2, 3, 4 & 5). The voltage is measured between the two innermost discs (3 & 4) which are d = m apart. In Configuration B the four outer discs (1, 2, 5 & 6) are used and the voltage is measured between discs 2 and 5. When the electrodes (discs) are d metres apart the conductivity is measured to a depth of roughly 1.5d metres.

A more thorough review of the typical signal contributions for a "Wenner array" (very similar in principle and to the Veris) revealed the following figure from John Milsom's 1989 book, Field Geophysics. It can be seen from this illustration that the signal contribution between different electrodes and through the various depths reached by the array is complicated. Indeed it *appears* that the signal contribution is ridiculously complicated when different regions in the array at the same depth contribute readings of opposite sign. However, Milsom points out that in relatively homogeneous soil with a short separation distance between the electrodes (as is the case with the Veris), the opposite signs returned near the electrodes "cancel quite precisely". Of greatest importance is the fact that despite the complexity of the physics, the array returns a signal which is the net result of relatively linearly weighted contributions through the signal depth. Each electrode contributes relatively equally, as does each depth within the soil profile. Subsequently, the Veris 0-300mm and 0-900mm readings should closely match the soil average EC within these soil volumes. The Veris achieves two separate depth readings by switching between the 6 available discs to increase or decrease the distance **"d"** separating the "excite" and "measure" discs.



(Click to enlarge)

The contour plots of the contribution made to the measured signal by each unit volume of soil. In this illustration the red regions have positive contributions and the blue regions have negative contributions.

Want to see what the signal contributions look like under the Veris? Click Here**!!**

What do the numbers mean?

It depends. The numbers generated by the VERIS should vary according to local variations in the soil electrical conductivity (EC). Soil EC depends especially on electrolyte concentration and its connectivity or continuity within the profile.

This then depends in turn on a number of factors, many of which are correlated in the field:

Moisture content will effect electrolyte concentrations within the soil profile and also have impact on the soil solution connectivity. A relatively wet profile will be more likely to exhibit uniform conductive properties than one which is approaching permanent wilting point where dry areas in the soil profile will act as insulating regions and inhibit EC.

Texture, especially the soil clay content will effect VERIS results. Clay, which has a large surface area has relatively more charge capacity than sand and silt and subsequently has greater ability to accommodate electrolytes. Additionally, it is typical for soil dominated by the clay fraction to retain more moisture than soil with a relatively higher percentage of sand.

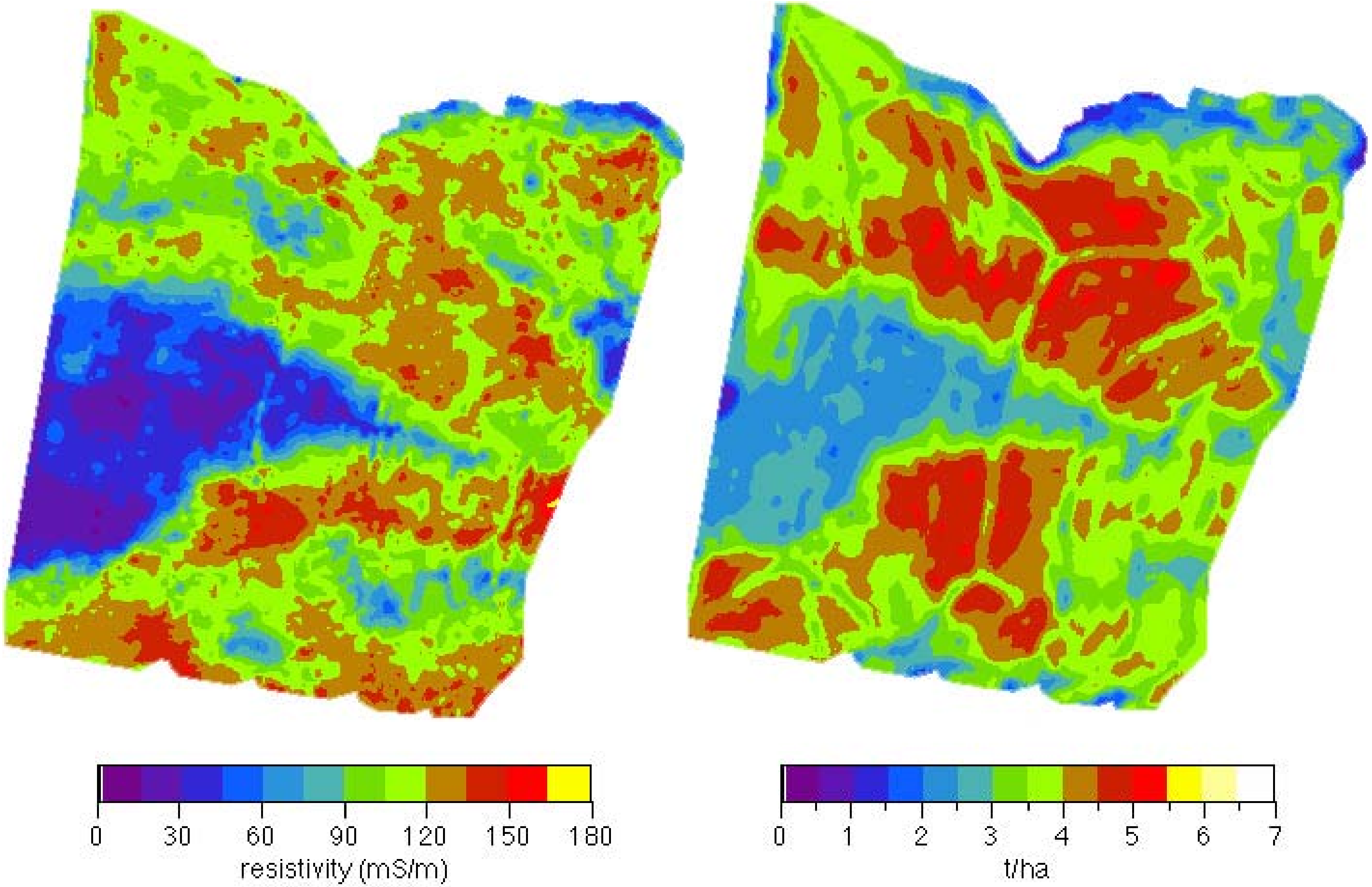
Bulk density (to a small degree). To some extent the more compacted a soil is (higher bulk density) the more likely it will be that there remains good connectivity across the profile. This should result in slightly higher EC readings.

Temperature may also influence VERIS results.

Preliminary surveys

1. **Creek paddock**

One of the first paddocks investigated by ACPA researchers was "Creek". Although only preliminary analysis has been performed, images of the results from a VERIS survey, durum wheat yield and a previously collected bare soil colour aerial photograph indicate a strong spatial correlation between each information layer



VERIS readings Durum wheat yield (1997)

True Colour aerial photograph taken during a bare soil fallow.

Future Work

1. **Practical**

The first practical work which we intend to perform involves the collection of data for a number of fields for which we already have existing *layers* of data. This existing information which includes yield map data, soil property maps and various remotely sensed data will be compared with the Veris data in an attempt to help us understand exactly what correlation we should expect between these relevant data layers under Australian conditions.

2 Research

a. calibration of instrument with respect to factors which affect EC

b. comparison with EM38

Conclusion

We believe that the Veris is a useful instrument which will find routine use in agriculture as more land users seek to characterise and manage their country at a more intensive scale

Acknowledgements

We would like to thank Veris Technologies Inc. especially Eric Lund and Colin Christy for their assistance with the acquisition of a Veris sensor and reference material. We also thank the University of Sydney, especially Professor David Siddle, Pro-Vice-Chancellor (Research), for providing the resources to purchase the VERIS instrument.

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THE UNIVERSITY OF SYDNEY

"PV or not PV?"

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Abstract

This paper outlines the theory and concepts of PA and how they relate to the viniculture industry, particularly in terms of quality, environmental and risk management. Some brief work on our experiences with Precision Viniculture is presented. Areas where we believe future research should be targeted are also discussed.

What is Precision Agriculture?

Precision Viniculture (PV) is a logical extension of Precision Agriculture (PA) technology into the horticulture sector. But what exactly does the term Precision Agriculture mean and imply? At the first workshop for PA in viniculture in Australia it is perhaps fitting to take a step back and evaluate the aims and misconceptions of Precision Agriculture before we are swept away on a tide of technology and data sets.

What it is

In 1997 the U.S. Congress passed a Bill on Precision Agriculture which they defined as "an integrated and production based farming system that is designed to increase long term, site-specific and whole farm production efficiencies, productivity and profitability while minimizing unintended impacts on wildlife and the environment".

Simplified, PA is the use of new information technologies together with agronomic experience to site-specifically:

i) maximise production efficiency

ii) maximise quality

iii) minimise environmental impact

iv) minimise risk

Practically this is achieved by first recording environment parameters, presenting the data in a form that is comprehensible, analysing these data with data from other sources, e.g. market prices, in a Decision Support System (DSS) and finally performing some differential management that can be recorded the following year, restarting the cycle. This is made possible by geo-referencing the data through the use of Global Positioning Systems. This is the primary enabling technology of PA - the principle reason why it has not been done before. The PA wheel is presented schematically in Figure 1. It is important to realize that it is a wheel and without one of the cogs it will not succeed.

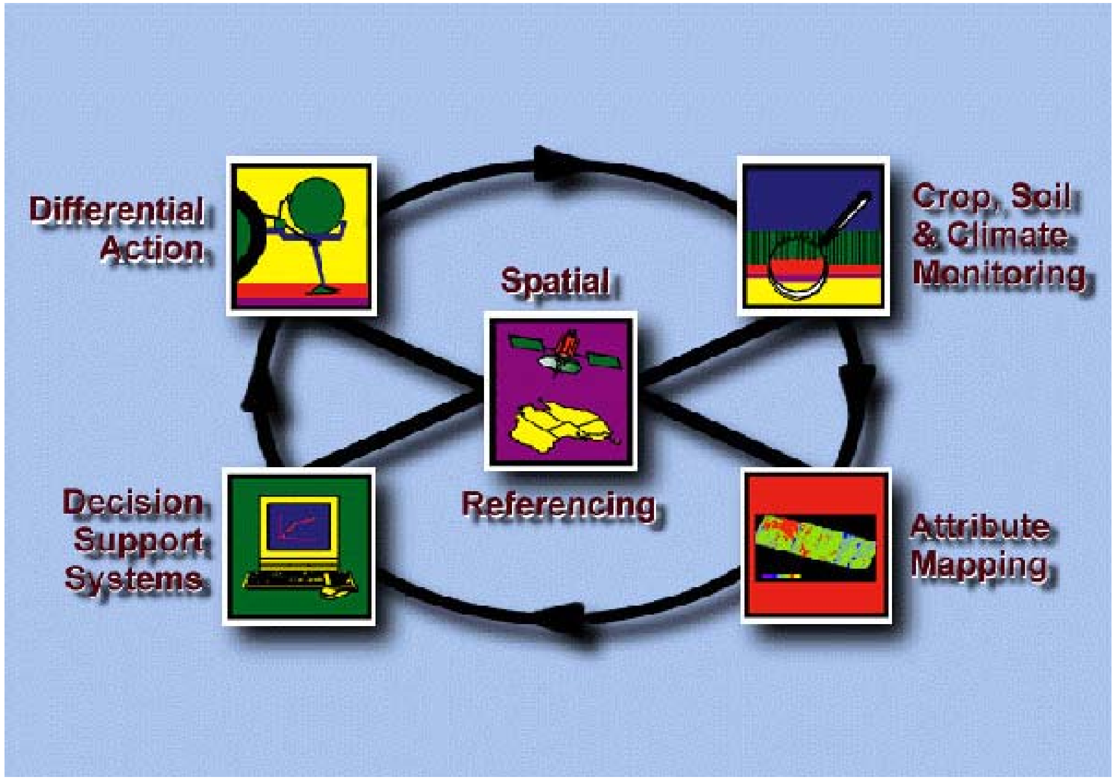

Figure 1 – The PA Wheel

Also central to the PA philosophy are the concepts of Total Quality Management (TQM) and Vertical Integration (VI) in the agricultural sector. Traditionally farmers lost contact with their produce once it left the farm. Now with traceability of products, farmers are able to follow the movement of their produce into the market place. Nowadays a farmer is concerned not only with quality at the farm gate but also the quality at the point of sale and how his product meets consumer demands. This will bring premiums and also will probably be used for environmental auditing.

What it is not

There are several mistaken preconceptions about PA. The first is that PA is a cropping rather than an agricultural concept. This is due to cropping systems, in particular broad-acre cropping, being the face and driving force of PA technology. However PA concepts are applicable to all agricultural sectors from animals to fisheries to forestry. In fact it might be argued that PA concepts are more advanced in the dairy industry where the "site" becomes an individual animal which is recorded, traced and fed individually to optimize production. These industries are just as concerned with improved productivity and quality decreased environmental impact and better risk management as the cropping industry however PA concepts have yet to be applied on the same scale in these areas. For example a graziers use of advance warning meteorological data and market predictions to estimate fodder reserves and plan livestock numbers is a form of PA.

The second misconception is that PA in cropping equals yield mapping. Yield mapping is a crucial step and the wealth of information farmers are able to obtain from a yield map makes them very valuable. However they are only a stepping stone in a PA management system. The bigger agronomic hurdle lies in retrieving the information in the yield map and using it to improve the production system. The advance of PA adoption (usefulness) in this country is may soon be bottlenecked at this point due to the lack of decision support systems (DSS) to help agronomists and farmers understand their yield maps. Yield maps may not tell the whole story either with other data sources, e.g. crop quality and soil maps, economic indicators or weather predictions, proving further information necessary for correct agronomic interpretation.

The final misconception is that PA equals sustainable agriculture. PA is a tool to help make agriculture more sustainable however it is not the total answer. PA aims at maximum production efficiency with minimum environmental impact. Currently it is the potential for improved productivity (and profitability) that is driving PA rather than the more serious issue of long term sustainability. PA will not fix problems such as erosion and salinity by itself although it will help to reduce the risk of these problems occurring. Sensible sustainable practices still need to be used in conjunction with PA.

Variability and the Production System

PA, and of course PV, is dependent on the existence of variability in either or both product quantity and quality. If this variability does not exist then a uniform management system is both the cheapest and most effective management strategy and PA is redundant. Thus, in PA, "Variability of production and quality equals Opportunity". Having said this the nature of the variation is also important in determining the potential for PA in a system. For example the magnitude of the variability may be too small to be economically feasible to manage. Alternatively the variability may be highly randomized across the production system making it impossible to manage with current technology. Finally the variability may be due to a constraint that is not manageable e.g. localized storms in large wheat paddocks. Thus the implementation of PA is limited by the ability of current variable rate technology (VRT - machinery/technology that allows for differential management of a production system) to cope with highly variable sites and the economic inability to produce returns from sites with low variability using PA (VRT).

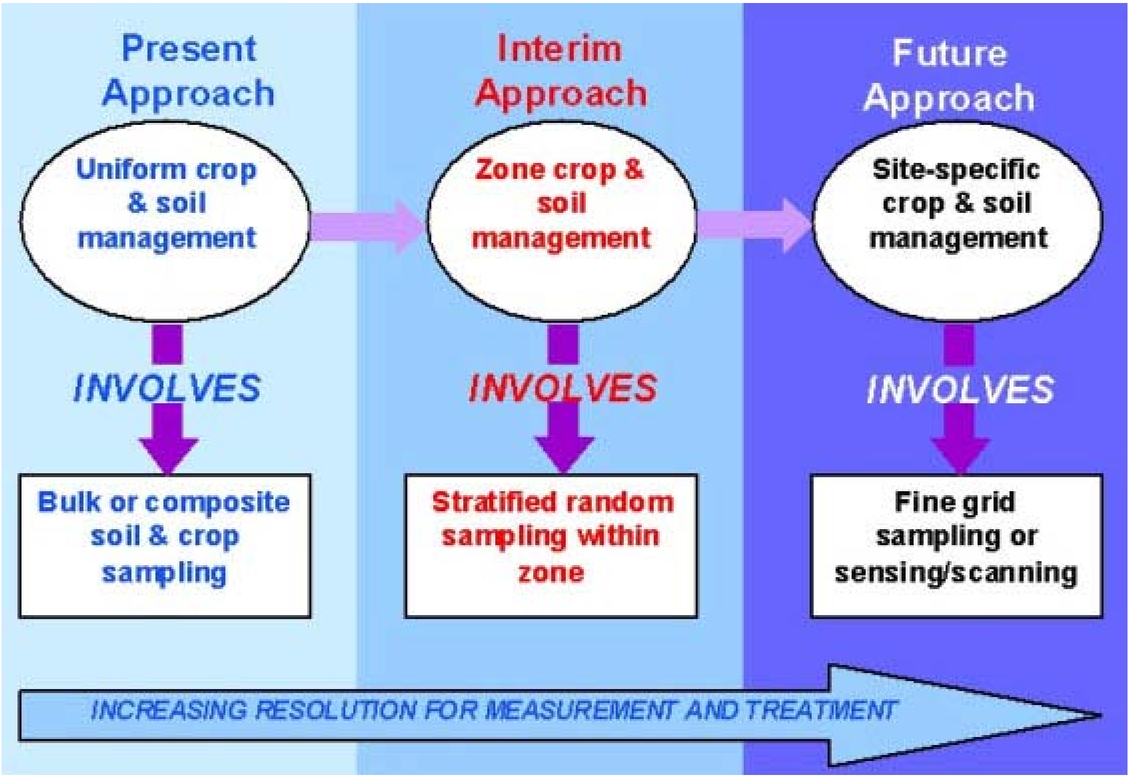

Figure 2 - The PA time line (adapted from Viscarra Rossel and McBratney, 1998)

Due to these constraints PA is at present operating on a zonal rather than a completely site-specific basis. As VRT improves and the capital cost of entering PA decreases, the minimum size of management zone needed to effectively implement PA will decrease till eventually a truly site-specific management regime is possible. Until this occurs there is a need to be able to quantify both the variability of a production system and the size of the minimum manageable zone (MMZ). If the variability in the production system dictates management zones smaller than the MMZ than PA is not relevant to the system at the present time (but may be in the future). It will be interesting to see how the concept of the management zone develops and to see how it compares with the concept of terroir.

Why Precision Viniculture?

In Australia several aspects of the winegrape industry lend themselves to the adoption of PA technology. Viniculture is intensive, highly mechanized, has high value adding potential and is dominated by large companies. Thus the incentive, ability and capital is available. Viniculture is one of the first horticultural crops in Australia to which PA methodology has been applied. While many of the lessons learnt from broad-acre cropping can be utilised, PV also offers new challenges.

Viniculture, and horticulture in general, has fixed perennial plants. Thus there is a long-term scale involved compared to the annual nature of cropping. Plants are cloned eliminating within varietal differences. This puts the emphasis on variability on the site specific clone-environment-management interaction. The system is more intensively managed allowing for more detailed ground truthing and data collection. Management decisions are also capable of having a much larger impact on yield in viniculture e.g. pruning strategies can affect yield by upwards of 100%. The majority of Australian vineyards are irrigated, minimising the impact of the biggest variable in crop production in Australia, and giving further control to the grower in yield and quality production.

Experiences so far…

As discussed previously PV is only applicable to production systems if variability is inherent in the system and while yield maps make pretty pictures there is no simple quantitative measure of the variation present. Fairfield Smith (1938) first proposed an empirical law for quantifying yield variation that looked at the heterogeneity of the field. Recently geo-statistics and in particular the variogram (McBratney and Pringle, 1999) have been used to describe variation of soil properties. Following on from this McBratney *et al* (pers comm.) developed a method of adapting Fairfield Smith's work to PA and yield variograms to describe variation. Variograms have proven very effective in describing spatial variation as they model the semi-variance of the data with respect to distance. An alternative method of estimating areal variability is the Opportunity Index.

The Opportunity Index (O_I) contains three terms. The first evaluates the area over which variation occurs, the second evaluates the magnitude of variation and the third term describes the economics of precision management. The O_I may be interpreted according to Table 1.

Opportunity Index (O_I)	**Potential for PA**
<1	Little to none
1-2	Small
2-3	Medium

>3	Large

Table 1 – The relationship between Opportunity Index and P.A. potential

(For further information on the derivation of the Opportunity Index please contact the authors)

It should be noted that the MMZ for a vineyard is considerably smaller than that required for broad-acre cropping. Viniculture tends to employ narrower applicators and travel at speeds slower than that in broad-acre situations. This means that PV has the ability to manage areas of high short-term variability that broad-acre PA cannot. For the calculations in this work the values in Table 2 have been assumed.

Parameter	**Broadacre**	**Viniculture**
β (m)	20	6
ν (ms^{-1})	6	3
τ (s)	3	3

Table 2 – Parameter values used for determination of MMZ

For this study the yield variograms and integral scales of the correlograms of various crops will be compared to winegrape yield data from the 1999 vintage at Richmond Grove Vineyard Cowra. The winegrape data was collected using a Harvestmaster Profile Grape Yield Monitor attached to a Gregoire G65 Grape Harvester. Data was collected for three varieties, Chardonnay, Cabernat Franc and Semillon. The semi-variance of yield is modelled using a double exponential function (McBratney *et al* pers. comm.). The variograms for winegrapes are shown in Figure 3 and parameters for all crops shown in Table 3. Yield maps are shown in Figure 4.

