PRECISION DECISIONS
For
QUALITY COTTON
A Guide to Site-Specific Cotton Crop Management
by
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Australian Government
Cotton Research and Development Corporation

The University of Sydney

Australian Centre for Precision Agriculture
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Publication Data

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Recent advances in computing have heralded the development of a range of new technologies that has brought farming and farm equipment to a whole new level of sophistication. Precision agriculture (PA) as a crop management philosophy was first hypothesised in the early 1990’s as a way of utilising this equipment such as the Global Positioning System (GPS) and variable-rate crop applicators to produce crops in a more sustainable fashion. A subcomponent of PA is site-specific crop management (SSCM) which centres around identifying variability within or across fields in an attempt to minimise the impacts of farming on the natural resource base. Once this variability has been quantified, the task turns to identifying ways to manage that variability for profitability and increased environmental sustainability.

PA has gained a significant amount of publicity in recent years. There has been a flood of rapidly developing technologies and techniques (often very costly) that have confronted producers claiming to aid in all aspects of farm management. Much of this information can be confusing and sometimes downright misleading. This booklet, an updated and expanded version of "The Potential for Site-Specific Management of Cotton Farming Systems" by McBratney and Whelan (1995), describes how these technologies operate, there uses and limitations and discusses how they can be integrated into a management system that will have both economic and environmental benefits for the cotton grower.

Research funded by the Australian Cotton Research and Development Corporation (CRDC) and the Australian Cotton CRC into adapting SSCM techniques to Australian cotton farming systems began at The University of Sydney in 1997. Over the last eight years our results have confirmed that there are many benefits to be gained from adoption of this technology. Our initial focus was to examine the accuracy and the reliability of the technology associated with estimating within field cotton yield. This began with an investigation into picker-mounted cotton yield monitors. Satisfied that this technology gave accurate data it was used in conjunction with traditional sampling techniques and an array of new sensing technologies to quantify the degree of spatial variability of agronomically important variables within and between cotton fields. Our research has highlighted that this variation is indeed
substantial and can occur over very short distances. Having identified significant variability in both cotton yield and soil properties within single fields, we examined the variable-rate application of crop production inputs as a method to manage this variability, with a particular focus on nitrogen management. Our experimentation has shown that there is a lot to be gained by embracing SSCM techniques in Australian cotton farming systems.

Armed with an improved capacity to measure and monitor the impact of spatial variability, cotton growers now have greater opportunities to improve their economic and environmental management through site-specific farming. This guide aims to provide an introduction to SSCM technologies and details how these technologies can be applied to cotton farming in Australia. For more detailed information on cotton production and solving some of the agronomic challenges discussed in this guide, the interested reader is encouraged to refer to SOILpak - for cotton growers; NUTRIpak - a practical guide to cotton nutrition; WATERpak - a guide for irrigation management in cotton; WEEDpak - a guide for integrated management of weeds in cotton; Integrated Disease Management and Integrated Pest Management Guidelines for Cotton Production in Australia. All these publications are available from the Australian Cotton CRC website (www.cotton.crc.org.au) or from the Australian Cotton CRC Technology Resource Centre, Narrabri.

Reference to commercial products or trade names in this booklet is made with the understanding that no discrimination is intended and no endorsement is implied by the authors.
ACKNOWLEDGEMENTS

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1

AN INTRODUCTION TO SITE-SPECIFIC CROP MANAGEMENT

The mechanisation of agriculture has lead to farmers implementing agronomic and land management practices on a whole-field basis. Basically, farmers have abandoned the idea of managing smaller than field-size parcels of land in order to take advantage of large horsepower tractors and the speed of increasingly wide tillage, spraying and planting implements. By treating larger areas, the modern cotton farm manager has been able to spend less time in the field and achieve a greater number of hectares per hour. In essence, increased productivity has been given precedence over any benefits from intensive management of smaller areas.

One consequence commonly resulting from this management approach has been the increasing adoption of averages. Whole-field management practices ignore variability in soil-related characteristics by applying crop production inputs in a uniform manner. On most Australian cotton farms, a field of some 100 hectares will almost always be planted to the one variety and have a uniform application of fertiliser applied across the whole area. This generally results in uniform field operations such as tillage, fertiliser application, irrigation, sowing and pest control treatments. However, farm fields still display considerable spatial variation in crop yield, reflecting spatial variation in the field-based factors (particularly soil properties) that affect crop yield.