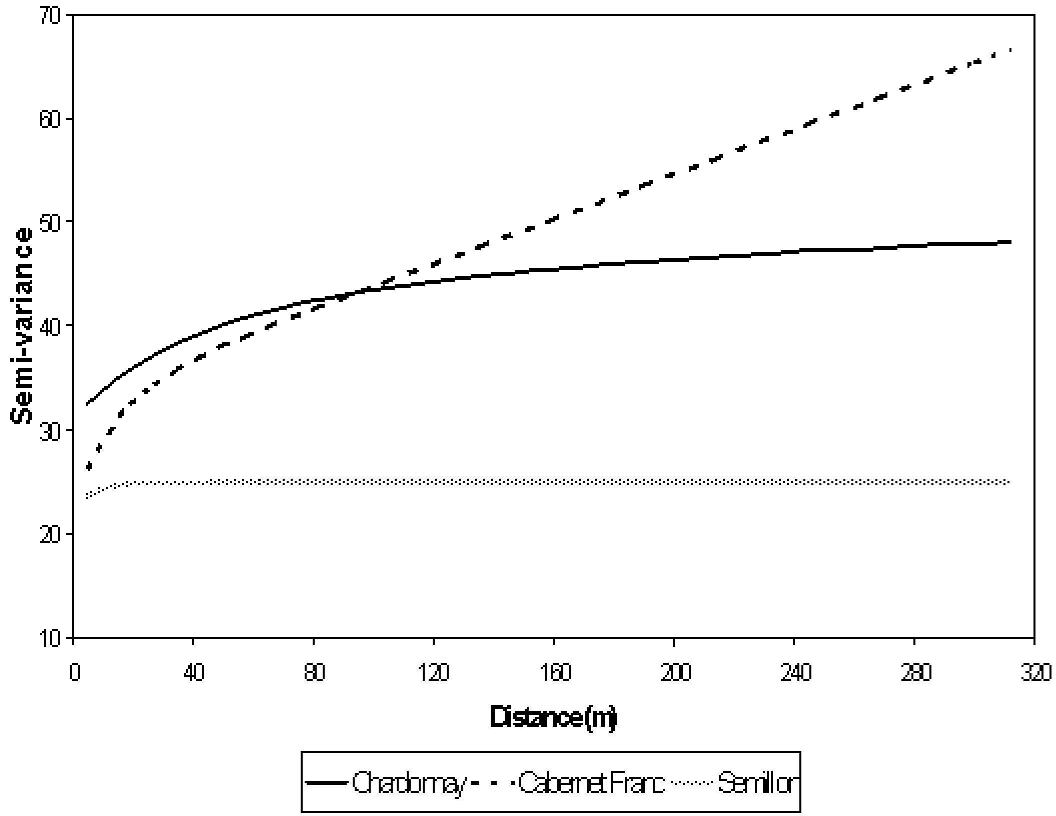

Figure 3 - Yield variograms for the three winegrape varieties.

Field	Crop	Location	Year	Mean yield (μ)	CV_s (%)	CV_v (%)	Variogram Parameters					J_a (ha)	MMZ (ha)	O_I
							C0	C1	C2	a1 (m)	a2 (m)			

D3-4	**Cab. Franc**	**Cowra***	**1999**	**20.4**	**53**	**49**	**18**	**13**	**8611**	**6**	**100000#**	**9216.0**	**0.005**	**6.6**
Horse	Wheat	Moree*	1995	2.7	46	44	0.12	0.07	137.44	13	100000#	9345.1	0.036	5.8
Home 3	Wheat	Wyalkatchem*	1998	1.5	39	38	0.03	0.08	23.72	40	100000#	9312.3	0.036	5.7
w80	Sorghum	Moree	1996	4.2	32	31	0.18	0.14	154.7	8	100000#	9216.0	0.036	5.6
Blackies 6	Lupins	Wyalkatchem	1998	1.1	43	41	0.02	0.04	0.42	36	2061	709.4	0.036	4.6
N3	Wheat	Moree	1995	2.2	59	53	0.32	0.47	1.26	392	784	82.8	0.036	3.8
West Creek	Wheat	Moree	1998	5.6	19	15	0.4	0.25	0.55	9	675	41.8	0.036	2.9
B1-B2	Wheat	Moree	1995	1.4	66	63	0.08	0.15	0.62	155	200	6.7	0.036	2.8
North	**Chardonnay**	**Cowra**	**1999**	**20.1**	**35**	**22**	**31**	**9**	**10.54**	**35**	**212**	**1.9**	**0.005**	**2.6**
B4	Wheat	Moree	1995	1.9	45	40	0.16	0.25	0.33	23	275	6.8	0.036	2.6
West Creek	Wheat	Moree	1997	3.7	29	25	0.29	0.53	0.35	210	213	7.0	0.036	2.4
East Creek	Sorghum	Moree	1996	7	15	12	0.49	0.23	0.44	18	134	1.4	0.036	1.4
Rowlands 1	Wheat	Wyalkatchem	1995	1.5	33	31	0.03	0.09	0.13	50	50	0.4	0.036	1.3
West Creek	Wheat	Moree	1996	5.4	12	10	0.11	0.17	0.12	15	145	1.3	0.036	1.3
Home 2	Barley	Wyalkatchem	1997	1.5	30	26	0.05	0.1	0.05	12	94	0.5	0.036	1.3

Norwood 10	Cotton	Moree	1998	7.8	21	16	1.1	0.46	1.1	7	100	0.8	0.036	1.3
Rowlands 4	Lupins	Wyalkatchem	1996	0.9	19	16	0.01	0.01	0.01	69	72	0.8	0.036	1.2
Home 8	Lupins	Wyalkatchem	1997	0.5	35	28	0.01	0.01	0.01	39	35	0.2	0.036	0.9
Oakville	Cotton	Narrabri*	1999	6.4	16	14	0.36	0.31	0.44	10	218	0.4	0.036	0.9
Telleraga 28	Cotton	Moree	1998	10.4	23	16	3.1	1	1.7	44	60	0.3	0.036	0.8
C1-2	**Semillon**	**Cowra**	**1999**	**23.9**	**21**	**8**	**21.5**	**3.22**	**-**	**7**	**-**	**0.0**	**0.005**	**0**

* Wyalkatchem is located in the W.A. wheat belt. Moree and Narrabri are located in NW NSW. Cowra is located 300km west of Sydney.

These data showed a large linear trend over the distance of the variogram fit (320m) resulting in large C_2 and a_2 values.

CV_s is the coefficient of variation standardised over a distance of 1000m $CV_s = \frac{\sqrt{\gamma(1000)}}{\overline{\mu}}$

Table 3 – Summary of yield variation measures for various crops. All data collected using yield monitors and GPS. The rows in boldface are from our winegrape studies at Richmond Grove. The data from W.A. are courtesy of Dr Simon Cook, CSIRO. The Moree and Narrabri data from the Australian Centre for Precision Agriculture

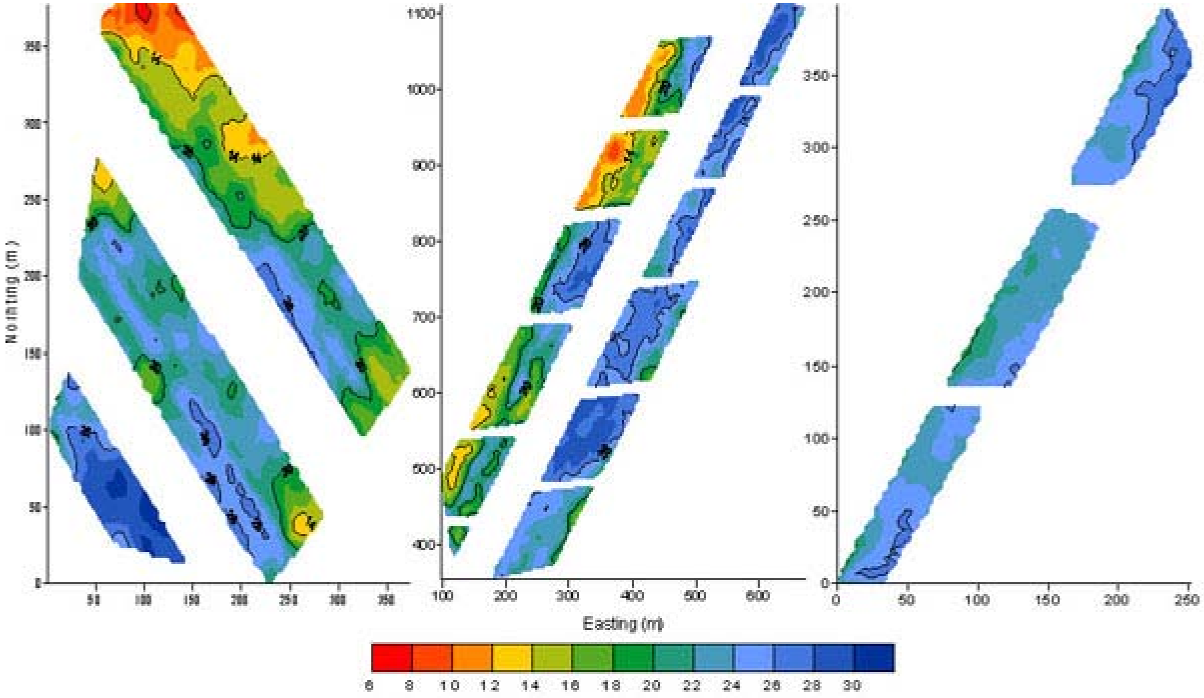

Figure 4 – Yield maps of the three winegrape varieties used in this study

Winegrapes display a high nugget variance (C_0), even when corrected for yield, relative to other crops. This is, possibly due to noise in the yield monitoring system and low plant densities. Even with this large inherent variability the variograms of the Chardonnay and Cab Franc data shows a spatial dependence. Both have relatively large sills (C_0 and C_1) compared to the other crops. Chardonnay has medium to large ranges (a_1 and a_2). The initial range for Cab. Franc is quite short (a_1 = 6m) however the second range is very large (a_2 = 8611m) indicating a large trend in the data. The Semillon data shows very little spatial dependence (low ranges and sills).

While the variogram tells us that there is a spatial dependence in yield it does not tell us the area over which yield varies. The areal scale indicates the area over which there is a correlation between yields. In the case of the Cab. Franc data the J_a value may not be entirely accurate due to a large linear trend over the distance of the modelled variogram (320m). This resulted in the fitting of large C_2 and a_2 values (also observed in the Horse, Home 3 and w80 data). To fit the variogram properly it may be necessary to model it over a larger distance. Both Chardonnay and Cab Franc have large J_a values indicating PV potential whilst Semillon has a very small J_a indicating little or no PA potential. When O_I is calculated the Cab. Franc. block apparently has a large potential, Chardonnay a medium potential and Semillon no potential.

This preliminary study indicates that PV is applicable to parts of the vineyard but not to all areas. In the case of the Semillon it highlights a valuable lesson, if variability does not exists then PV is not necessary and traditional uniform management is preferable. Having said this the data should be interpreted loosely due to the lack of temporal data. For an accurate calculation of O_I the analysis should be performed on data derived from several years' harvesting.

Making PV work

The main objectives of PA have been listed previously, and before we proceed any further it is pertinent to relate these to PV.

Maximising Yield and Quality:

In Viticulture quality is perhaps a more important parameter than yield in determining the value of the crop. There is generally considered to be a trade off between yield and quality in viniculture (and other crops). As noted above a viticulturist is able to exercise considerable control over the yield and quality of the crop. Heavy pruning and applying water stress can decrease yield but increase quality. However studies (Sinton et al) have shown that this trade off it not always necessary and both good quality and good yield can be achieved simultaneously. It is this scenario that is the objective for PV management of existing vineyards.

The first and potentially the biggest step in managing yield and quality and understanding the vine-environment interaction is the initial placement of vines. The long-term nature of a vineyard results in this becoming crucial for future management decisions. If vines can initially be planted in zones of similar environment or "terroir" it may reduce the need to differentially manage them later i.e. by differentially planting we can uniformly manage. This is much more economical than the reverse of uniformly planting and differentially managing. Unfortunately the latter is the more common situation facing existing growers entering into PV today. The benefit of planting varieties to soil type has already been recognised by the industry with soil surveys standard with new plantings. These surveys (usually on 75m grids) may not be detailed enough to provide the accuracy required for PA. Our work at Cowra shows a large proportion of variation at scales finer than this. The use of remotely and proximally sensed data may provide better information for more precise plantings and irrigation layout in the future.

Over the past few decades there has been an increase in consumer awareness of quality and government legislation on quality assurance. This has forced farmers to produce within defined accreditation standards and at a consistent quality. To help regulate this on a global scale the International

Organisation for Standardization (ISO) has developed a set of quality management standards (ISO 9000) and environmental management standards (ISO 14000 -discussed below) for a wide variety of industries. (These are not product standards but management standards and are often incorporated into national standards). ISO 9000 has been developed to meet customer quality requirements thus an accredited company is tailoring the quality of their product/service to the customer and gaining an advantage over their competition. In terms of quality product standards many wineries are now using HACCP (Hazard Analysis Critical Control Points). Under new legislation this will become mandatory for all food business, including wineries, in 2000. Currrently HCCAP is not applied to a vineyard situation (Small, 1999).

The quality issue is especially pertinent in the viniculture industry where inconsistency in grape quality will degrade wines even if average quality is good. Vignerons are also able to produce higher quality wines if the higher quality grapes can be segregated (Johnson *et al.* 1997). With variable grape yield and quality the norm in most production systems and harvesting done uniformly, viticulture is currently not taking advantage of the variation in quality across a vineyard. If, through remote or proximal sensing, quality can be mapped just prior to or at harvest the opportunity is there to segregate grapes to produce better and more profitable wines.

Minimising Environment Impact

Vineyards have two main environmental impact concerns, irrigation and the use of chemical fungicides. Irrigation and salinity is currently one of the biggest concerns in Australian agriculture and as a major user of irrigation water the viticultural industries need to be aware of the potential dangers of over irrigation. A general movement to drip rather than broadcast sprays will help but there is a need to continuously monitor water table levels and adjust management accordingly. There may also be an opportunity for vineyards to employ differential watering regime to further maximise the irrigation efficiency and minimise loss to ground water.

Vineyards are big applicators of chemicals, using upwards of 10 sprays a season to combat fungal and insect pressure on the grapes. A better understanding of the areas most prone to outbreak may allow for a differential application of chemical that is more cost effective and less environmentally damaging.

As mentioned above ISO 14000 standards have been developed for environmental management however the adoption and adaptation of these standards to agriculture is very limited. (For example Denmark has some 50 accredited farms (Langkilde 1999) while there is only one accredited cotton farm worldwide, which is in Australia). The ISO 14000 was developed in response to a need for sustainable development thus PA should be an integral part the guidelines. By adopting these standards produce can be targeted to the environmentally conscious and sold at a premium like free range eggs and dolphin free tuna currently are.

Minimising Risk

Risk management is a common practice today for most farmers. Economically many farmers hedge on the stock market to ensure a minimum price for their product. Others insure to avoid acts of God. With improved communication and information transfer, farmers in the future will hopefully have more data and a better chance of optimizing the use of these economic risk management options. Physically farmers practice risk management by erring on the side of extra inputs. Thus a farmer may put an extra spray on, add extra fertilizer, buy more machinery or hire extra labour to ensure that the produce is harvested/sold on time thereby guaranteeing a return. This is contrary to the concept of PA. PA needs to provide a better management system, to aid in risk management, to substitute for these extra physical inputs (Harris, 1997). This better management strategy will come about through a better understanding of the environment-crop interaction and a more detailed use of emerging and existing information technologies, such as overseas crop reports, short and long term weather predictions and agroeconomic modeling.

Incorporated also into the concept of risk management in PV are TQM and VI. Obviously the quality of grapes is vital in determining the quality of the wine as is expressed in the adage "wine is made in the vineyard". The concept of TQM is schematically described by the Deming Wheel (Figure 5). A TQM approach (using ISO 9000 guidelines) aims to increase quality by firstly decreasing the variability of the system then secondly improving the system (Bishop 1998). By decreasing the variability of the system the risk of the system failing is reduced.

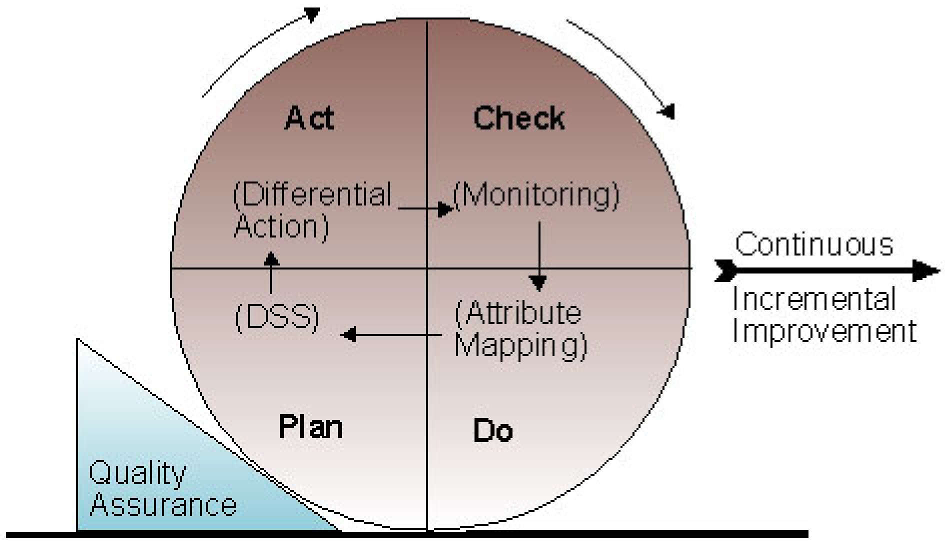

Figure 5 – The Deming Wheel of TQM (adapted from Hutchins, 1992) illustrating the similarities with the PA wheel

Viniculture is a very vertically integrated industry in Australian agriculture with many companies running both commercial vineyards and wineries.

This provides the opportunity for the company to value add to their product prior to sale. To do this efficiently there must be constant communication between vineyard and winery to ensure the correct product is produced. For example wineries will be able to look at overseas or local vintages, weather and market predictions and determine (or predict) what sort of wines are (or will be) limited. With an understanding of the plant-environment interaction, management practices in the vineyard can be applied to produce these wines allowing wineries to target particular markets with the right product. It is a challenge for PV that efficiency of production is maximised in the winery as well as the vineyard.

Where to now…

PV in Australia has barely learnt to crawl yet alone walk yet. At such an early stage it is important that the concept of PA is not misunderstood as it has been in other industries. PV is not a case of whacking a yield monitor onto a harvester and taking off at 100 miles an hour. To make PV work all areas of the PA wheel (Figure 1) need to be addressed. Currently most of the research is directed at data acquisition, environmental monitoring and attribute mapping to quantify variability in the system and identify MMZ's to determine if PV is applicable. If viniculture is not to fall into the same trap as the grains industry there is a need to formulate a PV approach that encompasses all aspects of the PA wheel.

Geo-referencing

Differential Global Positioning Systems are now common place on many farms and the technology is adequate for use in viniculture. One aspect that does need further refinement is the accuracy of DGPS in the z (or elevation) plane. While x, y data (latitude and longitude) is accurate to <1m, elevation is accurate to ± 3m. The use of Digital Elevation Models (DEM) in farm situations is increasing and therefore so is the value of this z information. The commercial potential for this information will result in this improvement coming mainly from private industries.

Crop, Soil and Climate Monitoring

Many sensors and monitors already exist for in situ recording. The challenge for PA and PV is too make these real-time on-the-go sensors. While the commercial potential of these sensors will mean that basic R&D will be done by private industry, research bodies have an important role to play in the development of the science behind the sensors. Market concerns will lead private industry to sell sensors prematurely to ensure market share. This may lead to substandard sensors and a failure to adequately realize the potential of the sensor. Scientists also need to determine what and how multiple indicators can be measured. For example a NIR baume sensor is currently being developed for commercial release. However NIR may also be used to measure other important must characteristics e.g. terpenes, or further characterise sugar content into sugar types. It is also important to utilize other sensors, e.g. ion-selective field effect transistors, to simultaneously measure other must characteristics, e.g. pH and K. The use of multiple sensors also creates new problems in the area of data fusion and decision making, an area which has had little research done on it.

Attribute Mapping

For several decades geostatisticians and pedometricians have been researching ways of describing and representing spatial data that accurately interprets the raw data. Most of this has been done with point data and low data densities. While PA and PV can utilize this previous work it offers new problems. Yield data is often convoluted in the harvester and needs to be post-processed (deconvoluted) before it can be used. PA also produces large dense data sets that are producing new challenges for interpretation and mapping. One of the largest problems is the determination of initial and future sampling schemes to ensure that the variability of the system is properly characterised. These challenges have seen many geo-statisticians and pedometricians move into the area of PA. PV can benefit from the work already done however differences in the production system between vinicultural and broad-acre crops means some research will be needed to adapt and expand these methods.

The other challenge is to bring together data from different sources and present it on a common platform. The development of Geographical Information Systems (GIS) is allowing this to occur however the adaptation of this technology to farm scales is still in its infancy.

Decision Support Systems

Techniques for data presentation and storage, e.g. GIS, developed in other industries are also applicable with some modification to viniculture. However DSS are not so flexible and it is in this area that real research needs to be done. The majority of engineering companies currently supplying PA technology are not interested in and are unable to produce DSS. Thus the onus will fall on the industry and to a lesser extent the government to fill the gap. Initially it may be sufficient to adapt an existing DSS such as AUSVIT to site-specific situations. In the long run a viniculture DSS that is able to site-specifically model vine-environment interactions in terms of yield and quality will be needed. This will need to be flexible enough to incorporate all aspects of the new information technologies, accept feedback from other parts of the PA cycle and be able to conform to standards such as ISO 9000/14000.

Differential Action

The production of VRT is essentially an engineering problem. Due to the commercial potential of VRT much of this engineering development will again be driven by the private sector. The main input from an agronomic point of view is the provision of accurate information on application rates (derived in the DSS) and interpretation of the results of the differential action for feedback into the DSS.

Vertical Integration and Total Quality Management

The other great challenge for PV that is unique in Australian agriculture is the successful implementation of a vertically integrated PV system. For this to succeed the PA wheel needs to be effective at the vineyard level and then brought into the winery. Existing industry standards and guidelines eg ISO 9000/1400, HACCP and Australian Standards need to updated and combined in the context of PA, particularly in areas of quality and environmental management and assurance.

It is inevitable that PV will become the dominant production system for winegrape production in Australia. The real question is how long will it be before this situation is reached. Before we can run we must be able to walk and before we can walk we must be able to crawl. By correctly identifying and targeting the major obstacles to PV implementation we shall facilitate its adoption in Australia.

Acknowledgments

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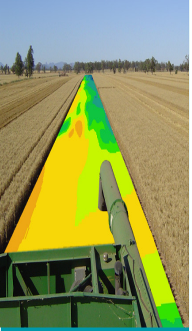
THE UNIVERSITY OF SYDNEY

A Process for Implementing

SITE-SPECIFIC CROP MANAGEMENT

Grains Research & Development Corporation

Australian Centre for Precision Agriculture



Grains Research & Development Corporation

A Process for Implementing Site-Specific Crop Management

from the Australian Centre for Precision Agriculture

Obviously we don't farm to intentionally loose money and in general this is not the case. But if we consider farming over a short time frame (say a growing season) then financial losses do occur. Incorporating Site-Specific Crop Management into farm management will be no gaurantee against future losses, but the risk of short-term financial losses may be minimised by using the information gained and optimising the product input/output ratio. All the while, we also profit from progress in long-term improvements in operability, landscape and environmental management, product marketing, storage of knowledge relevant to enterprise management and our contribution to society.

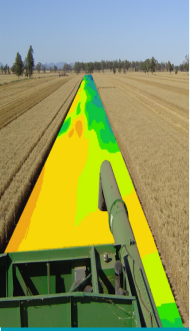
Stepping Through The Process

Site-Specific Crop Management (SSCM), should be considered as part of the continuing evolution in arable land management. Recent developments in technology (satellite navigation systems, geographic information systems, real-time crop and soil sensors) have essentially improved the scale at which we can observe variability in production.

Obviously, the variability found on individual farms and paddocks will be related to the location and previous management, but we can provide a generalised outline of how SSCM may be introduced to a farming system (Table 1).

In Table 1, the steps are to be considered in numerical order so that the most benefit is gained with the least additional cost. This does not mean they cannot be applied in conjunction, but each additional step in this process does require some new tools or techniques to be aquired and applied.

Steps 2 and 3 are where most work is concentrating now in an effort to identify practical ways to quantify and respond to observed variability.



Steps	Tools & Techniques that PA can offer
1. Optimise average crop management	Crop scouting and soil sampling tools, vehicle guidance and auto-steering, simple paddock experimentation tools.
2. Determine the magnitude, extent and responsiveness of spatial and temporal variability	Crop scouting and soil sampling tools, yield monitors, soil sensors and remote sensing, more advanced experimentation and analytical tools.
3. Optimise the production input/output ratio for quantity and quality *(to maximize gross margin and minimize environmental footprint)*	Crop scouting and soil sampling tools, crop yield and quality monitors, soil sensors and remote sensing, vehicle guidance and auto-steering, advanced experimentation, analytical and decision support tools, variable-rate controllers
4. Output quality control and product marketing	Crop quality monitors and segregation tools, variable-rate controllers, application map recording, electronic information tagging
5. Maintaining resource-base and operation information	Crop scouting and soil sampling tools, mapping capabilities and specialized storage software

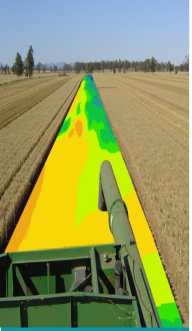
Table 1. Generalised steps to making progress with SSCM.

For SSCM to be tested/accepted/adopted across the agroclimatic zones in Australia, it is important that cost-effective, practical systems be offered to assess the within-field variability in crop production. Such systems should aim at investigating causal relationships between soil/crop factors and yield at the within-field scale along with the extent to which these relationships vary across the field. This information should be used to determine whether the observed variability warrants differential treatment and if so, direct a route through a SSCM decision methodology.

Differential Treatment Options

In implementing differential treatment, rate-based operations that influence crop yield can be targeted to achieve desired yield goals with the minimum input of resources. Such governing operations occur at nearly all phases of the crop growth cycle. The array of variable-rate control designs available or proposed range from simple control of flow rate to more complex management of rate, chemical mix and application pattern. The control segment of any variable-rate application should optimise both the economic and environmental product of the field and should ensure that estimates of operational accuracy and dynamics are included in the application process. This is an important point, as incorrect spatial application may be economically and environmentally detrimental.

In all the operations that are under consideration presently, the control commands may be instigated by accessing a map of application rates and locations (e.g. VRA



map for Lynx controller), combining real-time data with the real-time use of a response algorithm (e.g. Yarra N-Sensor), or a combination of both techniques. For the majority of cropping industries the important areas of managerial intervention would include:

- Fertiliser application (quantity and mix)
- Gypsum/lime application
- Sowing rates and depth
- Crop variety
- Pesticide application
- Irrigation water
- Soil tillage implements and depth of operation
- Crop growth regulator

Decision Methodology

The decision methodology may follow a tree-structure of questions which require a positive or negative answer to decide on a progress path. The information gathered using SSCM technologies would provide the basis for the answers. An example of the logic pathway required for a decision support methodology is presented in Figure 3. This model begins with the premise that variability in crop yield is the initial signal that variable-rate treatment might be warranted. Another model might begin with the observation of soil variability or crop reflectance.

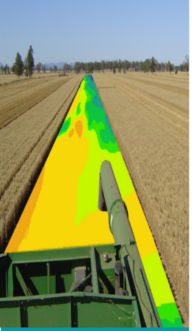
In this model, differential treatment is then examined as an option based on:

- the degree of variation
- the cause/s of variation
- suitability for management intervention

Uniform treatment, continuously variable treatment or the division of a paddock into potential management sub-units (management classes) are the considered options.

Ultimately the assessment and treatment of variability would be undertaken in real-time and the scale of treatment effectively restricted only by the functional specifications of the application equipment (i.e. continuously variable treatment). For the present, the state of agronomic and technological developments probably dictates that the most practical approach for Australian conditions is the identification and assessment of 'broad' management classes within a paddock using relevant layers of information.

If significant production differences can be identified between classess and if the class differences in requirements and responses to the input/s under consideration for VRA can be understood, then PA will be qualified to enter the practical management of cropping systems.



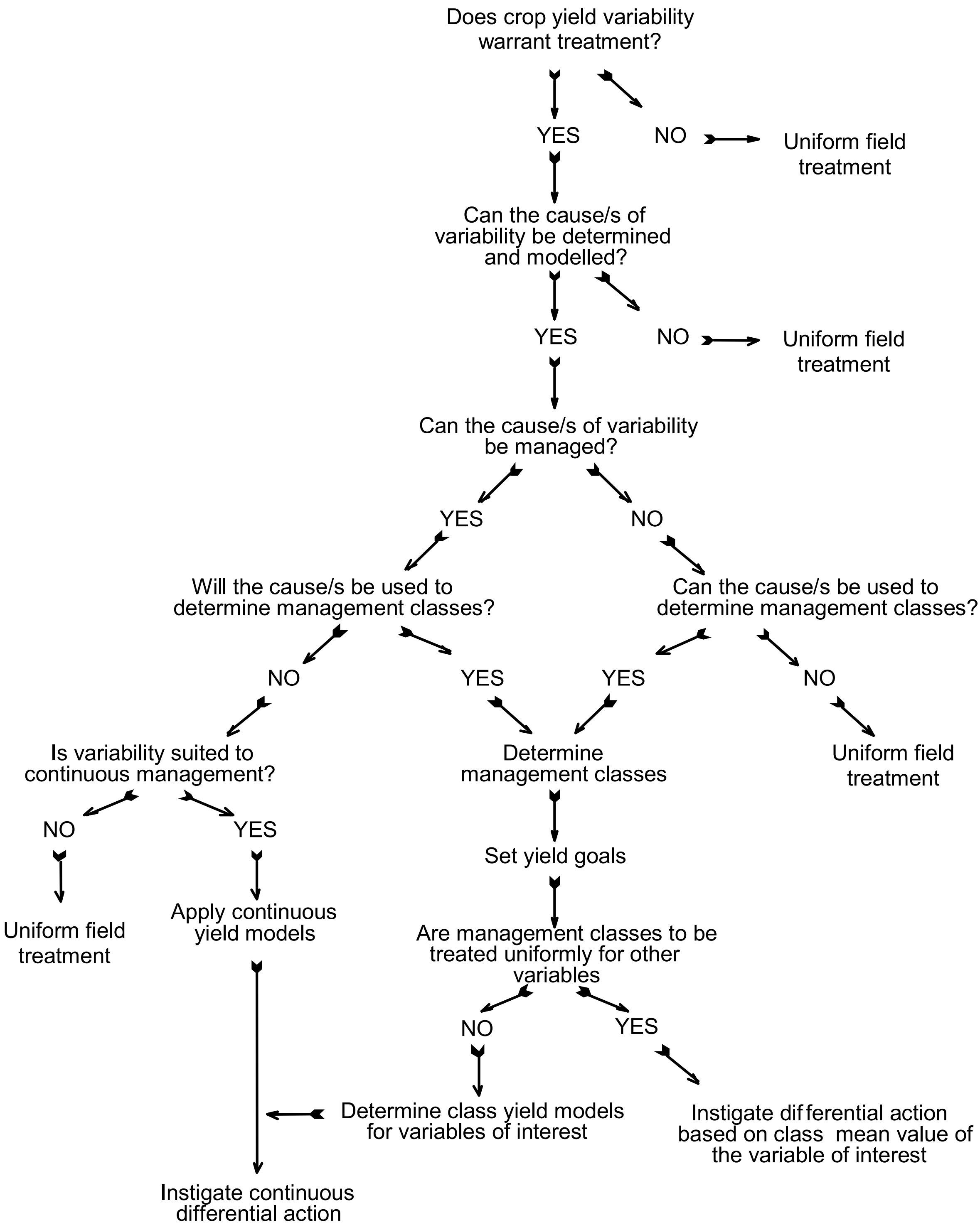
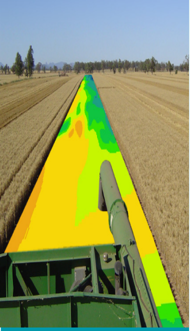


Figure 3. Management decision tree for SSCM – a simple model based on uniform, management class or continuous crop treatment.



Management Class Determination

Essentially, the management classes should partition the variability within the field so that:

- within-class variability is reduced below whole field variability.
- mean within-class variability is significantly different between management classes
- the reduction in variability will also be expressed in important attributes that have not been used to make the management classes.

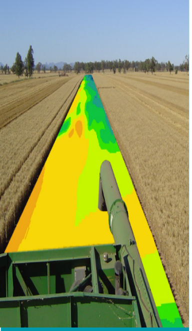
A Brief History

A In the United States, VRA began prior to the advent of yield mapping, using the analytical testing (chemical analysis of nutrients) of topsoil samples collected on a 100-yard grid. This approach is expensive (in Australian terms) and may be logically flawed. The idea presupposes that all areas in a paddock have the same yield potential and in order to reach that potential the optimum amount of fertiliser has to be applied at each point. Research in Europe and Australia (and only recently in the US) has suggested that it would be better to recognise areas within paddocks which have different yield potentials (and therefore management requirements), but which may be managed uniformly within the defined boundaries. These areas, called management classes are in essence, small fenceless paddocks within much bigger paddocks. This approach may be regarded as a risk-averse compromise between uniform management with little or no spatial information and continuous management of cropping variability.

There have been a number of techniques used in the delineation of potential management classes. They include:

- Polygons hand-drawn on yield maps or imagery.
- Classification of remote sensed imagery from an aerial or satellite platforms using both supervised and unsupervised procedures.
- Identification of yield stability patterns across seasons at fixed map nodes using correlation co-efficients, weighted taxonomic distance, temporal variance, normalised yield classification.
- Fuzzy multivariate cluster analysis using seasonal yield maps.
- Morphological filters or buffering.
- Spectral filters using Fast Fourier Transform.
- Multivariate analysis by hard k-zones.

Other options that have been raised are the classification of a soil fertility index calculated by factor analysis and the simple use of standard deviation and the frequency distribution to partition yield/soil maps or imagery.



A few studies have been undertaken to compare strategies for management unit delineation. Grid sampling at a fine scale (approx 50m) often proves more successful than using existing soil unit maps in delineating units with differing yield potentials but the cost of grid sampling always means that this option was is not the most profitable.

In some instances, aerial imagery of crop reflectance has produced more accurate and precise estimation of soil unit delineations than final yield maps. Importantly, the aerial photographs must be taken at the correct time of season to truly represent the yield variability induced by soil variability. The period just prior to flowering (anthesis) is suggested as the optimum window for cereals.

But most studies suggest that intensive grid sampling of soil attributes is the most accurate method of determining management classes (at least for single nutrient fertiliser application). The expense and labouriousness of the sampling regime has fostered the examination of alternative methods. Intuitively, management classes which are developed with the inclusion of data layers that represent an integrative attribute such as crop yield or vegetative index should be more robust for the application of a range of differential treatments.

Relevant Data Layers For Australia

Layers of accurate, spatially-dense, georeferenced information are required to begin the process. Maximising practicality and minimising cost are the major constraints. Crop yield maps obviously contain information on seasonal production that is essential to this process. Beginning this process without information on the spatial variability in the saleable product would appear to be financially imprudent.

It is, however agronomically sensible to include some information on soil and landscape variability in the decision process. Many studies have shown that the most dominant influences on yield variability (other than climate) are the more static soil physical factors such as soil texture, soil structure, and organic matter levels. These are known to indirectly contribute to cation exchange capacity, nutrient availability and moisture storage capacity of the soil.

Gathering direct data on these attributes at a fine spatial scale is problematic, but a number of correlated attributes can be gathered relatively swiftly. Apparent electrical conductivity of the soil (EC_a) has been shown to provide corroboration to the spatial yield pattern in many fields, and correlation with a number of deterministic physical soil parameters. Paddock topography has also been shown to provide an indirect indication of variability in soil physical and chemical attributes - again usually due to a high correlation with a deterministic attribute such as soil texture. Topography also provides indirect information on microclimate attributes that influence crop production potential.

These soil attributes are, however, extremely difficult or impractical to amend in the short-term. However if the more rigid factors are going to limit yield then it would seem prudent to allow these to influence the application rates of any inputs/ameliorants in the field. Intuitively, factors contributing to variability in the soil moisture regime and physical properties controlling soil water movement and nutrient supply may be the most significant causal factor in the spatial variability of crop yield in the majority of cereal growing regions in Australia. Many of the more easily adjusted soil factors such as available nutrient levels and pH could be expected to vary based on the consequences of variation in the physical properties of the soil. Using the variation in the indicator factors - crop yield, soil EC_a and elevation - as a basic data set to delineate areas of homogeneous yield potential may prove useful. The response of inputs/ameliorants to these factors will of course be site-specific, but the significance of their influence may not. Of course other data layers that may be gathered at the same spatial scale may be included if warranted.

At the ACPA, research suggests that a number of years yield data in combination with soil EC_a and elevation provides a very sound basis for management unit determination when subject to a multivariate clustering process.

How Are We Doing It?

The general approach we have been using is:

- Measuring spatial variability in the paddock (at present best simply described by soil EC_a maps, crop yield maps, and digital elevation models)
- Determine number and location of potential management classes if the variation is deemed suitable.
- Direct soil/crop sampling and analysis within the management classes to investigate practical causes of variation.
- Interpret test results and instigate remedial action if indicated, or design within-paddock experimentation for input response measurement which can be used in the future with basic seasonal prediction information.

Growers now routinely gather yield data using their own or contract harvesters and those with autosteer systems can collect data for the DEM during all navigation operations (tillage, sowing, spraying etc). The soil EC_a maps are generally gathered using a local contractor who uses an Electromagnetic Induction (EMI) instrument such as the EM38 or an Electrical Resistivity (ER) instrument such as the Veris 3100.

It is from this stage that the process takes on a bit more complication, and while a number of growers are taking on the tasks themselves, the techniques and software being used at present take time to master.

<u>A Method For Delineating Potential Management Classes With Some Certainty</u>

All attributes to be used in the 'classification' process for each paddock are predicted onto a single, 5-metre grid through local block kriging with local variograms using VESPER. With all attributes on a common grid, multivariate k-means clustering is used to delineate the potential management classes. This is an iterative method that creates disjoint classes by estimating cluster means which maximise the difference between the means of the classes and minimises the variation within the cluster groupings.

Of the available data layers, crop yield (or the income derived there from) has the greatest bearing on farm management and practices at present. Potential management classes, however they are derived, should therefore display significant differences in yield for VRA to be worthwhile. However, ensuring that the differences displayed in crop yield maps are genuine, let alone significant is difficult. Fortunately, the block kriging process provides an estimate of the prediction standard deviation at each point in a yield map, and we use the median value (σ_{krig} (median)) to calculate the confidence interval (*95% C.I.*) surrounding the mean yield estimate within a paddock (μ) (Equation 1).

$$95\%C.I. = \mu +/- (\sigma_{krig}\ (\text{median}) \times 1.96) \qquad \text{Equation 1}$$

And the absolute difference between mean class yields ($|Y_{class1}$ (mean) - Y_{class2} (mean)$|$) should then follow Equation 2 for the classes to be considered representative of regions of significantly different yield ($p<0.05$).

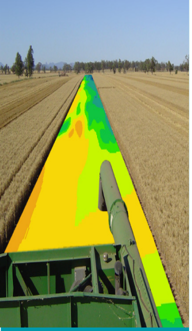
$$|Y_{class1}\ (\text{mean}) - Y_{class2}\ (\text{mean})| > (\sigma_{krig}\ (\text{median}) \times 1.96) \times 2 \qquad \text{Equation 2}$$

This gets us to the point where we can decide the number of potential management classes and set out sampling points within each class. The sampling is a vital point as it allows us to explore what may be causing the variability we have been seeing in our data layers.

Directed Soil Sampling

The basic layers used in determining the potential management classes provide an integrated assessment of changes in production potential using soil, landscape and yield attributes. The next step requires that the classes be interrogated for the cause of the observed yield variability. For SSCM, there are 4 propositions to consider:

- Whether one (or a correlated combination of) static factor/s can be identified that dominates the changes in yield potential in a field.
- Whether there is a transient, manipulable factor that is restricting zones of the field reaching seasonal yield potential.
- Whether complex interrelationships between observable factors need to be analysed and modeled.
- Whether the yield variability is caused by a change in the production process that was not measured (e.g. unobserved, localised pest damage or disease).



The first two proposals simplify management responses. The third may be optimal in terms of optimising yield and environmental benefits, but economically unviable (at present). The fourth would probably show up in a correlation with a static factor unless there was a breakdown in normal standard of agronomy management.

At present, soil sampling is undertaken using a form of stratified random sampling with the potential management classes as the strata. Constraints on the random allocation of sample points are imposed to avoid strata boundaries and to target class means. A minimum of 3 separate spatial locations, with segregated samples from the top soil (0-0.3m) and subsoil (0.3 – 0.9m (max)) are initially targeted for each potential zone. The depth of sampling can be adjusted to suit local agronomic testing regimes if need be.

Analysis of the soil test data should provide us with some explanation or highlight were we need to look further. If an amelioration issue arises (e.g. pH or sodicity problem) then VRA can take place based on the soil test results or further experiments can be laid out within the classes.

The whole process can be described in the flow diagram below:

Relevant Data Layers : Yield, soil conductivity, elevation

↓

Spatial prediction onto a single grid using block kriging

↓

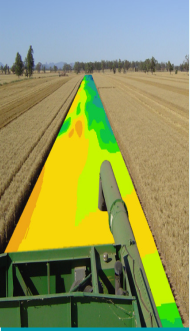
k-means clustering using all relevant layers to delineate production classes

↓

Utilise the mean kriging variance for yield to determine Confidence Interval (C.I.) for class partitioning

↓

Direct soil sampling into management classes to interrogate observed production variation



Practical Examples of Management Class Determination

Paddock 1

Data Layers

In this 75ha field, the data layers used are sorghum and chickpea yield in successive growing seasons (Figures 4a-4b), soil electrical conductivity (Figure 4c) and elevation data (Figure 4d) all collected on a similar spatial scale. The data was collected using (respectively) an Agleader yield monitoring system, the Veris® 3100 conductivity array and an Ashtech™ single frequency plus C/A-code RTK GPS with post-processing.