Over the last decade the spatial variation in crop yield, and the field-based factors that contribute to it, has become a subject of increasing importance to both the farming and wider communities. Recent scientific research has substantially improved our understanding of the impact spatial variability has on the efficacy of modern farming systems. It has become clear that there are economic and environmental challenges faced by managers of traditional cotton cropping enterprises that arise from the spatial variation of attributes in the soil crop system. In most instances these challenges have arisen from a decision to use ‘field average’ information to guide the amelioration of an area. The significance of these costs, such as input waste, yield reduction and soil, water and air contamination are of serious concern.
The Impact of Spatial and Temporal Variability on Modern Cotton Systems

The application of agronomic inputs in uniform quantities over an entire field, or more commonly, a farm or district has been shown to be startlingly inefficient in terms of materials and energy usage. Fertiliser recovery by crops is generally very low, for example, applied nitrogen fertiliser recovery has been calculated to be as low as 10% in adverse conditions and rarely above 60% under ideal conditions (Hearn, 1981; Gibb and Rochester, 1994). Similarly, it has been shown that not all applied pesticides reach their intended targets; the rest cause unintended damage both on and off site (Pimentel, 1991).

It has become clear in recent times that a major factor linked to the high inefficiencies of applied crop production inputs is a neglect of the fine-scale variation that exists within each field. As most fields contain a mosaic of soil types, when a single application rate of fertiliser is applied there is the occurrence of regions within a field where there is still nutrient deficiencies and furthermore, regions where there are excesses of nutrients. Research has demonstrated that this can be so extensive that some portions of a field may require no fertiliser, while other regions will require significant amounts of fertiliser (Mulla, 1993). This scenario can be extended to any number of crop production inputs including herbicides, pesticides and gypsum. Consequently, the impact this spatial variability has on crop yields can be momentous. Studies by Elms et al. (1997) and Elms and Green (1998) in the USA found cotton yield ranges in excess of 4 bales per hectare within single fields.

Not only do crop and soil characteristics vary over distance, they vary over time. Temporal variation, the year-to-year changes in crop yield and soil properties, is of no less importance. In fact in many instances, temporal variation may be greater in extent and be of more significance from a management point of view. Climatic variability is usually the major source of temporal variation in cropping systems. The difference in crop yield between poor and excellent climatic years can often be one order of magnitude or greater (Huggins and Alderfer, 1995).

Consequently, there are a number of noteworthy problems associated with the uniform application of resource inputs to crop production systems with a high degree of variability. These include: economically significant yield losses, excessive chemical costs, gaseous or percolatory release of chemical components into the environment, unacceptable long-term retention of chemical components and a less than optimum crop growing environment.
At present, the issue of input resource waste and maximising yield remain economic dilemmas of the individual producer. Escaped fertiliser and pesticide from production across all agricultural industries, along with contamination of follow-on enterprises with residual pesticides has entered the public domain. In Europe, environmental thresholds for nitrogen loss from agricultural production systems already prevent the excessive application of agricultural chemicals and these are becoming increasingly more stringent (Bouma, 1997). 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. It is critical that the cotton industry has in place crop-production systems that will be capable of meeting any environmental thresholds which may be imposed in the future. Failure to comply will undoubtedly bring another economic dilemma for the individual producer.

Many of these problems associated with spatial and temporal variability may be eventually addressed by treating the field variation in these cropping system attributes using precision agriculture (PA) techniques and technologies. Further improvement via site-specific farming can only improve yields and increase input efficacy.

What is Precision Agriculture?

An integrated information- 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.  

US Farm Bill 1996

Site-Specific Crop Management Systems

Site-specific crop management (SSCM) is part of the broader concept of 'Precision Agriculture' (PA) used to describe a new notion in agricultural crop production which utilises the recent development of hardware such as the Global Positioning System (GPS) and variable-rate crop applicators to produce crops in a sustainable fashion. SSCM is based on the postulate that, by identifying within-field variability, this will permit the optimisation of crop production inputs such as pesticides and fertilisers on a point-by-point basis within a field. By reducing the over-application and under-application of these crop production inputs, this strategy aims to increase profitability. Furthermore, from an ecological point of view, this precision offers the prospect of reducing the environmental risk associated with blanket field treatments thus reducing the likelihood of groundwater or surface
water contamination from agrochemicals. Collectively, these actions are referred to as the 'differential' treatment of field variation as opposed to the 'uniform' treatment that underlies traditional management systems.