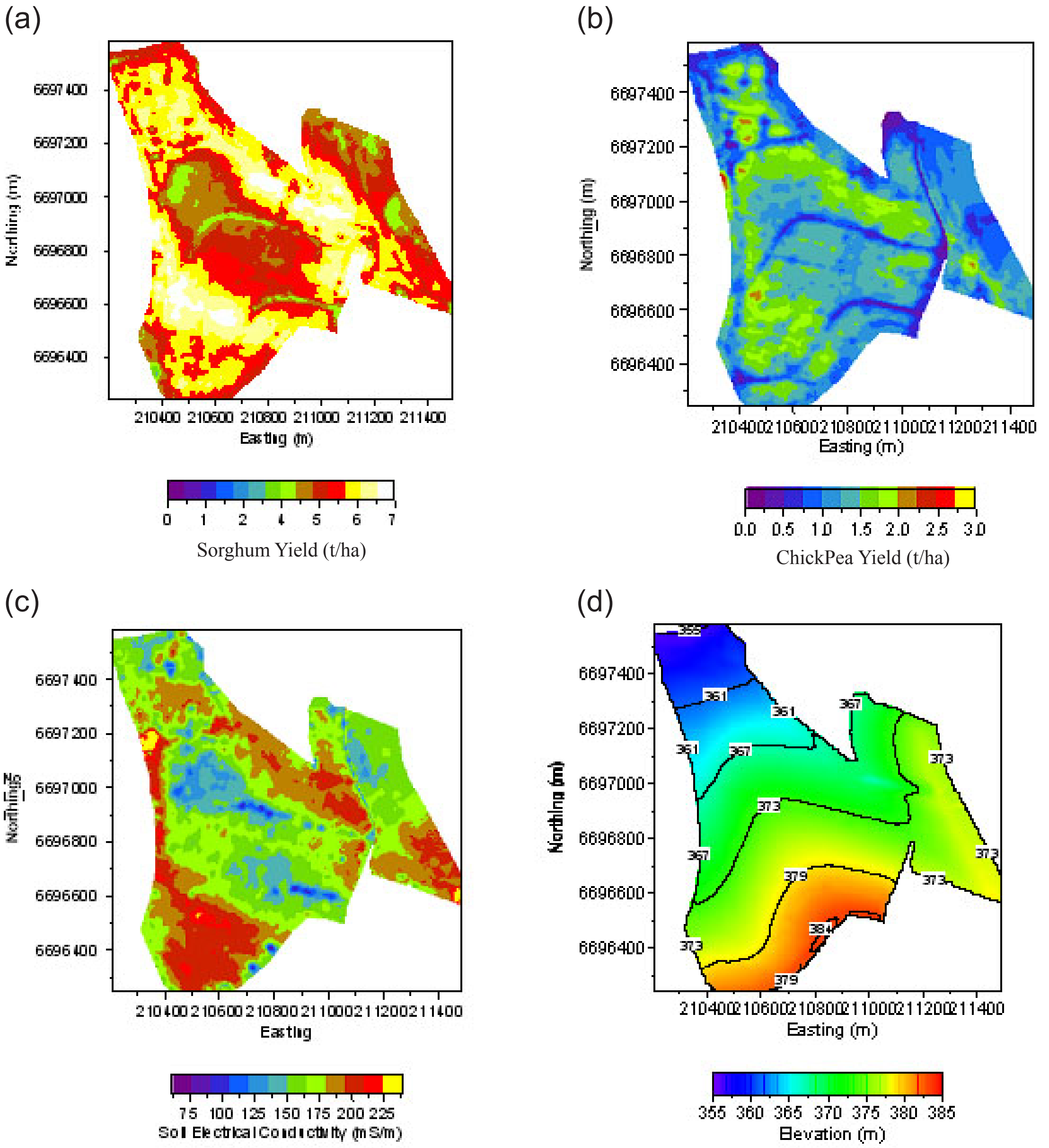
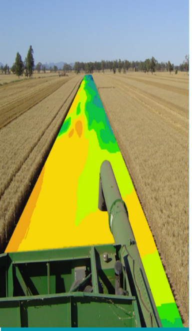


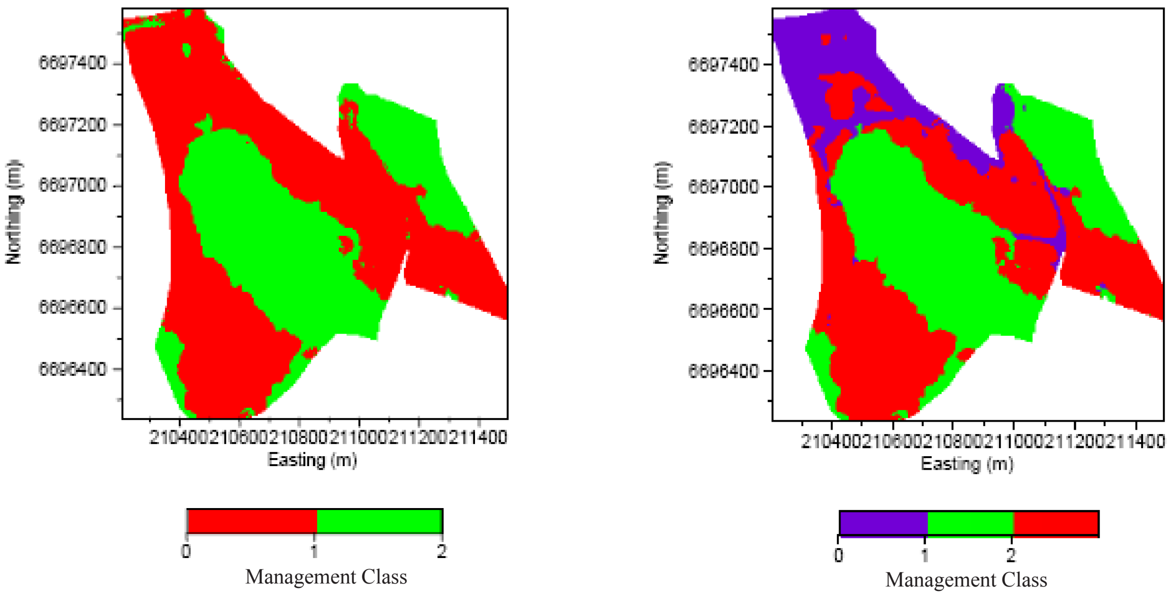
Figure 4. Data layers from a 75 ha paddock in northern NSW – (a) Sorghum yield (b) Chickpea yield (c) soil ECa (d) elevation.



Potential Management Classes

Two and three potential management classes were delineated (Figure 5) for the purposes of testing the validity of the multivariate clustering and significance procedures through subsequent soil analysis. The delineation of classes using this procedure has provided a C.I. for the two crops in question (Table 2).

(a) (b)



	Sorghum Yield (t/ha)	Chickpea Yield (t/ha)	ECa (mS/m)	Elevation (m)
2 Classes				
Class 1	5.8	1.4	185	371
Class 2	4.8	1.1	156	375
3 Classes				
Class 1	5.9	1.4	189	374
Class 2	4.7	1.1	155	375
Class 3	5.5	1.2	173	363
C.I. (+/- t/ha)	0.2	0.1	13.6	

Table 2. Class means for the data layers used in the delineation process. Values for 2 and 3 class scenarios are shown along with C.I. values.

Concentrating on sorghum, a C.I. of +/- 0.2t/ha means that a difference of at least 0.4 t/ha between the mean sorghum yields in the potential classes should be seen to negate the possibility that the variability carried through the mapping and classification procedures is incorrectly depicting the spatial patterns. From Table 2, the 2-class difference is 1.0 t/ha and the smallest three-class difference is 0.4 t/ha. This suggests that a split into 3 classes is on the border of being justified based on the mean sorghum yield differences. For chickpea, a difference of 0.2 t/ha between the mean yields in the potential classes should be seen to warrant further investigation. This is clearly the case for 2 classes but if we increase the number of classes to 3 the differences are not large enough.

Directed Soil Sampling

The classes have been delineated using production information gathered in great detail. Soil sampling sites have been directed within each of the 3 classes in Figure 5b in an attempt to explore causes for the yield differences (Tables 5 and 6). In Tables 3 and 4, the sample sites have been reallocated to one of 2 classes described in Figure 5a.

In the case of 2 potential classess, analysis of the top soil (Table 3) shows that class 2 has produced lower crop yields despite a higher CEC and a lower sand fraction than class 1. Soil nitrate is also double in class 2. An examination of the soil below 0.3m (Table 4) shows that the CEC and clay content of class 2 are significantly lower than in class 1, and the soil nitrate remains double. The difference in the physical properties of the subsoil, combined with the fact that the soil is on average 40% shallower in class 2 conspires to restrict the quantity of available moisture in the profile compared to class 1. This relative limitation in soil moisture in class 2 would limit crop yield and therefore reduce the nitrogen requirement. Under uniform fertiliser management, accumulation of soil nitrogen reserves (as evident in nitrate and total N levels in Tables 3 and 4) would be expected.

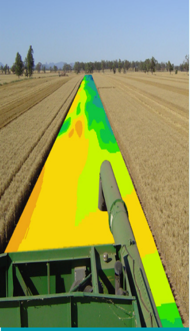
If the field is broken into 3 potential classes, the process essentially divides the previous class 1 into 2 classes. The soil analysis (Tables 5 and 6) shows that the partitioning is reflected in a more refined separation of texture, CEC, depth, soil profile moisture content and nitrogen reserves between all 3 classes. Combining this information with the uncertainty analysis would suggest that in this instance, 3 classes are probably warranted for cereal crops where nitrogen is applied.

Soil Attribute	Class 1 (Red)	Class 2 (Green)	Paddock Mean
pH (CaCl)	7.5	7.6	7.6
O.C. (%C)	0.7	0.9	0.8
N03 (mg/kg)	15.0	30.4	22.7
P (mg/kg)	4.5	5.3	4.9
K (meq/100g)	0.7	0.6	0.7
Ca (meq/100g)	45.9	62.3	54
Mg (meq/100g)	20.2	13.2	16.7
Na (meq/100g)	0.8	0.2	0.5
Total N (mg/kg)	868	1026	947
CEC (meq/100g)	67	76	72
Ca/Mg	2.3	4.8	3.6
ESP %	1.13	0.25	0.69
Sand %	14	10	12
Silt %	13	15	14
Clay %	73	75	74
E.C.	137	163	150

Table 3. 2 classes - soil test results for the 0-0.3m soil layer.

Soil Attribute	Class 1 (Red)	Class 2 (Green)	Paddock Mean
pH (CaCl)	7.9	7.7	7.8
O.C. (%C)	0.7	0.8	0.8
N03 (mg/kg)	8.7	14.7	11.7
P (mg/kg)	2.8	3.7	3.3
K (meq/100g)	0.6	0.42	0.51
Ca (meq/100g)	42.9	42.1	42.5
Mg (meq/100g)	23.3	9.5	16.4
Na (meq/100g).	2.4	0.3	1.3
Total N (mg/kg)	610	887	749
CEC (meq/100g)	69	53	61
Ca/Mg	1.9	5.2	3.6
ESP %	3.5	0.7	2.1
Sand %	13	17	15
Silt %	11	17	14
Clay %	76	66	71
E.C.	159	126	143
Soil Depth (m)	1.22	0.71	0.97
Profile avail. H20 at sampling (mm)	118	68	93

Table 4. 2 classes - soil test results for the 0.3-0.9m soil layer.

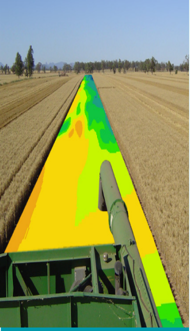


Soil Attribute	Class 1 (Red)	Class 2 (Green)	Class 3 (Purple)	Paddock Mean
pH (CaCl)	7.8	7.6	7.2	7.5
O.C. (%C)	0.6	0.9	0.8	0.8
N03 (mg/kg)	10.6	30.4	19.3	20.1
P (mg/kg)	2.7	5.3	6.3	4.8
K (meq/100g)	0.5	0.6	0.9	0.7
Ca (meq/100g)	51.3	62.6	40.5	51.5
Mg (meq/100g)	22.1	13.2	18.3	17.9
Na (meq/100g)	1.0	0.2	0.5	0.6
Total N (mg/kg)	658	1026	1079	921
CEC (meq/100g)	75	77	60	70
Ca/Mg	2.3	4.8	2.2	3.0
ESP %	1.35	0.25	0.92	0.84
Sand %	12	10	16	13
Silt %	13	15	13	14
Clay %	75	75	71	74
E.C.	136	163	138	145

Table 5. 3 classes - soil test results for the 0-0.3m soil layer.

Soil Attribute	Class 1 (Red)	Class 2 (Green)	Class 3 (Purple)	Paddock Mean
pH (CaCl)	8.0	7.7	7.8	7.8
O.C. (%C)	0.6	0.8	0.7	0.7
N03 (mg/kg)	5.6	14.7	11.9	10.7
P (mg/kg)	2.5	3.7	3.0	3.1
K (meq/100g)	0.48	0.42	0.65	0.5
Ca (meq/100g)	47.0	42.1	38.9	42.7
Mg (meq/100g)	24.9	9.5	21.5	18.6
Na (meq/100g)	2.7	0.3	2.1	1.7
Total N (mg/kg)	532	887	687	702
CEC (meq/100g)	74.8	52.3	63.4	63.5
Ca/Mg	1.9	5.2	1.8	3.0
ESP %	3.6	0.7	3.2	2.5
Sand %	11	18	15	15
Silt %	11	17	11	13
Clay %	78	65	74	72
E.C.	155	126	162	148
Soil Depth (m)	1.24	0.68	1.17	1.03
Profile avail. H20 at sampling (mm)	128	68	108	101

Table 6. 3 classes - soil test results for the 0-0.3m soil layer.



Paddock 2

Data Layers and Potential Management Classes

For this 325 ha paddock , wheat yield , soil ECa and elevation were collected as described earlier. The mean results from delineating 2 classes (C1 yield = 3.7 t/ha, ECa = 114 mS/m ; C2 yield = 4.9 t/ha, ECa = 140 mS/m) and 3 classes (C1 yield = 3.4 t/ha, ECa = 112 mS/m ; C2 yield = 4.9 t/ha, ECa = 132 mS/m ; C3 yield = 5.0 t/ha, ECa = 144 mS/m) suggest that there is little increase in management opportunity revealed by the 3 classes. The C.I. calculation (+/- 0.35 t/ha) adds weight to this assessment. Figure 6 shows the delineation patterns for 2 classes (a) and 3 classes (b) respectively.

(a) (b)

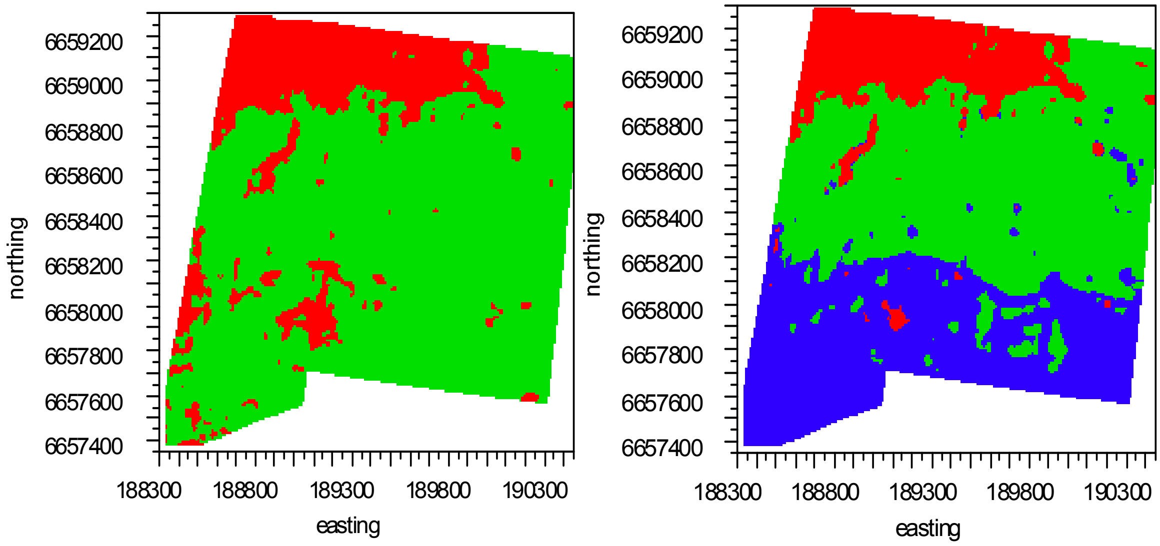
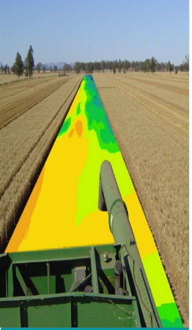


Figure 6. (a) 2 and (b) 3 potential management classes as defined by multivariate k-means clustering. Class 1 = red, Class 2 = green, Class 3 = blue.

Directed Soil Sampling

The results for soil sampling into the 3 classes are shown in Tables 7 and 8. The most striking class deviations from the estimated paddock mean show up in the ESP%, clay content and profile available moisture. If an ESP% >6 is taken as indicating problematic soil structure, sampling for an average would suggest the paddock was not yet in need of treatment. Class sampling, however, identifies class 1 as having a much higher ESP% than the other clases, and importantly, above critical limits in the topsoil (where treatment is more practical). The high ESP% can be hypothesised to be contributing to surface-sealing and reduced infiltration in class 1. A lower clay content helps magnify the difference in the ability of this class to store moisture, as seen in Table 7.

The C.I. calculation suggested that 2 classes were likely warranted in this paddock



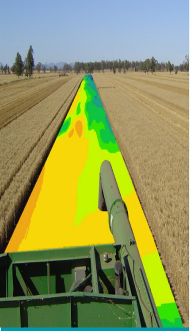
and this has been born out by subsequent, directed soil sampling. The similarity of soil conditions in clases 2 and 3 reflect the closeness in mean yield observed in the wheat yield map. VRA of gypsum, or directed deep-ripping offer potential remedies.

Soil Attribute	Zone 1 (Red)	Zone 2 (Green)	Zone 3 (Blue)	Field Mean
pH (CaCl)	7.8	7.8	7.9	7.8
N03 (mg/kg)	9.2	12.2	15.1	12.2
P (mg/kg)	9.7	10.3	8.7	9.6
K (meq/100g)	0.71	1.03	0.97	0.9
Ca (meq/100g)	17.7	21.4	26.8	22.0
Mg (meq/100g)	11.3	14.0	12.8	12.7
Na (meq/100g)	2.4	1.8	2.0	2.1
Total N (mg/kg)	501	600	496	532
CEC (meq/100g)	32.1	38.2	42.7	37.7
Ca/Mg	1.5	1.5	2.1	1.7
ESP %	8.1	4.7	4.7	5.8
Sand %	31	16	16	21
Silt %	22	19	23	21
Clay %	47	64	60	57
E.C.	0.143	0.113	0.137	0.131

Table 7. 3 classes - soil test results for the 0-0.3m soil layer.

Soil Attribute	Zone 1 (Red)	Zone 2 (Green)	Zone 3 (Blue)	Field Mean
pH (CaCl)	8.3	8.3	8.3	8.3
N03 (mg/kg)	6.0	6.4	9.7	7.4
P (mg/kg)	21.2	12.0	9.7	14.3
K (meq/100g)	0.64	0.81	0.81	0.75
Ca (meq/100g)	17.2	18.6	22.5	19.4
Mg (meq/100g)	14.1	17.6	15.2	15.6
Na (meq/100g)	6.5	5.1	5.4	5.7
Total N (mg/kg)	275	339	419	344
CEC (meq/100g)	38.5	42.1	43.9	41.5
Ca/Mg	1.2	1.1	1.5	1.3
ESP %	17.3	12.1	12.2	14.1
Sand %	27	13	15	18
Silt %	20	23	22	22
Clay %	53	64	63	60
E.C.	0.373	0.233	0.256	0.287
Soil Depth (m)	0.8	0.85	0.8	0.82
Profile avail. H20 at sampling (mm)	24	58	56	46

Table 8. 3 class - soil test results for the 0.3-0.9m soil layer.



Summary

In the Australian dryland environment, it is not unexpected that factors controlling the interaction between crops and the climatic environment should be prominently influential in the variability displayed in crop yield maps. For management, this suggests that it will be necessary to use this class information in conjunction with early season environmental indicators and crop response models (or simpler, empirical budget models) to guide differential action decisions.

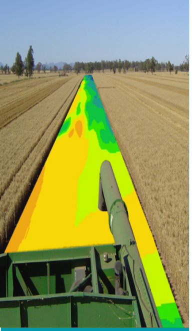
These decisions should not focus on treating a paddock to produce a uniform yield unless the potential is uniform. The benefits from this type of analysis will only be realised by acknowledging diversity in yield potential and environmental conditions when formulating paddock management operations. For example, well-documented areas of low yield potential may be removed from production, have the land-use changed or have their inputs reduced to minimise potential financial losses.
The process of potential management class delineation described here offers a relatively simple, practical approach to using production data gathered at a fine spatial scale. The directed soil sampling should identify whether there is a/are manipulatable limitation/s on production or definable variability in crop yield potential. The process described here is not designed to correct poor traditional (managing to the average) agronomy. Farmers will get greater financial gains by ensuring uniform management is reasonable before venturing down the SSCM path. For those ready to explore improvement on uniform management.

When contemplating the number of agronomically significant classes, care must also be taken to consider and test for the major limiting factors in each zone. Much research will be required to understand the agronomy of response at the within-field scale, under site-specific conditions.

Within-Class Experimentation

Where there are no amelioration issues, field scale experiments can be established to estimate the response in each identified potential management class to a single input. The choice of input for experimentation in each field will be made on the basis of results obtained from the strategic sampling missions within the potential management classes. A marked build-up or depletion in a soil parameter between classes could be used as a criterion along with the magnitude of contribution the associated input makes to the variable costs of production. A zero rate treatment should be included in all trials while the alternative treatments can be multiples of the farmer's uniform application rate. The design of the experiments should consider application equipment capability and size, spatial constraints due to management class pattern and a desire to minimize the area/financial impact of the experiment.

The classes must also be interrogated for the cause of the observed yield variability and the results carefully considered before contemplating any within-field experimentation. What a farmer would be looking for is a managerial significant difference in indigenous soil nutrients, soil restrictions or crop growth/disease



parameters. When the data suggests that response experimentation within the classes is an option, a ‘strip’ or ‘fleck’ design is proposed here, whereby randomised block experimentation is performed with spatial constraints and economic considerations.

Strip or Fleck Design for Experimental Fertiliser Application

The treatment and plot-layout designs have dimensional and orientation constraints imposed by the harvesting operations/equipment. Specifically:

- Treatments must be laid out in the direction of sowing and harvesting.
- Physical dimensions of each treatment plot should be at least three harvest widths wide to ensure that at least one full harvest width can be achieved from each treatment without the possibility of contamination from adjoining treatments. Therefore the minimum plot width will be controlled by the minimum multiple of the application machinery width that will meet this target.
- The minimum length of each treatment plot shall be constrained by the operational mechanics of the harvesters. With grain mixing within the harvester occuring along the direction of operation, yield data gathered at the beginning and end of each treatment plot should be regarded as contaminated by surrounding treatments (usually standard paddock treatment). The plots should be a minimum of 80 m long, and a generic rule of thumb suggests 100 m would ensure most mechanical set-ups are covered. It is suggested that data from the first and last 20m of each treatment plot be discarded from response analysis.

An economic constraint is also included, based on the desire to minimise any penalty to the farmer’s expected profit by using potentially sub-optimal application rates over much of the field. Most of the field can have an initial uniform treatment which the manager considers his best practice. Data from the whole field treatment can be used in the analysis.

Examples of Experimental Layouts

Paddock 44

A 130ha paddock located near Yarrawonga in Victoria (Figure 7a). The experiment was established without variable-rate controlling equipment which reduced the treatment level options. A zero:single:double rate design was implemented by marking the plot locations with a DGPS and shutting off the spreader for the zero rate and making two passes for the 200 kg urea/ha rate. Mean deep soil nitrogen levels (DSN) prior to sowing in 2003 and 2004 are listed in Tables 1 and 2 respectively. The paddock was sown to canola (Brassica napus) in 2003 and wheat (Triticum aestivum) in 2004.

Bill's Paddock

A 50ha paddock located near Crystal Brook in the north-west region of the Yorke Peninsula , South Australia (Figure 7b). The paddock was delineated into 3 potential management classes. A three treatment rate (0, 30, 45 kg N ha^{-1}) with two replicate experimental design was established with a Zynx variable-rate controller. The rest of the padock received 15 kg N ha^{-1}. Mean deep soil nitrogen levels (DSN) prior to sowing in 2003 and 2004 are listed in Table 3. The field was sown to wheat (Triticum aestivum) in 2003 and barley (Hordeum vulgare) in 2004.