A SSCM system is potentially more profitable as it may increase crop production revenue and/or reduce input costs.

**Site-Specific Crop Management offers the Potential for:**

- Higher yields with the same level of crop production inputs reallocated.
- Similar yields with a reduced level of crop production inputs.
- Higher yields and a reduced level of crop production inputs.

A precision agriculture management system involves five conceptual components operating in a cyclical fashion.

**Figure 1.** Precision agriculture management cycle illustrating the key processes of attribute/yield mapping, decision support (using models and GIS), differential or variable rate application, and crop soil and climate monitoring with each process spatially referenced by GPS (from Whelan, 2001).
The acquisition of data on the short-range variation of influential soil and crop attributes is essential to the operation of a site-specific management system. This is possible due to the development of vastly improved ground positioning systems that permit the detailed mapping of soil resource and crop yield variability within a field. Mapping variability patterns in this manner offers a wealth of production information to the land manager.

**Spatial Referencing**

The central process in this PA wheel is spatial referencing and refers to the global positioning system (GPS). This navigation system utilises a set of orbiting satellites to calculate locations within a field to errors typically less than 1 metre (but potentially better than 1 cm). This electronic location can be used to guide applications within the field in addition to providing a record of sampling locations. The entire process is made possible, and indeed relies upon, the ability to accurately resolve ground position during all operational facets using the GPS. The GPS network enables this information to be swiftly obtained with an accuracy here in Australia of approximately +/- 1 to 2 metres. Greater accuracy can be obtained using more advanced (and expensive) GPS receivers for precision vehicle guidance.

**Crop, Soil and Climate Monitoring**

Influential factors affecting 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 under way worldwide into real-time analytical soil sensors that will eventually automate the sampling and analysis procedures in the field. The use of surrogate information (colour and temperature variation in soil and crop) gathered by remote sensing is also increasing in use. This information can be particularly useful for monitoring pest and disease dispersal and crop growth indicators such as water stress.

**Attribute 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, but it is essential that the errors or uncertainty in these maps be minimised and reported.

**Decision-Support Systems (DSS)**

The degree of spatial variability found in a field will determine whether differential treatment within the field is warranted. Correlation between the
variation in crop yield potential and the mapped variability in factors influencing crop yield can be used along with economic analysis to formulate agronomically suitable treatment strategies. This can be undertaken using a computer system capable of integrating diverse data sources with expert knowledge and decision models.

**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 using the DSS to guide rate control mechanisms in the field. Yield monitoring at harvest can be used to assess applied treatment effects and refine yield potential goals for the subsequent season and the cycle commences again.

**Will SSCM increase the amount of traffic on fields?**

Each of the components of the SSCM wheel may be undertaken as separate, temporally spaced operations or carried out in real-time, allowing information to be gathered, decisions formulated and actions taken in single passes of a field. The future should see more operations of the later kind. It is envisaged that it will be possible for the entire data acquisition process to be undertaken in the field during relevant farming operations, thereby avoiding any increase in the amount of traffic on any field.
Contemplating such a precise approach to crop management would not be feasible without some impressive enabling technologies. The invention and availability of a multitudinous array of new technologies has made the concept of SSCM a reality. These technologies have reached a level that permits a cotton grower to measure, analyse and manage within-field variability that was previously known to exist but unmanageable from a practical point of view.

**Satellite Positioning Systems**

A critical requirement for collecting data on the spatial variation of any land-based attribute is an ability to accurately resolve ground positions in the field. All data must be geo-referenced to facilitate the production of a representative field map for the purpose of correlating the information on various attributes obtained from a field. Two practical cost-effective methods of achieving ground positioning have been developed. The NAVSTAR Global Positioning Systems (GPS) owned by the government of the United States of America and the Global Navigation Satellite System (GLONASS) controlled by the Russian Government. A third system called Galileo is to be implemented by the European Union in the next year. Both the GPS and GLONASS systems are similar, however many more receivers have been developed by commercial companies to utilise information from GPS satellites. Thus only a review of GPS operations is given.

**What is GPS?**

GPS is a worldwide radio-navigation system first developed in the mid 1970s and is currently managed and operated by the United States military. At its core is a constellation of at least 24 satellites (there are often more than 24 operational satellites as new ones are launched to replace older satellites) that orbit the earth and transmit information to associated ground support facilities. In essence, it provides specially coded satellite signals that can be processed in a GPS receiver, enabling the receiver to compute position, velocity and time.
The operational configuration of the GPS consists of 24 satellites (called space vehicles - SVs) that orbit the earth in six orbital planes (with four satellites SVs in each), equally spaced (60 degrees apart), and inclined at about fifty-five degrees with respect to the equatorial plane. Each orbit takes 12 hours at an altitude of 20 000 km. This constellation provides the user with between five and eight SVs being visible at any one point on the earth all the time.

**How Does GPS Calculate Position?**

The principal idea behind GPS is to use satellites in space as reference points for locations here on earth. In basic terms, position is obtained by very, very accurately measuring our distance from a number of satellites. The distance measurement is accurately calculated by timing how long it takes for a signal sent from the satellite to arrive at our receiver. This signal contains information on the satellite orbit, the current position relative to the centre of the earth and time information which is provided by four extremely accurate atomic clocks on-board the satellites. There are three general techniques for calculating these distances based on this information provided on two transmission frequencies from the satellites.

1. The C/A (Coarse/Acquisition) code, also known as the Standard Positioning Service (SPS), in which distances are estimated by measuring the travel time of a coded signal from each satellite and multiplying it by the transmission velocity (the speed of light).
2. The P-code (Precision) which is reserved for military use.
3. Codeless techniques which require more sophisticated and expensive receivers.

Combinations of C/A and codeless techniques can also be used.

A resection process is used to calculate the receiver position (Figure 2). The distance to four satellites must be instantaneously determined by a user’s receiver 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 receivers time pieces. The 4th measurement greatly improves the measurement accuracy and allows comparatively cheap time pieces to be used in the receivers. Given that the travel time of the signal to the receiver is about 0.07 seconds, the clocks must still be capable of accurately measuring small time periods.

**GPS Error Sources**

Although the GPS uses very sophisticated technology its accuracy is still degraded by several unavoidable errors. These include:

+ Measurement error caused by the Earth’s atmosphere
+ Satellite positioning errors, known as "Geometric Dilution of Precision" or GDOP
+ Satellite clocks which contain minute discrepancies
+ Multipath errors related to how a signal may bounce off various local obstructions before it gets to a receiver.
+ GPS receiver error caused by noise due to electronic interference.

One GPS satellite (space vehicle (SV)) only provides a location as somewhere on a sphere with a radius of around 20,000km.

1 SV locates a sphere.
2 SV's locate a circle where the two spheres intersect.
3 SV's locates 2 points where the three spheres intersect.

The real point is easily detected as the second point it is unrealistically located in relation to the earth or is moving at unlikely speeds. A 4th SV is used to correct timing inconsistencies between the SV's and the receiver which greatly increases the overall accuracy of the location.

Figure 2. Obtaining position location using the GPS (from, Whelan, 2001).
The largest and most significant of the GPS error sources is caused by the earth’s atmosphere. As a GPS signal passes through the charged particles of the ionosphere and then through the water vapour in the troposphere it is slowed, creating a small timing error. Atmosphere-induced errors may be reduced by using an advanced “dual frequency” receiver that compares the relative speeds of two different signals.

As the accuracy of a position computed from the observations made by a single receiver is limited by these errors (accuracy is 3 to 15 metres), for SSCM a differential GPS (DGPS) is necessary to obtain approximately one-metre accuracy.

### Differential GPS

The idea behind all differential positioning is to correct bias errors at one location with measured bias errors at a known position. A reference receiver, or base station, computes corrections for each satellite signal. This is known as differential GPS (DGPS). There are a number of systems that have been developed to minimise the errors associated with GPS to improve positional accuracy to approximately 1 metre. These devices vary considerably in price ($2,000-$15,000) depending on their capabilities and are generally more expensive than basic GPS receivers. Real-time DGPS allows instantaneous position reckoning to be obtained and the associated ability to store position information with other observations such as yield data while they are being observed. The differential signal is calculated from a GPS located at a known site and is transmitted to the DGPS via a number of methods:

1. **AM coast-guard beacon system** that broadcasts the correction signal for ships. The accuracy of the transmitted signal declines with distance at about 1 metre error per 150 km from the station.