(a) (b)

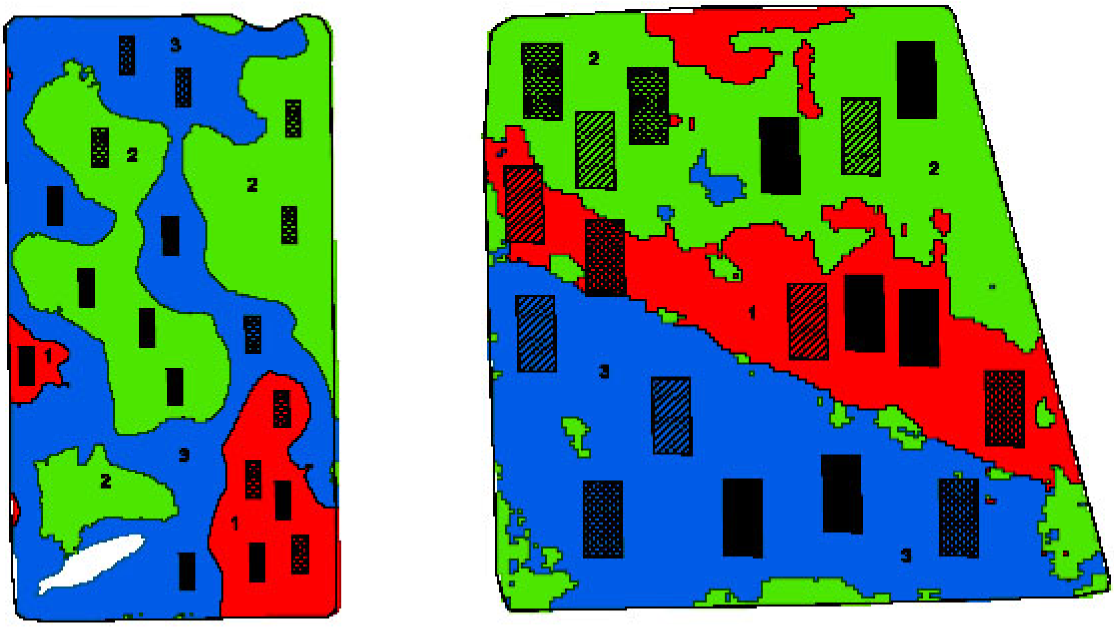


Figure 7. Experimental design for 2 fields, the potential management classes are designated 1,2 and 3; (a) Field 44 (130 ha): 0 kg urea/ha = black, 200 kg urea/ha = cross hatch, rest of field = 100 kg urea/ha (b) Bill's Field (50 ha): 0 kg N/ha = black, single hatch = 30 kg N/ha, cross hatch = 45 kg N/ha, rest of field = 15 kg N/ha.

Analysis

Yield estimates were obtained using on-harvester yield monitors. The estimates were spatially predicted onto a whole-of-field 5 metre grid using local block kriging with localvariograms. The yield data was then extracted for each treatment plot and spatially trimmed to a central kernel by removing 20 metres from the leading/trailing edges and 10 metres from the remaining two sides. This left a 60 metre long, by at least one harvest comb width (depending on the original plot widths), strip of data for analysis. The average yield from each treatment plot was calculated.

Paddock 44

The nitrogen response functions for the two years are shown in Figure 8. The urea rate for maximum yield and also economic optimum in each class using a marginal rate analysis is shown in Table 9. In 2003, the response data shows that the input/output ratio from the different classes would have been economically optimised by applying different average rates in each. In 2004, the results suggest that the whole paddock may have been economically optimized with 0 kg urea/ha.

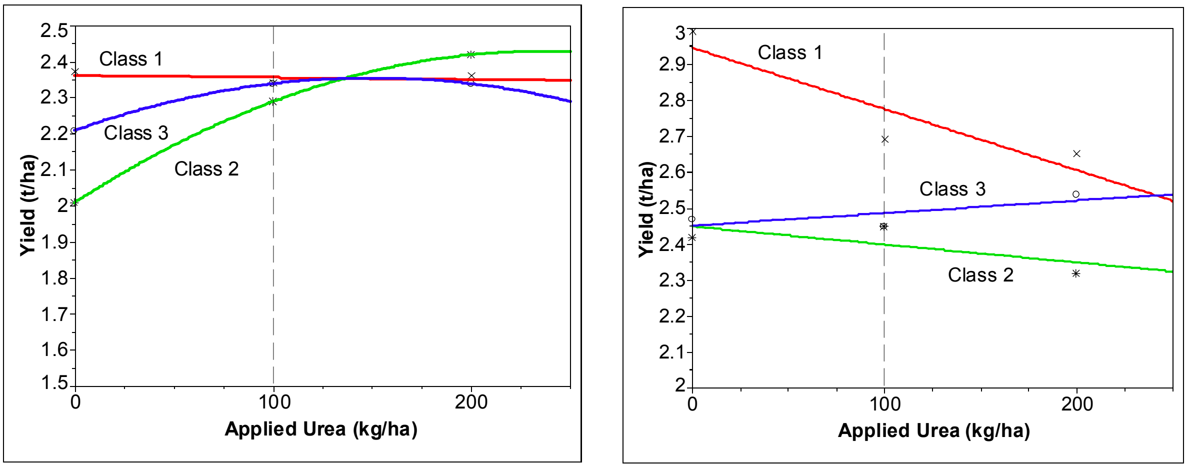


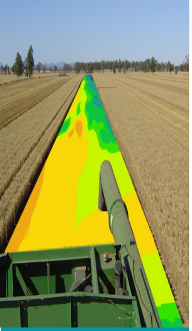
Figure 8. Nitrogen response functions for Paddock 44 (a) canola season 2003 (b) wheat season 2004. Dashed line shows the uniform application rate for the field (100 kg urea/ha).

Class	*Presowing DSN 2003*	*2003 urea rate to maximise returns (kg/ha)*	*2003 urea rate to maximise yield (kg/ha)*	*Presowing DSN 2004*	*2004 urea rate to maximise returns (kg/ha)*	*2004 urea rate to maximise yield (kg/ha)*
1	209	0	0	186	0	0
2	99	169	237	89	0	0
3	151	72	151	150	0	200

Table 9. Urea rates to achieve maximum yield and economic optimum per potential management class in 2003 and 2004.

The 2003 season was considered excellent for the region with an annual rainfall of 523mm (mean annual = 516mm) and 303mm distributed fairly evenly during the growing season (June – Nov.). Annual rainfall for 2004 was restricted to 365mm with 243mm falling during the growing season and only 5mm falling during the crucial October grain filling period.

In 2003, the presowing DSN figures suggested that for a target yield of 2.5 t/ha canola, class 1 was adequately supplied with indigenous nitrogen and the other two



classes would probably benefit from the addition of nitrogen fertilizer. The experimental results bear testament to these expectations. At the time of urea application in 2004, the target yield was 3.5 t/ha wheat and again the DSN suggested that class 1 was adequately supplied compared with the other two classes. The results from 2004 show that the classes in the paddock maintained their potential production relationships (1>3>2) from 2003. However, the final outcome was the result of a crop with good initial nitrogen status, sustaining good vegetative growth, only to be restricted in access to moisture in the final growth stages. The differences in the class response to this moisture restriction is noted as function of soil ECa (mean class ECa: 1 = 61, 2 = 20, 3 = 34) and position in the landscape (data not included).

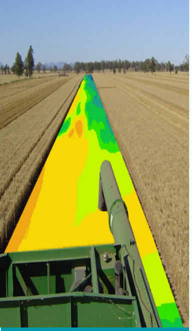
Using the response functions from the typical 2003 season, it is possible to make a simple estimate of what gains or losses in gross margin would have been made if this information had been used to formulate fertiliser decisions at the beginning of the season. Table 10 documents a comparison with the paddock average treatment of 100 kg Urea/ha. As can be seen in Table 10, in 77ha of the field there was more fertiliser than required, and in 53ha of the field an extra application of 69 kg/ha would have brought in over 5 tonne more canola. The total waste in this scenario is A$3028 or A$23.29 per hectare.

Fertiliser waste	ha x kg = t	x $400/t =$A
Class 1	18 x 100 = 1.8	720
Class 3	59 x 28 =1.65	660
Yield loss		x $400/t =$A
Class 2	53 x 100 =5.3	2120
Yield gain		
Class 3	59 x 20 = 1.18	472
Total Wastage		3028 (23.29/ha)

Table 10. Paddock 44: analysis of gross margin differences between variable-rate and uniform (100 kg urea/ha field average) fertilizer application.

Bill's Paddock

The nitrogen response functions for the two years are shown in Figure 9. The urea rate for maximum yield and economic optimum for each class using a marginal rate analysis is shown in Table 11. In 2003, the response data shows that the whole field would have been economically optimized with an application of 0 kg N/ha. In 2004, the response data shows that the input/output ratio from the different clases would



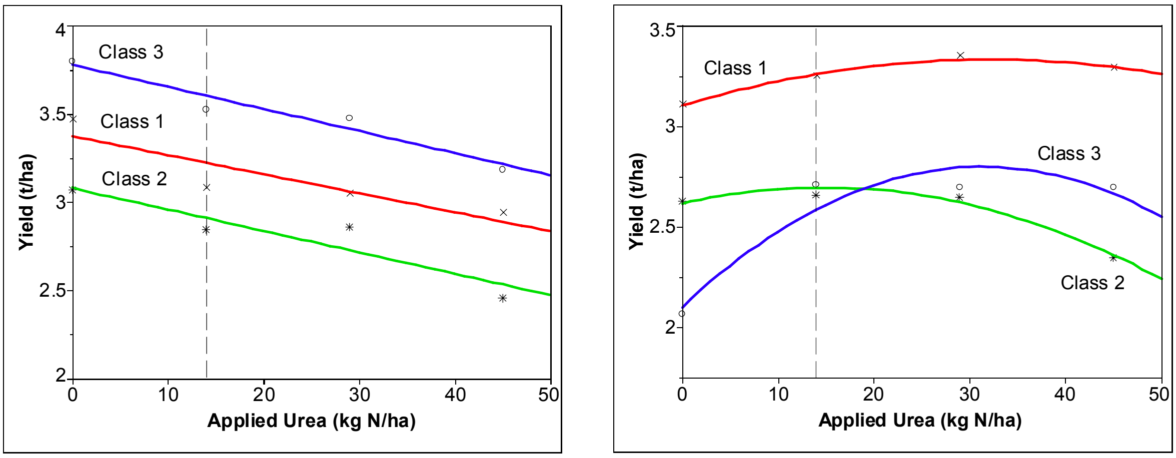


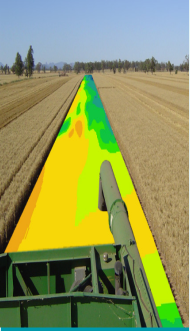
Figure 9. Nitrogen response functions for Bill's paddock (a) wheat season 2003 (b) barley season 2004. Dashed line shows the uniform application rate for the field (15 kg N/ha).

Class	*Presowing DSN 2003*	*2003 N rate to maximise returns (kgN/ha)*	*2003 N rate to maximise yield (kgN/ha)*	*Presowing DSN 2004*	*2004 N rate to maximise returns (kgN/ha)*	*2004 N rate to maximise yield (kgN/ha)*
1	76	0	0	42	17	32
2	60	0	0	39	6	15
3	54	0	0	39	27	31

Table 11. Urea rates to achieve maximum yield and economic optimum per potential management class in 2003 and 2004.

have been economically optimised by applying different average rates in each. The 2003 season was not a good season for the region (mean annual rainfall = 400mm) even with the annual rainfall reaching 383mm. 199mm of this fell in the growing season (June – Nov.) however 78% of this fell in the first 3 months leaving a dry finish to the crop. 2004 saw average yearly rainfall (401mm) achieved, 232mm of which fell during the growing season, but again 77% arrived in the first 3 months and only 4mm during the crucial October grain filling period.Economic analysis of the 2003 wheat season shows that the uniform treatment at 15 kg N/ha produced a gross wastage of A$ 2417 (A$48.34/ha). Yield loss and fertilizer wastage account for 73% and 27% of this figure respectively. This particularly negative response was induced by both the seasonal weather conditions and the fact that the experimental design was laid down as a side-dress following the uniform application of 30 kg N/ha at sowing.

In 2004 the experimental design was established after crop establishment and no N fertilizer was applied at sowing. As can be seen in Table 12, 18.5ha of the paddock



was given more fertiliser than required, and in the remaining 31.5 ha of the paddock an extra application of 17 kg/ha would have brought in 3.9 tonne more wheat. The total waste in this scenario is A$574 or A$11.48 per hectare.

Fertiliser waste	ha x kgUrea = t	x $400/t =$A
Class 2	18.5 x 20 = 0.37	-148
Yield loss		x $130/t =$A
Class 1	12 x 14 = 0.17	-22
Class 3	19.5 x 193 = 3.76	-489
Yield gain		
Class 2	18.5 x 35 = 0.65	+85
Total Wastage		-574 (11.48/ha)

Table 12. Bill's Field: analysis of gross margin differences between variable-rate and uniform (15 kg N/ha field average) fertilizer application

Summary

The confirmation of potential site-specific yield response functions is not new. However, the condition of minimal soil moisture limitation that accompanies these assessments is rarely met in Australia. The response function information presented here shows that variability in N response can be expected in Australia. A very basic partition of the gross margin analysis helps to highlight the potential for environmental as well as financial gains in the Australian environment.

All paddocks on all farms can provide the information relevant for individual management. Input response data from individual padocks may then be used directly or as a replacement for generic models in crop simulation programs. More sophisticated spatial analysis of the N response data, along with intensive grain protein data, will improve its usefulness.

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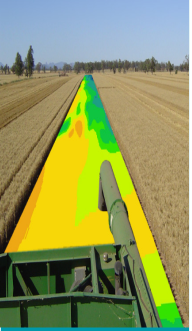
www.usyd.edu.au/su/agric/acpa



Useful Software

Vesper
Spatial prediction software for mapping irregularly sampled data onto a regular grid.
(http://www.usyd.edu.au/su/agric/acpa)

JMP
Statistical analysis and visualisation software that performs k-means clustering.
(http://www.jmp.com)

Geod
Coordinate converter for Australia. Transforms data between geographic and cartesian coordinates and between reference datums.
(http://www.lands.nsw.gov.au/Records/Surveying/GDA/GEODSoftware.htm)

Yield Editor
A filtering program that allows a number of indicators to be used to clean up raw yield data files. It also converts between geographic and cartesian coordinates using the UTM projection.
(http://www.ars.usda.gov/services/software/download.htm?softwareid=208modecode=36-20-15-00)

Splus
Programmable analytical software for basic and advanced statistics and clustering.
(http://www.insightful.com/products/splus/default.asp)

Australian Centre for Precision Agriculture

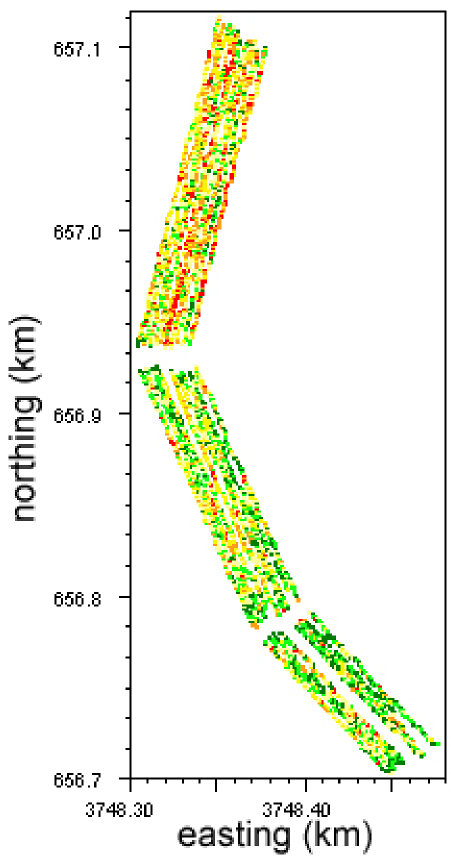
Some Very Preliminary Grape Yield Monitoring

(written 11th March 1999)

James Taylor, Brett Whelan (& a wee bit of help from Alex)

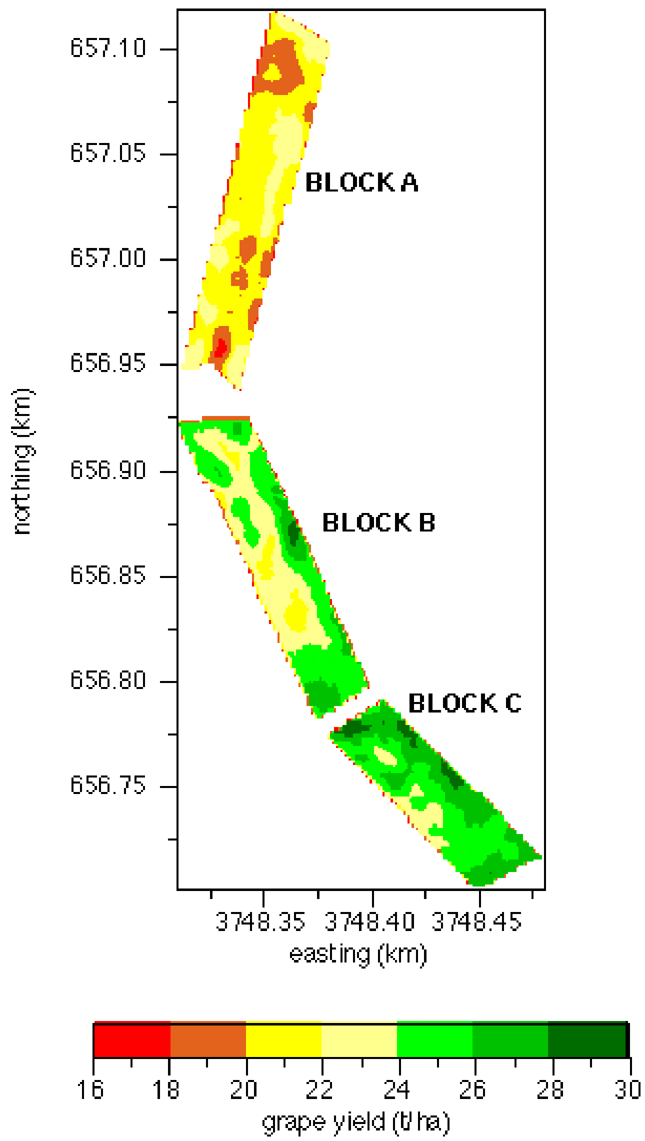
Until now the ACPA has concentrated most of its effort on broadacre crops (grains and cotton). This year sees a shift as the ACPA broadens its research field and begins to look at the application of precision agriculture technology to horticultural crops. Such work has previously been impractical due to the absence of satisfactory yield monitors. The last year however has seen the release of yield monitors for a variety of machine-harvested horticultural crops including potato, tomato and wine grapes.

Using a HM-570 grape yield monitor kindly supplied by Ron Campbell HarvestMaster, Utah, USA, James Taylor of the ACPA has begun monitoring the vintage at Orlando-Wyndhams Richmond Grove vineyard at Cowra. While the majority of the vineyard is yet to be harvested some varieties have been completed and preliminary analysis begun. Below are two yield maps of part of the verdehlo crop. Map 1 shows the raw yield data as retrieved from the yield monitor. The yield data has been divided into 25% quantiles and mapped (Red = 0-25%, Yellow = 25-50%, Light Green = 50-75%, and Dark Green = 75-100%). While the raw data is noisy it can be seen that Block A has a greater percentage of red compared with Blocks B and C indicating lower yield.



Map 1. Shows raw yield data as retrieved from the yield monitor and plotted in Jmp. The data is divided into 25% quantiles. (Legend: Red <14 t/ha, Yellow 14-18 t/ha, Light green 18-22 t/ha, Dark green >22 t/ha)

Grape yield can be better estimated by the use of local block kriging. In this instance we have applied ordinary 5 metre by 5 metre kriging function with local exponential variogram to the data to produce a more coherent map on a 2metre raster. (Map 2). This clearly shows the lower yield in Block A compared with Block's B and C. Map 2 also indicates a low yielding area in the centre of Block B. The difference in yield between Block A and Blocks B/C can possibly be explained by their location. Blocks B and C are located on fertile river flats while Block A is situated on a gentle slope. A change in topography is often associated with a change in soil type which in turn affects yield. However soil testing will be needed to confirm such a hypothesis. The low patch in the centre of Block B may also be due to a localised soil difference. Alternatively it may be a result of a localized pest/disease outbreak or management error. Liasing with the farm manager and staff will help to identify such problems.


657.10
657.05
657.00
656.95
656.90
656.85
656.80
656.75
northing (km)
BLOCK A
BLOCK B
BLOCK C
3748.35
3748.40
3748.45
easting (km)
16
18
20
22
24
26
28
30
grape yield (t/ha)

Map 2. Yield map after local 5-metre block kriging of raw yield data onto a 2x2m grid.

Collection of yield data is the first step toward precision viticulture however it is not the most important step. It is the ability of the farmer/manager to interpret the cause of the yield variation that will be determine how valuable the yield data is. Accurate identification of yield determining characteristics and effective remediation will allow the farmer to improve both productivity and profitability.

To do this we then need to understand the specific plant-soil-climate interactions at each site in the field. It is our aim to try and understand these site-specific interactions through the use of several data layers including yield maps, soil maps, satellite imagery, plant tissue analysis, management decisions, disease/pest maps etc. By analysing and intergrating these data layers we hope to be able to derive yield-determining factors at each site in the field and then a method to differentially apply inputs to satisfy each individual sites requirements. Through such research the huge potential for precision agricultural technology will be realised in Australian viticulture.

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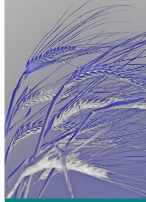

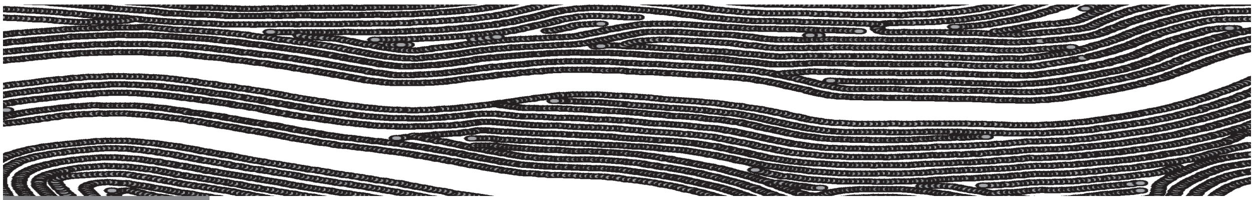

Making Yield Maps:

A guide for the Australian Grains Industry

In Australia, yield monitors are now standard on many new makes of combine harvester. Coupling these monitors with GPS technology allows growers to geo-reference their yield information. Nevertheless, to make decisions from this information it needs to be presented in a form that is easy to interpret. Yield maps permit this by visually displaying the data. However if yield maps are incorrectly constructed and/or displayed then any decision stemming from them may be incorrect. There are many options for making and displaying yield data and a protocol to aid Australian grain growers in making correct maps is provided here.

Introduction

This short guide is designed to firstly provide some tips on the management of precision agriculture data sets and secondly to provide a simple guide to the production of yield maps using local block kriging (an interpolation method) in the shareware program Vesper.

Yield Data Management

As we all know Precision Agriculture produces a lot of data. If the management of this data is incorrect then the data becomes difficult to analyse and interpret. A definitive approach to data management is difficult as there are many different yield monitors and associated software being used. However there are some generic concepts and approaches that should be applied to help in data management.

Backing-up data

Firstly: REGULARLY DOWNLOAD YIELD DATA DURING HARVEST!!! This ensures that the card doesn't become full and that points are not logged or existing data is over-written.

Secondly: ALWAYS BACK-UP YOUR DATA REGULARLY!!! If your hard disk crashes and you lose the data it may be gone for good.

These are basic protocols but still many people do not follow them. The best way to ensure download and backing up occurs regularly is to establish a routine for data administration. Once a day is ideal, at the change of crop type (when the header is being cleaned down) is less ideal, but however the timescale is determined, incorporating data download and backup into some routine will ensure that it is downloaded with some regularity.

Basic Data Storage

1) When using the software that comes with a yield monitor (or other suitable PA software) the raw yield files (that come straight from the yield monitor) will be read into the PC by the software and stored in a directory on your computer. The software will usually break files into paddocks for display if the files contain more than one paddock. If the software provides a backup facility, use this to copy the files to another disk drive or external disk. If this is not possible, it is a good idea to copy the raw files directly from the mobile storage device into a seperate disk or disk drive. Alternatively, locate the storage folder in the software and copy that to another disk. As long as the raw data is kept intact somewhere then data manipulation can be redone later if a mishap occurs or alternative approaches are developed.

2) Ensure that yield data has been properly adjusted with the correct calibration before beginning analysis

Basic Folder Organisation

Most PA software will store yield and other data in a hierarchical structure similar to that shown in Figure 1. This allows for rapid data retrieval and minimises the chance of mixing up files. If commercial PA software is not being used, which may be the case for growers and consultants wishing to analyse data sets with more complex techniques, then establishing a

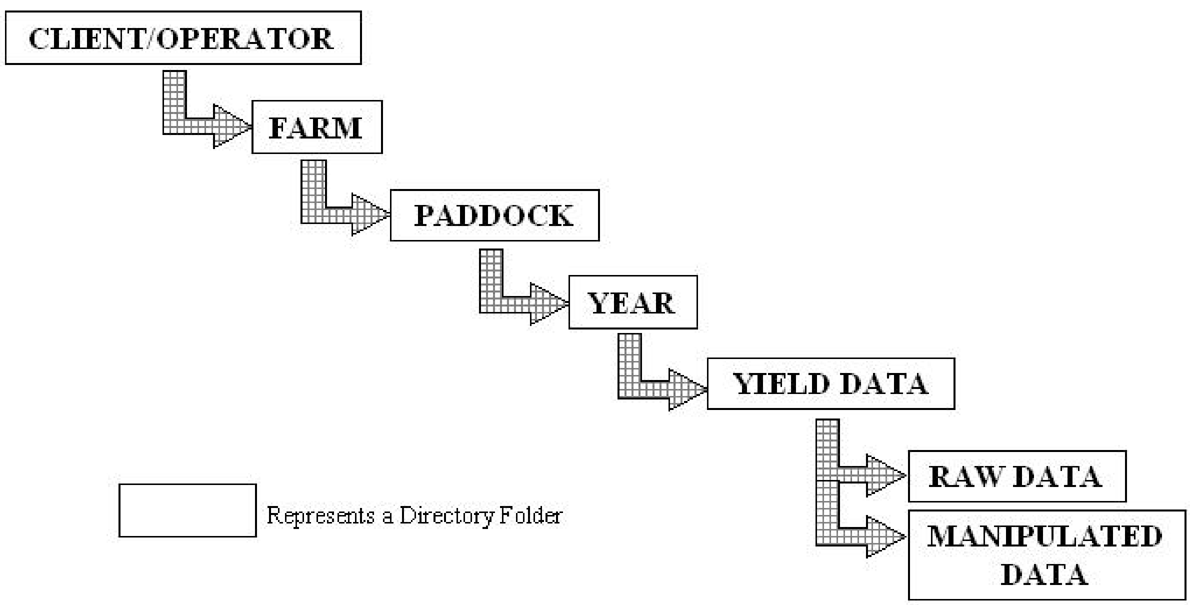

Figure 1: Suggest hierachary for data storage propsed by the GRDC Strategic Initiative No. 9 (Precision Agriculture)

logical folder hierarchy becomes very important. Obviously organisation inolves some degree of personal preference, however the GRDC SIP09 Precision Agriculture Project has developed a basic structure to act as a template from which growers/consultants can customise their own hierarchy (Figure 1).

The aim of the GRDC hierarchy is to ensure that each field is kept unique and the data from each year is also kept separate. The folder for each year in Figure 1 has been separated into "RAW DATA" and "MANIPULATED DATA". In this instance the raw files would most likely be those exported from the monitor software after calibration. Most yield monitor software uses a proprietary file format for internal storage and operations but all should have an ability to export and import data in a generic "comma separated values" (.csv) or "text" (.txt) file. Text files can be delimited using commas, tabs or space(s) thus are more versatile. Proprietary file types are more limiting in the software that will read them. For this reason we strongly recommend that data analysts store their data in either ".csv" or ".txt" files for ease of data dissemination and usage. The "RAW DATA" file allows the original data to be stored unaltered. If the raw data is manipulated then a new file should be saved with the altered data into the "MANIPULATED DATA" folder.

File Naming Protocol

Correctly naming files exported from proprietary software will help minimise confusion and permit files to be properly categorised. File names should contain:

Field name
Crop type (wheat, canola, barley etc.)
Year collected
Data type (raw, trimmed, interpolated etc.)

Examples: A raw yield file containing wheat data from Home paddock harvested in 2002 would be named

Home_wheat_02_raw.txt

If the data was trimmed (abbreviated to tr) and converted into UTM coordinates then the new file may be called

Home_wheat_02_MGA_tr.txt

Further, if the data had been interpolated by kriging (see the mapping section) (abbreviation K) then the resultant file would be

Home_wheat_02_MGA_K.txt

Abbreviations can be used, e.g. wht for wheat and can for canola, to shorten the file name. It is likely that different people prefer different abbreviations. This is fine as long as you can understand the abbreviations. By including the above information in the file name the grower, as well as any contractor/consultant who uses the data, can easily identify what the file contains.

Basic Data Manipulation

1) Converting geographic coordinates (Latitude and Longitude) into Cartesian coordinates (Eastings and Northings)

Most yield monitors log position using geographic coordinates, i.e. latitude and longitude, which use degrees to identify position on a sphere (the earth). This is preferable as geographic coordinates are absolute values, therefore, there is no doubt about where the reading was taken. The disadvantage with using geographic coordinates is that while the position is absolute the distance (in metres) between points separated by a degree is relative to latitude. Points separated by a degree at the equator are much further apart than points separated by a degree near the poles. To overcome this problem and present the data in sensible units (metres), yield data is usually transformed onto a flat surface and given in cartesian coordinates (Eastings and Northings). The projection (surface) that is commonly used is Universal Transverse Mercator (UTM). However, Eastings and Northings are relative values, not absolute like latitude and longitude, and their value at a particular point depends on the datum used. Unfortunately there are many datums in use, therefore, if a position is quoted in Eastings and Northings it is ambiguous unless the projection and datum used are also given.

Australia has its own datum, Geodetic Datum of Australia 1994 (GDA94), which is based on the Geodetic Reference System 1980 (GRS80) and is very similar to the World Geodetic System 1984 (WGS84). Effectively the three can be interchanged with little loss in data accuracy. There are several older Australian datums (e.g. Australian Geodetic Datum 1966 (AGD66)) however GDA94 is now the standard and recommended datum. For users already using an older or different datum there is no problem as long as the datum is recorded so transformations between datums can be done if data sets are merged. Some advanced PA software can perform coordinate transformations. The NSW government has also produced a freeware program, GEOD, that can perform coordinate transformation on large files. It will transform between datums but also between geographic and cartesian coordinates. Details of GEOD can be found on the Department of Lands website (http://www.lands.nsw.gov.au/Records/Surveying/GDA/GEODSoftware.htm) (last viewed October, 2006).

The main advantages of converting yield positions into Eastings and Northings (i.e. metres) is the ability to be interpolated onto a regular grid and the measurement of distances and areas within fields is in metres. The yield data is then also compatible with other data sources e.g. imagery, both aerial and satellite, that are usually deliverd in cartesian coordinates.

2) Removing erroneous data points

Raw yield data files will contain erroneous data due to many reasons including loss or incorrect GPS signal, spikes in the yield or speed sensors, a narrowing of the actual cutting width, turning with the comb down and numerous other operational problems. Some of these errors produce data points that lie outside of the range of the majority of the data and are termed *outliers*. Some error points however lie within the range of the majority of the data and are termed *inliers*..

Outliers are generally easy to remove following these steps:

Firstly, remove any data above and below a certain threshold. In general the Australian Centre for Precision Agriculture uses upper and lower thresholds of 10 ton/ha and 0 ton/ha. The rationale is that yield above 10 t/ha in grain, oil and pulse crops are highly unlikely in Australian conditions (rice and some corn crops excluded). Yield files will also contain zero values which are artifacts of harvest operations, in particular harvester fill-up and empty when beginning and ending runs or turning.

Secondly, after removing these extreme values, remove values that lie outside the range of the mean (average) plus or minus 2.5 standard deviations. This will remove the top and bottom 1.5% of data which should eliminate the outliers in most yield files. The best way to test that this is the case is to identify points that lie outside this distribution and plot a histogram of the data. In some cases outliers will remain and the distribution should be restricted to the mean plus or minus 2 standard deviations This process can be achieved in Microsoft *Excel* or other statistical packages. In general yield data tends to have a fairly well defined range of values however some datasets will have skewed data. In this case further data mining is need to determine if the "tail" is real. The best way to do this is to label the data points in the tail then plot as an X by Y graph. If the data fall into a discrete area then they are probably real. If they are scattered randomly throughout the plot then they are probaby artifacts.

Inliers are harder to identify and remove. Inliers often occur when the effective cutting width is decreased or the speed of harvest changes dramatically. Positional errors are also possible when GPS problems occur or when cutting around trees or other operations that mean previous harvest paths are crossed or closely approached. These points are less problematic though if a spatial prediction process (mapping algorithm) is used that allows for the possibilities of these errors. This is discussed futher on. However, there are a number of yield data filtering software programs available that identify these points with varying degrees of success. They are listed on the ACPA website (www.usyd.edu.au/su/agric/Software.htm).

At the moment the ACPA believes that following the simple protocol above and using an appropriate mapping tool then the resulting maps will be suitable for use in PA management.

Spatial Prediction of Yield Data

Why is this necessary?

When plotted as individual points, raw yield data can be difficult to interpret. To make the data more presentable, most software used in PA will produce a continuous surface map from the yield points. Continuous maps are usually smoothed to remove some of the noise in the raw data and present a more coherent map that may be more easily interpreted. A variety of approaches can be used to perform spatial prediction of the raw data (discussed below).

Apart from making a map, spatial prediction is also valuable from an analytical perspective. If done correctly it can correct for inliers in the data by analysing 'regions' of data and removing extreme peaks and troughs from the final prediction. Spatial prediction also permits data from different times and/or sources to be compared. When a field is harvested it is highly unlikely that the same location will be recorded in different years. This makes it difficult to merge data from different years and perform statistical analysis. If the data is interpolated onto a standard grid each year then data from different years can be analysed. This allows the statistical, rather than visual, identification of stable and variable areas of crop production. Similarly data from other sensors, for example aerial imagery and on-the-go soil sensors, can be expressed on the same grid to try and understand yield determining factors.

Methods of Spatial Prediction

There are many different ways of spatially predicting yield data including:

1) Nearest Neighbour - The value of the raw data point nearest the grid node is used

2) Moving Mean or Moving Median - The mean or median of raw data points within a specified distance from the grid node is used

3) Inverse Distance Weighting (IDW) - The interpolation uses raw data points which are weighted according to their distance from the grid node (with closer points receiving a higher weighting).

4) Kriging - The interpolation uses the relationship between variance and distance of the raw data to assign weights to raw data points at different distances from the grid node.

Each approach has a particular use depending on the data type and data density. For yield data, characterised by dense data sets, the preferred approach is to use kriging.

Kriging Using Vesper

The advantages of using kriging to map dense spatial data are being realised and incorporated into larger more advanced software packages, particularly Geographic Information Systems (GIS). Most PA software however only use a moving mean or inverse distance weighting function. A shareware program, Vesper, has been developed by the Australian Centre for Precision Agriculture. It can be downloaded from the ACPA website (http://www.usyd.edu.au/su/agric/acpa/vesper/vesper.html). This program is aimed specifically at the interpolation of large, dense datasets like yield data. Vesper is currently set up as a research tool and this section is aimed at providing guidelines for lay people to use the program. It is not an attmpt to explain the statistics and theory behind kriging. More detailed information on the program and the kriging procedure can be found in the operating manual and in Whelan *et al.* (2001) at the end of this document.

Vesper is setup to accept comma-separated text files. It requires at least three columns - Eastings, Northings and one variable to be predicted. Vesper will accept up to 50 variables in a single input file. Vesper relies on cartesian coordinates not geographic so positional information must be converted from Longitude/Latitude to Eastings/Northings.

The program contains four master buttons and three tabulated pages. The four master buttons are always accessible regardless of the tab being viewed. The first master button ("Run Kriging Program") activates the prediction process. The second button ("Save Control File") saves the control file and is seldom required. The third and fourth master buttons provide information about the program ("About") and close the program ("Exit"). The three tabulated pages are described below in the context of setting up the program to predict yield data.

1) The Files Tab Interface (Figure 2)

i) Specify the **trimmed** yield file, with **cartisan coordinates** (Eastings and Northings), either by navigating in the windows on the left-hand side of the screen or clicking on button A and browsing.

ii) Click the "Select Data" button and specify the X (Eastings), Y (Northings) and desired data column.

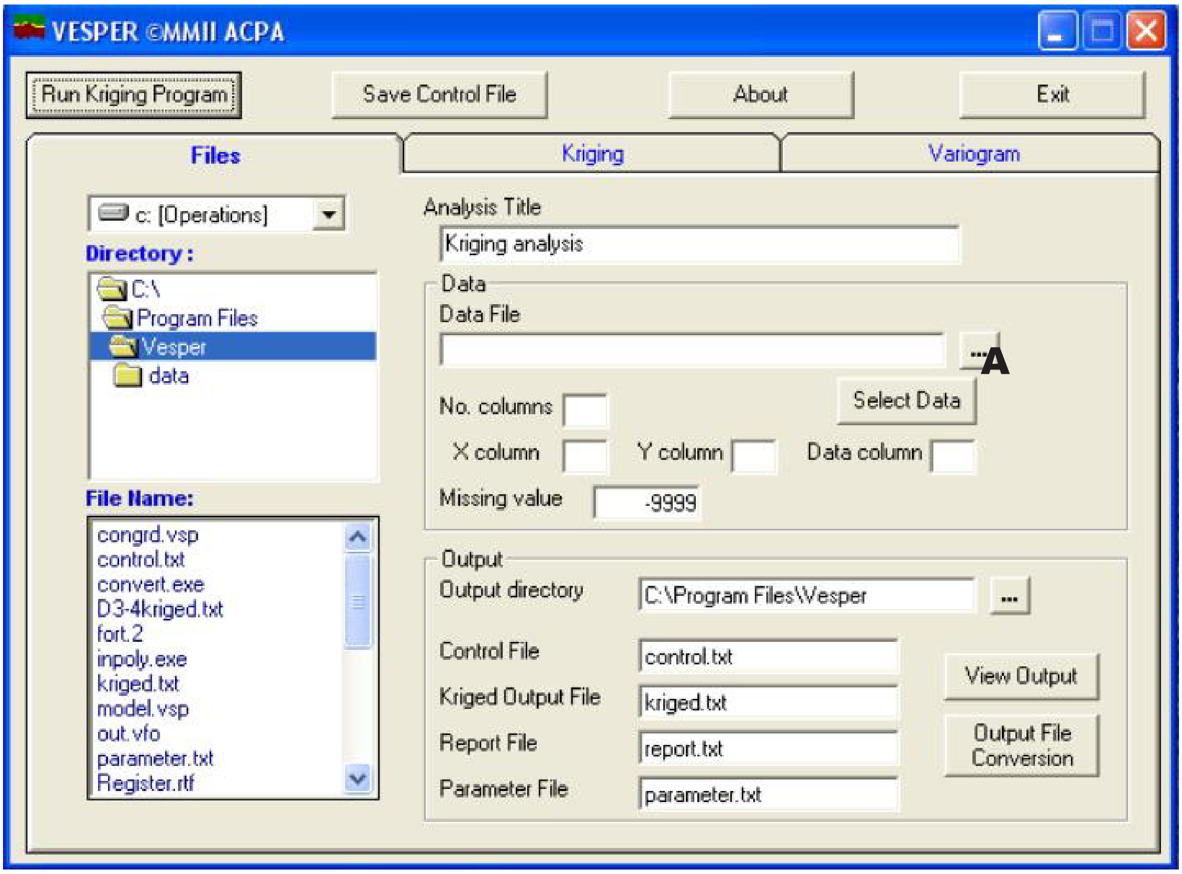

Figure 2: Files Tab Interface of Vesper.

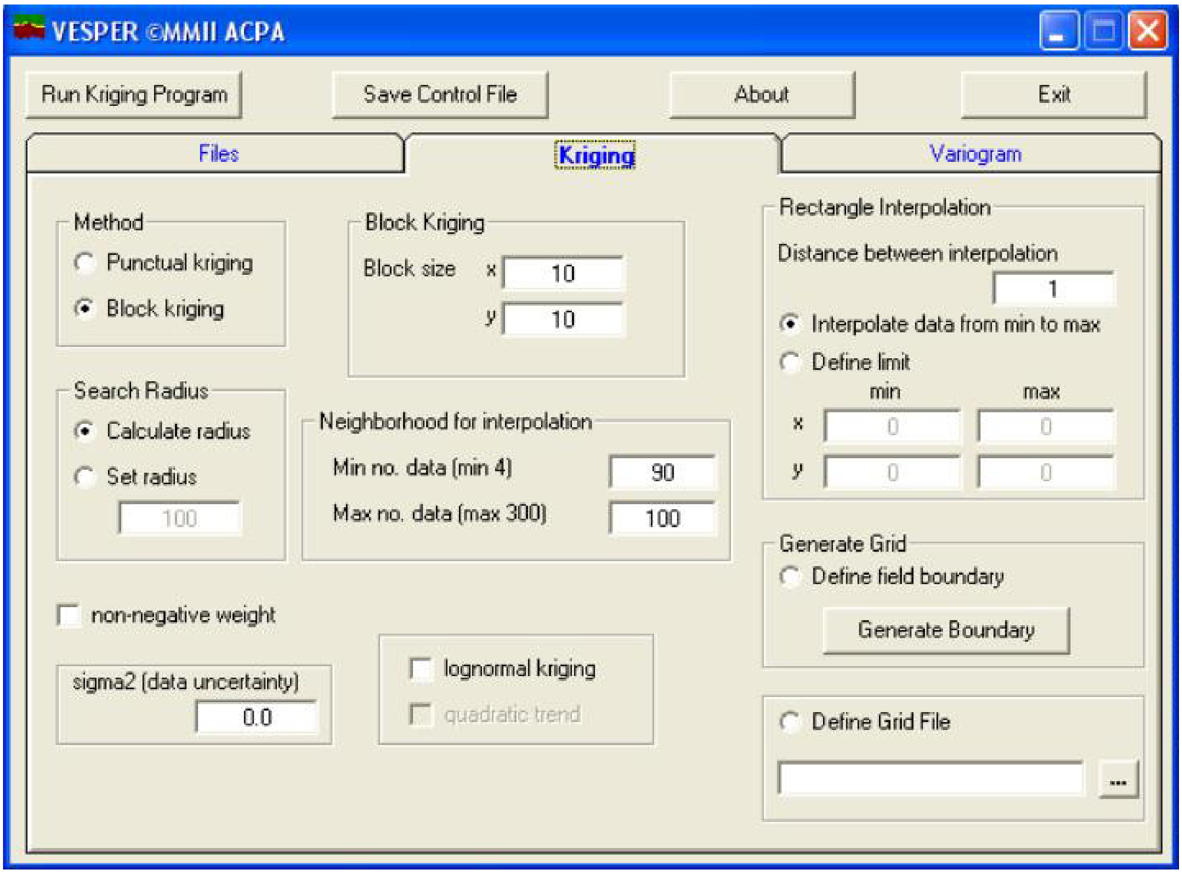

Figure 3: Kriging Tab Interface of Vesper.

iii) Specify the desired output location (“Output directory”) and file name (“Kriged Output File”). Ensure that the file name has a “.txt” extension.

iv) Leave the Report File, Control File and Parameter File as is.

2) Kriging Tab Interface (Figure 3)

i) Select Block Kriging for the Method

ii) Specify the ‘Block Size’ as 20m. This figure is used as it has been found to approximate the scale over which a harvester mixes the grain before it reaches the sensor.

ii) Leave the default values for “Search Radius” and “Neighbourhood for Interpolation”.

iv) Do not check the “non-negative wright” or “lognormal krging” boxes

v) Ignore the “Rectangle Interpolation”

vi) Specify the grid file on which the data will be predicted.

If a grid file already exists then click the “Define Grid File” point, browse to the desired file and select. REMEMBER the same grid file should always be used for a field.

If a grid file does not already exist then click the “Generate Boundary” button. This prompts a new window displaying the data points (shown in Figure 4). This window is designed to create a boundary within which the grid will be made. Right click the mouse button on a vertice of the field then left mouse click around the field in an orderly clockwise or anti-clockwise direction to form a polygon. Right mouse click to finish. This will prompt you to save the

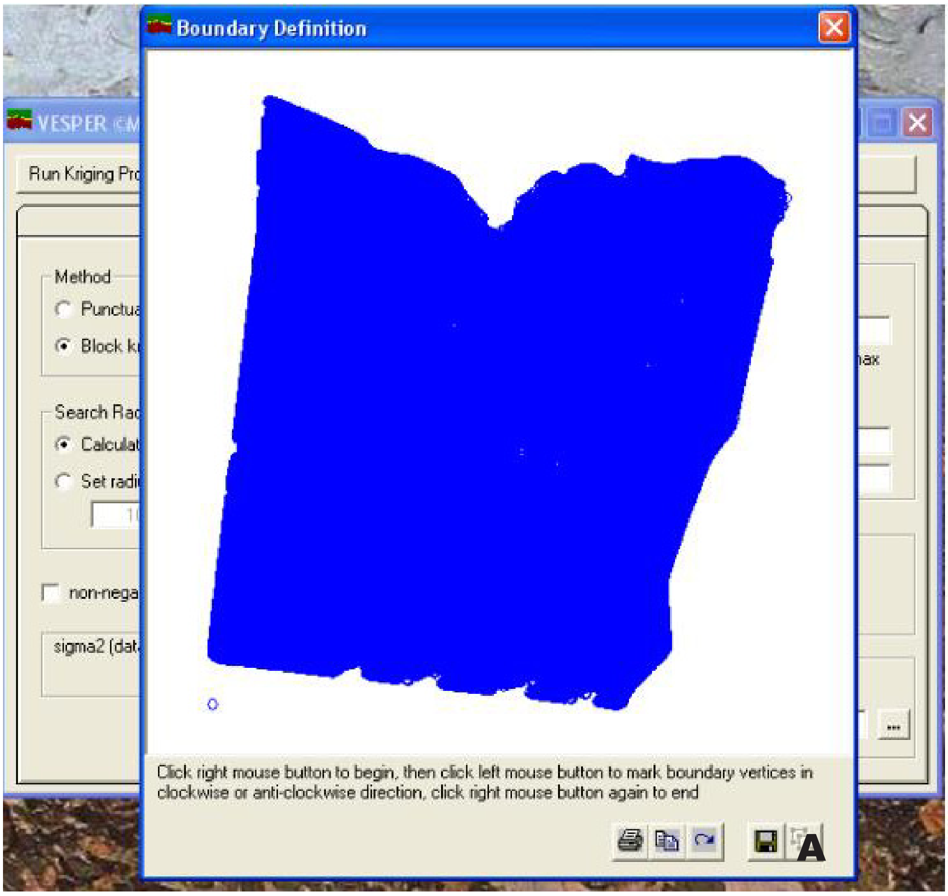

Figure 4: Boundary definition window of Vesper.

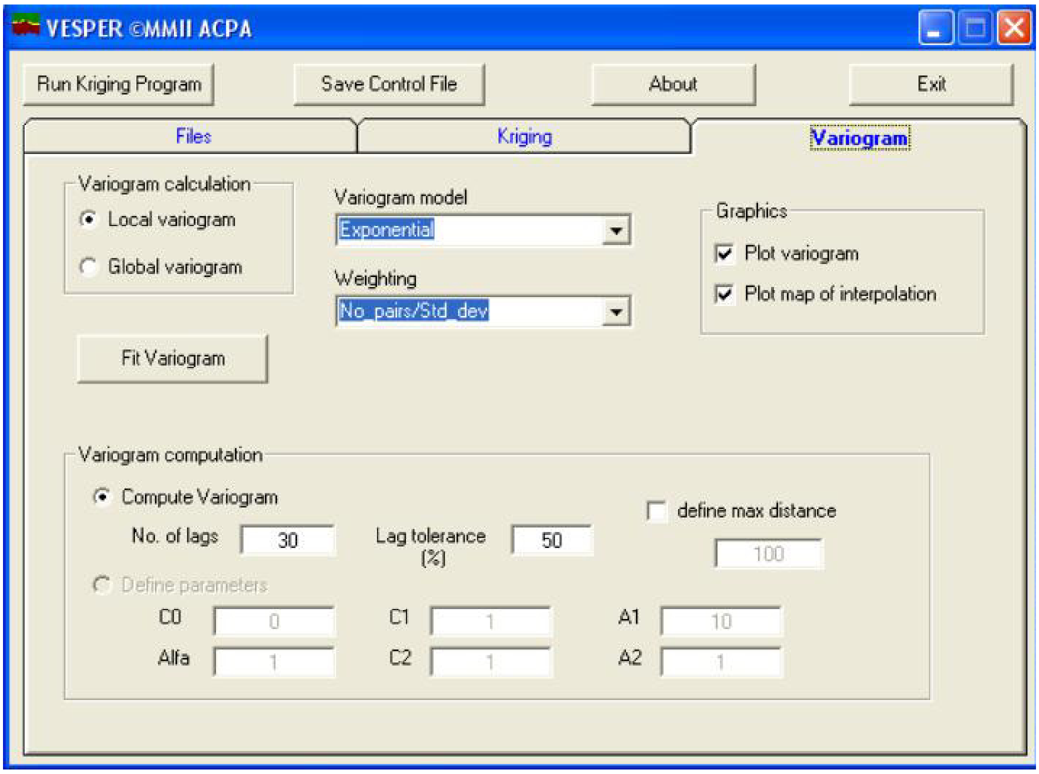

Figure 5: Variogram Interface of Vesper.

polygon as a boundary file. Click "OK" and save the boundary.txt file. With the boundary still displayed in the window click the "generate grid using current boundary" button in the bottom right of the window (Label A in Figure 4). This will prompt to save the grid file and specify the grid size. A 5m grid is recommended for most broadacre crops. The grid file should be saved somewhere accessible as it will be used for the interpolation of other data sets.

If only a few points are displayed instead of the entire field it is likely that there are some errorneous coordinate data points (e.g. a (0,0) reading) and the X and Y columns need to be checked for outlying points. After creating the boundary file, if a grid cannot be derived make sure that the field is being displayed in cartesian (metres) and not geographic (degrees) coordinates.

3) The Variogram Tab Interface (Figure 5)

1) Select "Local Variogram" in the Variogram calculation

ii) Select "Exponential" for the Variogram model

iii) Select "No_pairs/Std-dev" for the Weighting

iv) Check the "Plot Variogram" and "Plot Map of Interpolation" boxes if you wish to see the variograms and map as it is made. The program will run slower with these options on however you can see if the process is working correctly.

v) Ignore the "Fit Variogram" button

vi) Ensure the "Compute Variogram" point is checked.

vii) Check the "define max distance" box and specify a distance of 60m. Leave the other boxes in the "Variogram Computation" box at default settings.

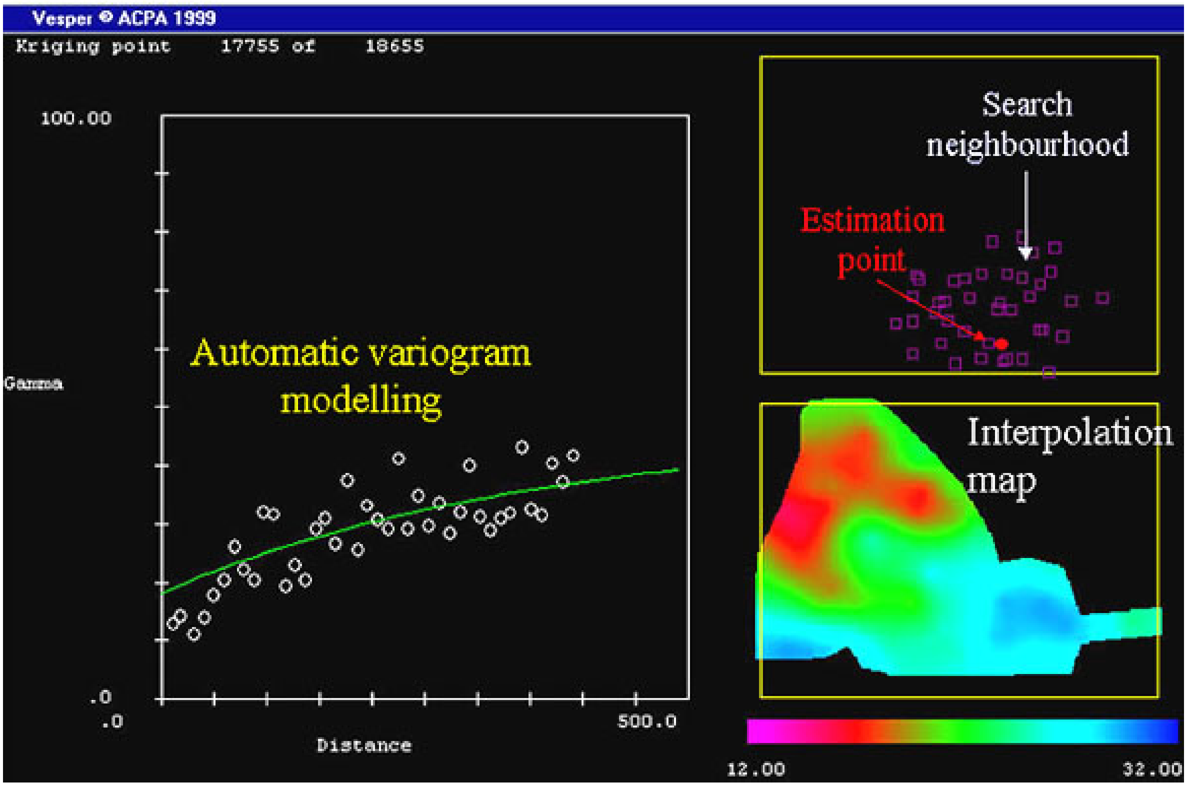

Figure 6: Screen snapshot of local kriging in operation. The left hand plot shows the local variogram estimation. The top right hand plot shows the grid point being estimated and the raw data points being used for the prediction. The bottom right hand side plot is a real-time map of the variable being interpolated.

When all this is done click the "Run Kriging Program" in the top left hand corner of the general interface. The program will initally sort the data then start the kriging process. If the "Plot Map of Interpolation" and "Plot Variogram" boxes have been left checked in the Variogram tab then each local variogram function will be displayed along with a continously updated yield map (Figure 6).

At the end of the prediction process a prompt of "Program Finished Exit Window?" is given. Select "Yes". Following this a prompt to "View Output Graph?" is given. Selecting "Yes" here will give two basic maps of the yield (left hand side) and the "error" associated with the estimation which can be basically ignored in this context (see Whealn et al. 2001 for further details if interested). Selecting "No" will terminate the prediction process.

The mapping program at the back end of Vesper is a very basic program. It does have some basic functionality to alter the legend and to open other output files for display however as a mapping tool it is limited. Its main purpose is to display the interpolated output to identify any obvious errors before proceeding to properly analyse and display the data. Before using yield maps it is important to consider the reason for any regular patterns or straight line effects in the map (if present). Yield data is biological data and should be continuous. Strong features of discontinuity that do not align with management practices (e.g. old paddock boundaries, different treatments/management) indicate a potential problem. The range of the legend shown should also be representative of the expected range of the yield. Creative cartography can often hide important features or exaggerate insignificant ones. In many cases these errors are a result of insuffient data trimming and cleaning prior to prediction. A few examples of the errors that may be expected are shown in Figure 7. If further data trimming does not solve the problem then there may be an issue with the data and external advice may be required.

Interpolating Other Datasets

Vesper can also be used for ipredicting other data sets derived from real-time on-the-go sensors such as apparent soil electrical conductivity (ECa), gamma radiometrics, high precision GPS for elevation, moisture sensors and protein sensors. For all these data sets following the basic rules above will provide maps of the variables. However the protocol outlined here is not valid for sparser, point sampled data, for example tiller counts and soil pit survey data.

Vesper - Basic Rules for Spatial Prediction

Before Vesper
Always trim the yield data to remove artifacts
Convert Longitude and Latitude to Eastings and Northings (metres)

Kriging Tab
Use Block Kriging with Block Size at 20 metres for yield mapping
First time around establish a grid for the field (either 5m or 10m)
Always use the same grid file when predicting yield data from different years

Variogram Tab
Use a local Vaiogram with Exponential model and Weighting of No_pairs/Std_dev
Define the maximum distance for the variogram computation (60m for yield data)

DON'T PLAY WITH THE OTHER BUTTONS....

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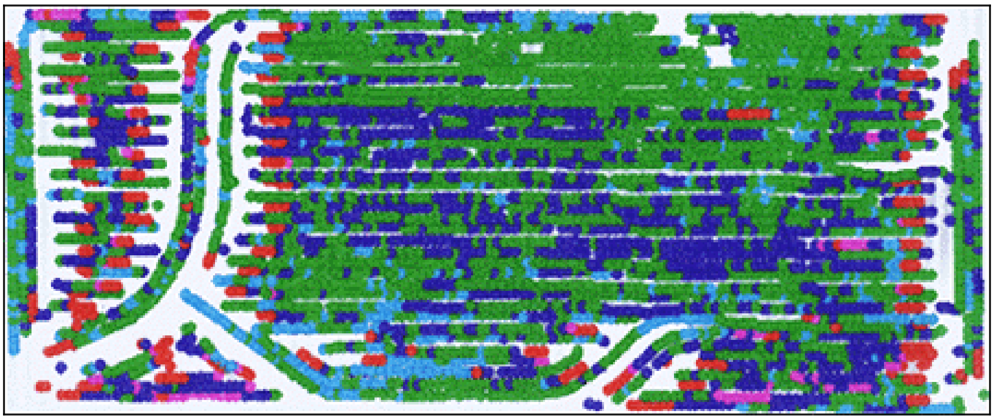
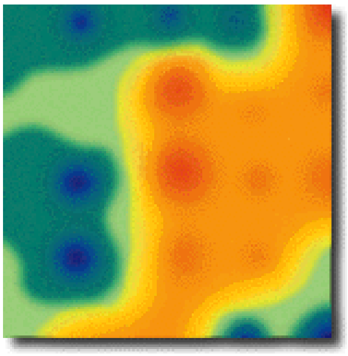
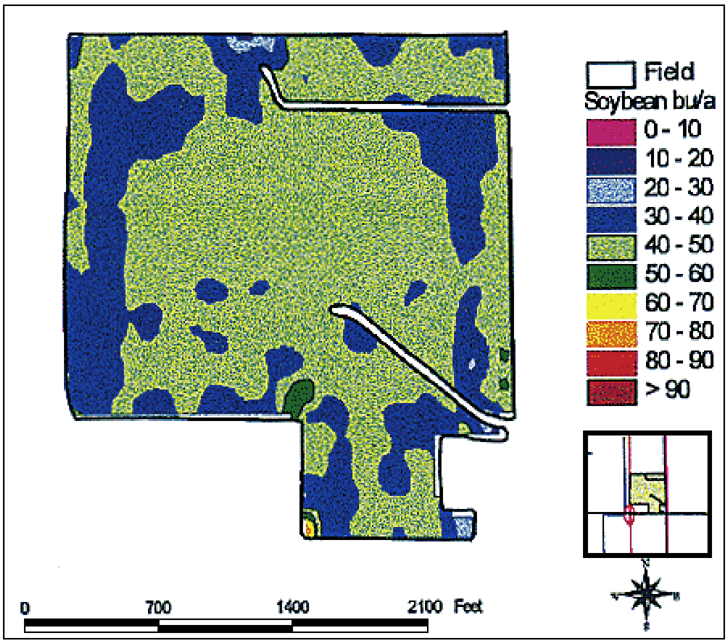
Examples of Poor Yield Maps



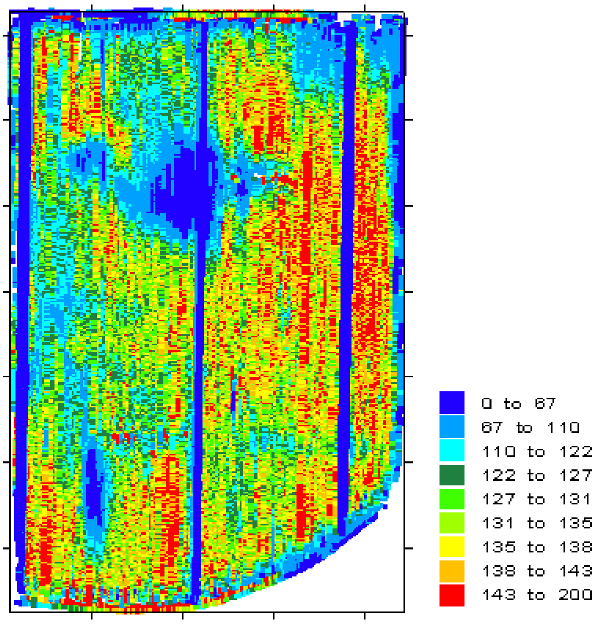
poorly trimmed and with an incorrect flow delay and no legend or scale



inverse distance weighting with sparsley observed data and no legend or scale

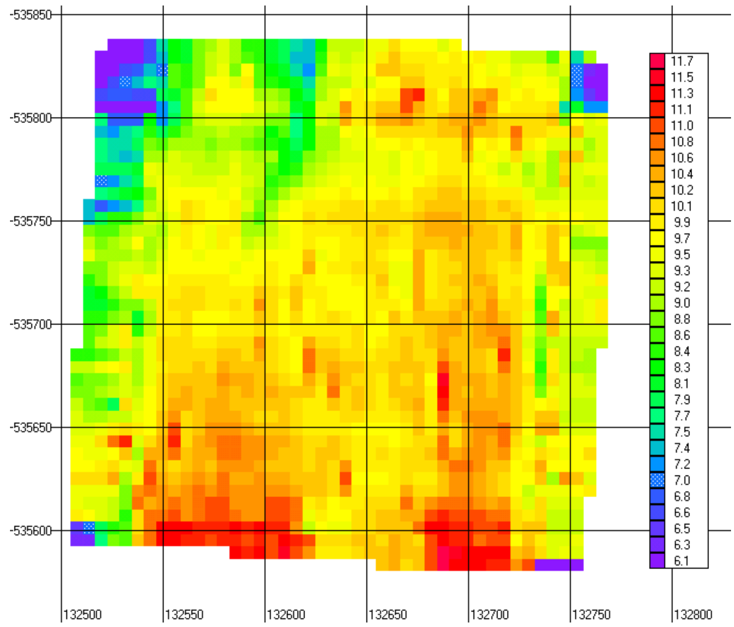


Scale is far to wide for the range of data so the map is dominated by 2 out of a possible 10 colours

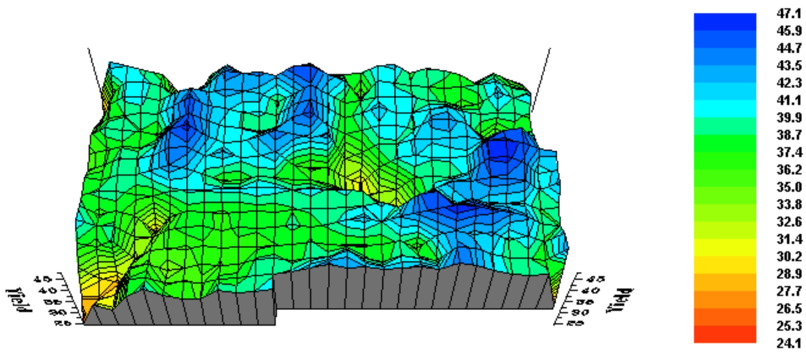


possible harvest artefacts remain and the scale is not equal range for each colour

pixellated presentation makes it difficult to interpret



Yield in file outYieldMean_2000_235.asc

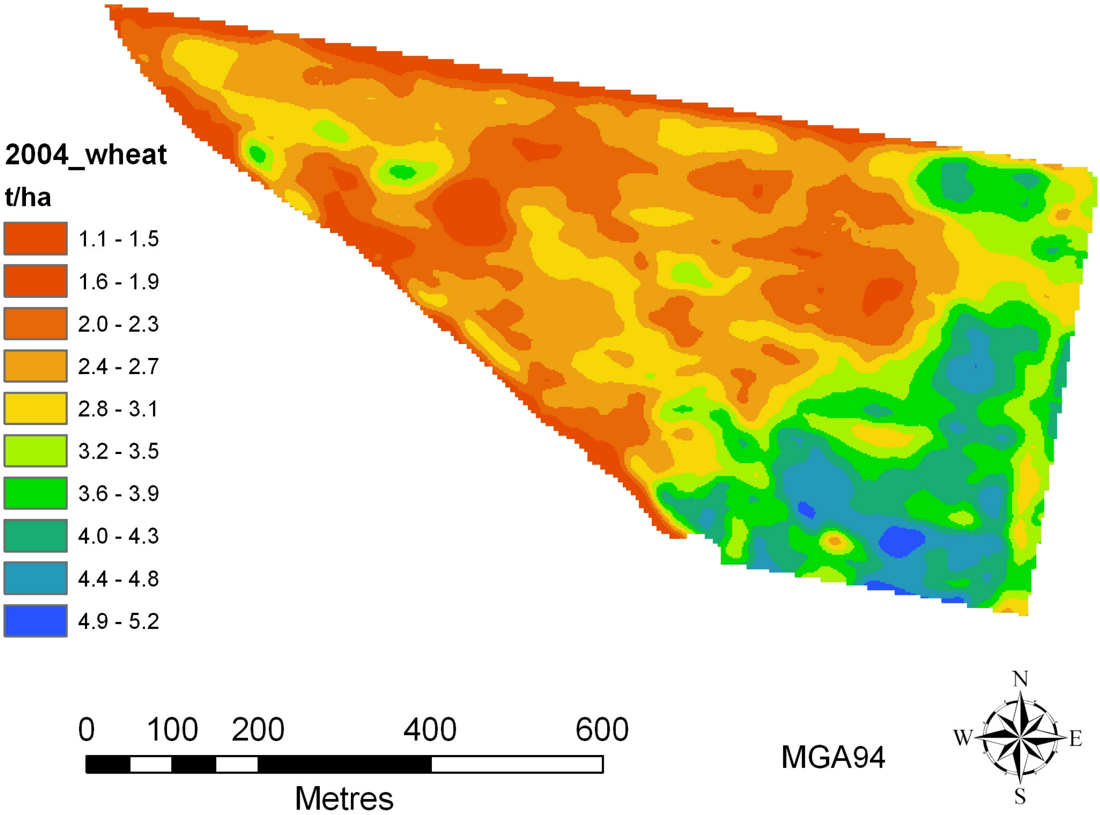


contours and elevation underlay crowd the viewer with too much information

Crop yield (bu/acre)

A Good Yield Map

Bridge Paddock



The map has a scale and legend with units. It has projection information and an orientation marker. The legend range matches the yield data range and the map is a smooth, continuous depiction of the yield in the paddock. The colour ramge visually discriminates between high and low

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VESPER–SPATIAL PREDICTION SOFTWARE FOR PRECISION AGRICULTURE

B.M. WHELAN, A.B. M^{c}BRATNEY AND B. MINASNY

ABSTRACT

VESPER is a user-friendly software program, written at the ACPA, to calculate global and local variogram models, undertake global and local kriging in either punctual or block form and output the parameters and estimates in an ASCII text format. The program provides control of the semivariogram calculation and choice of models that may be fit to the input data. A boundary and prediction grid may be generated in the software or supplied as an external file. VEPSER allows user defined neighbourhood and prediction-block sizes, along with a number of more advanced controls. It provides a real-time graphical display of the semivariogram modeling and a map of the kriging estimation progress. Having the ability to tailor the prediction process to individual data sets is essential for Precision Agriculture (PA) where data quantity, density and measurement quality varies.

INTRODUCTION

Precision Agriculture (PA) tools, in particular crop yield monitoring, soil electrical conductivity measurement and intensive soil sampling have provided spatially dense data sets for use in crop management. The desire to extract valuable information from these data sets has also brought the process of digital map construction into wider use. All digital maps are based on some form of map model and usually require a spatial prediction procedure to produce a continuous surface map. The particular map model and the spatial prediction procedure chosen will have an impact on the predictions and the final map.

MAP MODEL

Digital maps are constructed using a map model whereby values are represented as a set of blocks the centres of which are located on a grid (G). These models may take a number of general forms. According to Goodchild (1992) the blocks may have sides equal to the grid spacing (a raster model), the blocks may be points on a regular grid (a grid model) or they may be points and the grid irregular, or infinitely fine, with missing values or values equal to zero (a point model).

SPATIAL PREDICTION

Any form of spatial prediction is based on the premise that observations made in close proximity to each other are more likely to be similar than observations separated by larger distances. This is the concept of spatial dependence. The process of spatial prediction requires that a model of the spatial variability (spatial dependence) in a data set be constructed or assumed so that estimates at the unsampled locations (prediction points) may be made on the basis of their location in space relative to actual observation points.

B.M.Whelan, A.B. McBratney, B. Minasny. 2001. Vesper - Spatial Prediction Software for Precision Agriculture. In G. Grenier & S. Blackmore (eds) ECPA 2001, Proceedings of the 3rd European Conference on Precision Agriculture, Montpellier, France, agro-Montpellier, Montpellier, France pp 139-144.

It is the form of these models, and the assumptions underlying the choice of the same, which generally distinguish the major spatial prediction methods. Global methods use all the data to determine a general model for spatial dependence. This model is then applied, in association with the whole data set, in the prediction process at every prediction point. Local prediction methods use only points 'neighbouring' the prediction point in the prediction operation. In the case of local predictors, a singular form of the spatial variance model may be constructed for the entire data set and applied in each neighbourhood, or an individual model may be constructed, and used exclusively for, each neighbourhood. Local methods may therefore be the preferred option, especially on large data sets, and where a single variance model may be inappropriate.

Spatial prediction methods whose principle requires the prediction to exactly reproduce the data values at sites where data is available are said to act as interpolators. There is a variety of prediction techniques which may be applied to mapping continuous surfaces. The most widely known include: global means and medians; local moving means; inverse-square distance interpolation; Akima's interpolation; natural neighbour interpolation; quadratic trend; Laplacian smoothing splines; and various forms of kriging.

The prediction technique of choice for map production in precision agriculture will depend on the expected use of the map. However, real-time sensors that intensively sample variables such as crop yield, produce large data sets containing a wealth of information on small-scale spatial variability. By definition, precision agricultural techniques should aim to identify the quality of the data and preserve the appropriate degree of detail.

Comparative Examples

Individual wheat yield values, collected at a frequency of 1 Hz from a 100 ha field in NSW, Australia, were randomly allocated into one of two equal-size datasets. One data set was used as input values for the prediction processes, the other provided the prediction locations and test values for a comparison of prediction techniques. Inverse-distance squared, local mean, local kriging with a global variogram are compared along with the less common technique of local kriging with a local variogram (Haas, 1990). A search neighbourhood of 100 data points was standardised.

Technique	No. of observ.	Max. (t/ha)	Min. (t/ha)	Mean (t/ha)	Sum of ranks	Median rank	No. of ranks = 1	Final Rank
Test data	26337	6.26	0.92	3.71				
Local kriging w/ local variogram	26337	5.99	1.01	3.71	59152	2	9150	1
Local kriging w/ global variogram	26337	5.88	1.11	3.71	60688	2	7421	2
Inverse distance-squared	26337	5.71	1.01	3.72	63382	3	4480	3
Local mean	26337	5.01	1.87	3.72	80168	4	5284	4

TABLE 1. Wheat yield frequency distribution and performance rankings for spatial prediction techniques on a 100ha field in NSW, Australia.

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Table 1 shows the resulting frequency distributions and rankings of the prediction techniques in comparison to the observed values at the locations. The rankings (1:4 - closest prediction to the observation value = 1) are calculated at each point and then summed for each technique. The final performance rank is allocated from the lowest to the highest sum of ranks.

Here the estimates from the kriging procedures most closely match the observation values and thereby maintain more of the original frequency distribution. Local kriging with a local semivariogram has performed the best. Inverse distance-squared, while performing third overall, has registered the smallest frequency of number one ranks.

To visually demonstrate the results of the different prediction methods on crop yield data, a small portion (~1ha) of another field and crop has been chosen. Sorghum yield data, acquired using a real-time yield monitor in 7 metre wide harvest runs, was predicted onto a regular 1 metre grid using the punctual prediction methods of local inverse distance-squared, local kriging with a global semivariogram and local punctual kriging with a local semivariogram. In addition, local block kriging with a local semivariogram has been undertaken.

Block kriging has rarely been used since Burgess & Webster (1980) introduced geostatistical spatial prediction techniques into soil science, and software for performing it is rather scarce. Block kriging attempts to predict the weighted average of a variable over some block of length (*dx*) and width (*dy*) centred about some prediction point (*x0, y0*). It should be noted that the locations (*x0, y0* - the prediction grid or raster) can be closer together than the block length or width. This in fact gives an aesthetically pleasing, smooth map. The major advantage of using block kriging is that the estimate of the block mean, not surprisingly, improves as the block dimensions increase.

In Figure 2a, the inverse distance method places a lot of varibility in the map by virtue of honouring the very high and low peaks in the harvest data. It is easy to distinguish the harvest lines in the data. Because the inverse distance model is fixed, and its radius of influence is small, the map takes on the characteristic "spottiness" of maps made using inverse distance squared. Local kriging with a global semivariogram (Figure 2b) has smoothed out the map to a degree and the harvest lines are not evident because the variogram has captured a longer spatial dependence in the data set than the fixed inverse distance model. Data points from further out in the neighbourhood have been given some influence on the prediction at each point.

Local Kriging with local variograms (Figure 2c) restore some of the local variability because the changes in spatial dependence between the local neighbourhoods is included. Changing the map model from point estimates to estimates representing the weighted average yield in a 10 metre block around each prediction point (Figure 2d) removes some of this variability from the estimates.

That the form of spatial prediction chosen for map construction may be significantly influential on the final prediction surface is not a new concept. A number of studies (e.g. Laslett et al. (1987), Wollenhaupt et al. (1994), Weber & Englund (1994), Whelan et al. (1996), Gotway et al. (1996)) show that in general inverse distance techniques are sensitive to the degree of inherent variability in a data set, the neighbourhood population used in each prediction and the power of distance used in the weighting calculation. Alternatively, the accuracy of ordinary kriging generally displays little sensitivity to the variability in the data sets and the accuracy of the estimates improves with increasing neighbourhood populations.

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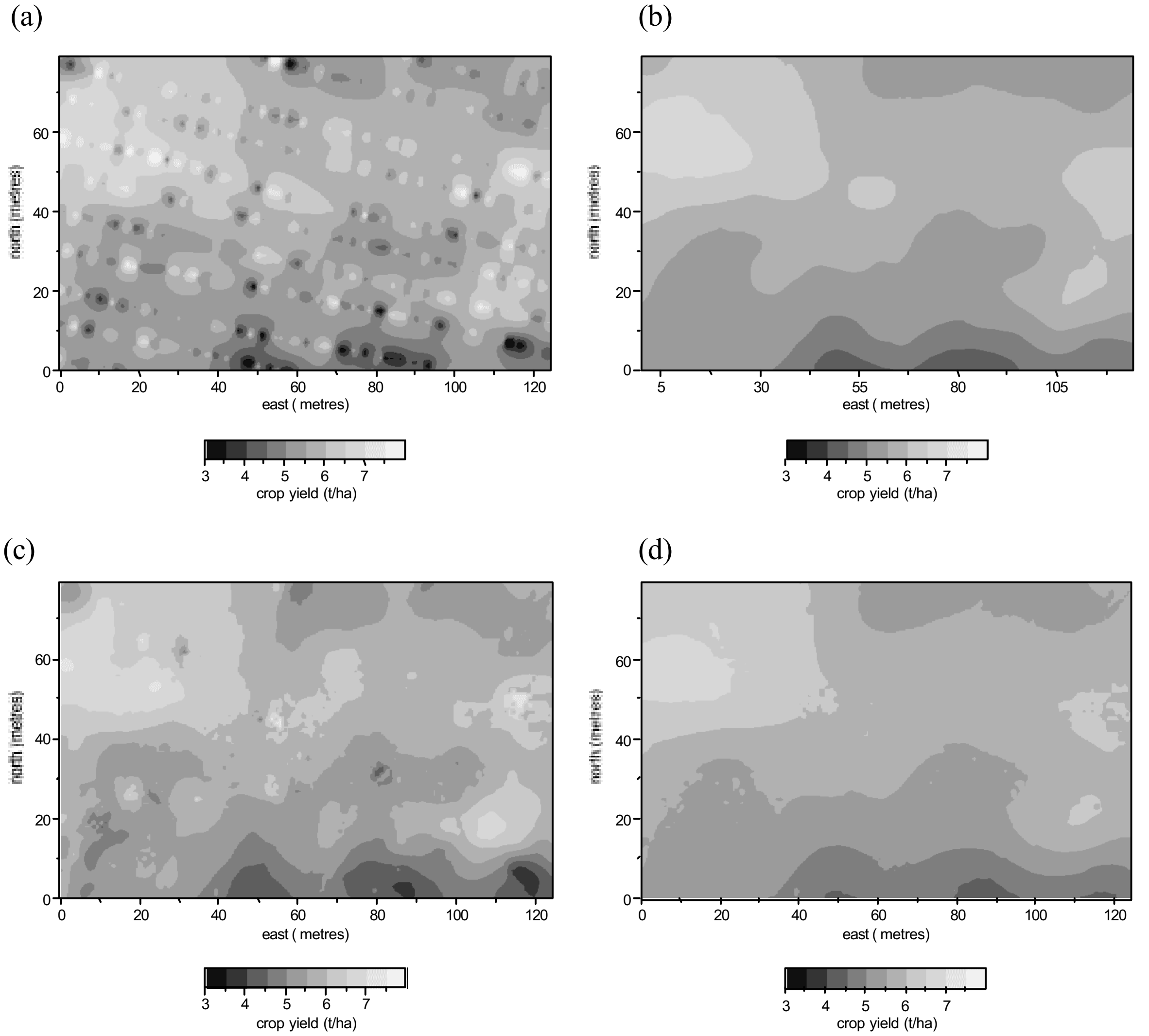

FIGURE 2. Crop yield maps constructed using different prediction procedures. (a) inverse distance-squared (b) local punctual kriging with a global variogram (c) local punctual kriging with a local variogram (d) local block kriging with a local variogram.

The observed inefficiencies of the inverse distance squared prediction technique can be attributed to two main problems. Firstly, the spatial variability in a data set is not used to determine the spatial dependence model for use in the prediction process. Secondly, the method is an exact interpolator that passes through the data points, and this may not be sensible if there is uncertainty in the observations. Kriging only operates as an interpolator if the semivariogram nugget value (C0) equals zero. With any positive C0 value, close range uncertainty in the observations will be reflected in the kriged surface. Such uncertainty may arise in either the value of the observed attribute or its spatial location.

This point is often overlooked in assessing the suitability of prediction techniques but should be given a high priority in PA owing to the potential (and real) errors associated with real-time sensors and GPS receivers (Whelan & McBratney (1997); Lark et al. (1997)). In such cases, block kriging estimates for an area should prove extremely useful in reducing the carryover of errors into the final maps. Block kriging also offers a robust method for estimating values for the smallest differentially manageable land unit (usually governed by implement width and operational dynamics).

Block kriging may be undertaken using a global semivariogram but once the number of data points rises above 500 it seems wasteful to assume a single semivariogram within the field. A global semivariogram may prove too restrictive in its representation of local spatial correlation whereas local semivariogram estimation and kriging offers the ability to preserve the true local spatial variability in the predictions. If the chosen neighbourhood is reasonably small, the use of local semivariograms should also negate the possible requirement for trend analysis and removal prior to semivariogram estimation and kriging.

A further advantage in the use of kriging techniques lies in the provision of a prediction variance estimate (Laslett et al., 1987; Brus et al., 1996) which may be used to produce confidence limits on the predicted values. The reporting of such limits should be mandatory for digital maps as they will have important ramifications on the extrapolation of management information (Whelan & McBratney (1999). The uncertainty may also be used to determine the most suitable mapping class delineations. For example, if the 95% confidence interval in crop yield estimates is +/- 1.0 t/ha, classifying a field using classes less than 1.0 t/ha may be misleading. A classification system based on the uncertainty in the yield data may prove useful in the future.

VESPER

VESPER (Variogram Estimation and Spatial Prediction with Error) is a PC-Windows software program developed by the ACPA that allows the geostatistical spatial prediction procedures of punctual and block kriging to be applied to data sets gathered for PA management. The program also offers the further options of global or local kriging, using global or local semivariograms.

Figure 3. shows the main VESPER interface panels. Input and ouput files are controlled in the first panel (Figure 3a). Input data with associated Cartesian coordinate locations is required to enable spatial analysis. The output files record the specific session setup details, variogram model parameters and the prediction locations, values and associated prediction variance.

The variogram panel (Figure 3b) provides the choice of global or local semivariogram estimation and provides access to a choice of models which may be fit to the semivariogram using 3 possible weighting procedures. Nonlinear least-squares estimation is used in the model fitting process. The model may be chosen from a comprehensive range of options. Provision is made for comparison of the ‘goodness of fit’ of the numerous models through the Akaike Information Criteria (Akaike, 1973) and sum of squared error (SSE). If a global semivariogram is required, the ‘Fit Variogram’ button provides access to an interactive calculation and modeling panel from which the final model parameters are extracted for use in the subsequent kriging procedures. Local semivariograms are calculated for each neighbourhood during the local kriging process, but the maximum distance and number of lags required for estimating the semivariograms may be set through this panel. Kriging with local variograms involves searching for the data points within the defined neighbourhood surrounding each prediction site, estimating the variogram cloud for the data points and fitting a model, then predicting a value (and its uncertainty) for the attribute under question at each prediction site.

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The kriging panel (Figure 3c) provides kriging type (ordinary or simple) and method (punctual or block) options. Here it is also possible to define the block size (if relevant), set neighbourhood limits based on radial distance or number of data points and manipulate the kriging region. For most PA applications, the field boundary will provide the limits of the kriging region. VESPER provides the option of importing an existing boundary file or describing the field boundary using an interactive drawing tool (Figure 3d). The prediction grid (at user-defined distances) may then be produced with the software or a previous grid file imported. These features are important for the continuity of prediction sites through time within a field.

In operation, VESPER provides a window displaying the operational progress (Figure 4). For all forms of kriging a prediction progess map is produced along with a count of visited versus total prediction sites. For local kriging, individual semivariograms and the fitted models are displayed for the search neighbourhood around each prediction point. The graphical progress facilities can be disengaged to increase the speed of the prediction process.

The output for all kriging operations is a four column ASCII text file containing the prediction point location coordinates, the predicted value and the kriging variance. An input file detailing the exact settings for each prediction session is also saved along with a report file logging global variogram parameters or the parameters of each local variogram depending on the operation. Other details of the data and the kriging session are also recorded in this file for future reference.

VESPER is available as freeware from the ACPA at www.usyd.edu.au/su/agric/acpa

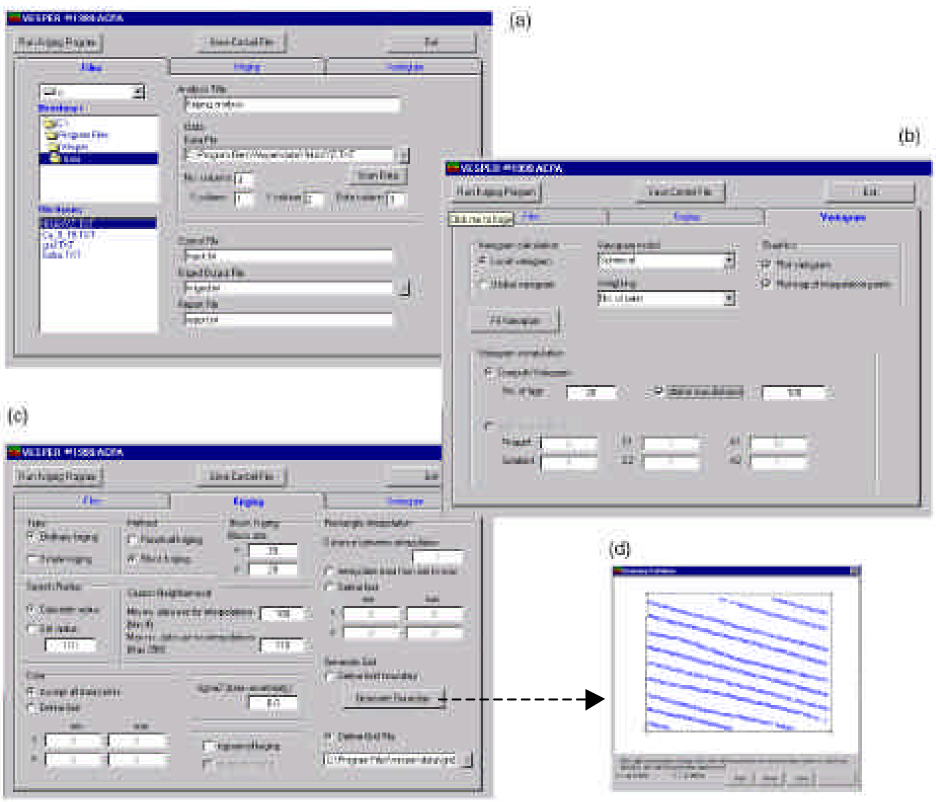

FIGURE 3. VESPER operational panels (a) input panel (b) variogram panel (c) kriging panel (d) boundary and grid construction tool.

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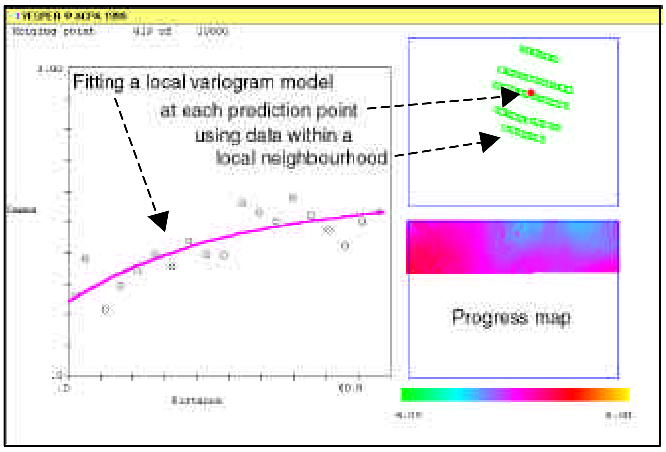

FIGURE 4. Kriging progress screen showing local variogram, prediction point with search radius, and the progress map.

CONCLUDING REMARKS

Spatial prediction methods used in PA should accurately represent the spatial variability of sampled field attributes and maintain the principle of minimum information loss. However, data used in any spatial prediction procedure should be of known precision and that precision used to guide the choice of spatial predictor. Due to imprecision in crop yield measurement and within-field location, interpolators (exact spatial predictors) are generally not optimal.

The results presented show that the form of spatial prediction chosen for mapping yield has a significant influence on the final prediction surface. Local kriging using a local variogram appears well suited as a spatial prediction method for dense data-sets. In particular, local block kriging reduces the estimate uncertainty when compared with punctual kriging and may be an optimal mapping technique for the current generation real-time yield and soil sensors.

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