2. **An annual subscription to a Wide Area Differential GPS (WADGPS) network.** These are satellite-based differential correction sources supplied by specialised GPS operators (Fugro and Thales Survey in Australia). These providers use wide area networks (such as the one illustrated in Figure 3) to transmit correction data from geo-stationary satellites. Basically these networks incorporate a wide network of fixed position receivers that communicate with the GPS satellites and calculate an individual correction which is then passed to a master station. The

### What is Selective Availability (S/A)?

This was an additional non-naturally occurring source of error added by the US Department of Defence to degrade the quality of the signal for civilian use. S/A was turned off on May 1st 2000. However, even without this error, the accuracy of stand-alone receivers is not sufficient for SSCM purposes.
master station computes a vector correction from all the individual stations and uplinks this to a waiting geo-stationary satellite that re-transmits the correction data to a remote user on the earth.

Table 1 lists some of the advantages and disadvantages with each of these correction sources.

Table 1. A summary of the different methods of DGPS which are available.

<table>
<thead>
<tr>
<th>Correction Source</th>
<th>Advantages</th>
<th>Disadvantages</th>
</tr>
</thead>
<tbody>
<tr>
<td>AM Maritime Beacons</td>
<td>* Free signal</td>
<td>* Less accurate away from coast</td>
</tr>
<tr>
<td></td>
<td>* Cheap receivers ($1,500)</td>
<td>* Limited coverage area at present</td>
</tr>
<tr>
<td>Satellite Provider</td>
<td>* Total coverage across Australia</td>
<td>* Receivers can be expensive ($6000-10,000)</td>
</tr>
<tr>
<td></td>
<td>* Highly accurate (sub-metre)</td>
<td>* Subscription fee</td>
</tr>
</tbody>
</table>

Figure 3. A configuration of a wide-area differential GPS network - WADGPS (from Whelan, 2001).

Figure 4. A selection of GPS units for agricultural purposes.
GPS Guidance Systems

Guidance systems use GPS positioning technology to improve the accuracy and efficiency of a number of farming operations. When properly installed and operated, such benefits include: the ability to generate straighter rows with no wide or narrow middles, the establishment of controlled traffic lines to minimise compaction areas within fields, permit equipment to be operated at higher ground speeds with less operator fatigue, they reduce the amount of overlapping of sprayers and fertiliser equipment beyond that of the current foam marker system and they allow data to be downloaded on application areas for future reference.

In essence, all guidance systems operate by having a GPS receiver mounted on the cab of a tractor to which differential data is transmitted, from either a local base station or one of the sources of differential correction previously discussed. The accuracy of these systems depends on the type of GPS that is used. High-accuracy GPS units such as real-time kinematic (RTK) or carrier phase receivers, have superior hardware that allows positions to be reported to within a few centimetres. These systems may require a local base station located within approximately 5 kilometres of the mobile GPS units. The base station GPS location is corrected to its known location, and the correction factor is transmitted to the mobile GPS units by FM radio signals. Standard differential GPS units which use correction data from geo-stationary satellites provide accuracy to approximately 1 metre. When the GPS receiver is not being used for guidance, it may be used for other operations in the SSCM system including yield monitoring, crop scouting and variable-rate applications.

There are two types of guidance systems currently on the market.

Visual Guidance Systems

Visual guidance systems use a visual tool, such as a light-bar or revolving compass, to aid the operator in the direction of travel. As these systems rely on the driver to maintain full control of the operation, there may be a low degree of overlap direction changes depend on the operators reaction time. A traffic pattern map can be reproduced from the GPS data however, unlike the more advanced assisted steering systems, a traffic map can not be repeated. Most visual guidance systems are easily installed to the steering assembly.

Assisted Steering Guidance Systems

Assisted steering guidance systems feed signals from high accuracy GPS units to the electrohydraulic steering actuators or to steer-by-wire controls of the tractor. A computer on board uses the data to steer the tractor the shortest distance connecting two points. Once a row has been established, the computer then spaces subsequent rows parallel with it. These systems allow a traffic pattern map to be created prior to the operation which can be then loaded into the on-board computer to be navigated
by the tractor. All assisted steering guidance systems have a driver over-ride steering system which allows an operator to avoid within-paddock obstacles. Assisted steering guidance systems, although considerably more expensive than visual systems, have the added benefits of less driver fatigue, are more conducive to night operations and applicable to applications, such as row cropping, where accuracy would need to be less than five centimetres.

Figure 5. A Trimble EZ-guide Plus visual guidance system (photo from Trimble Guidance family Brochure).

Figure 6. Assisted steering systems from Autofarm (left) and Farmscan (right).

Table 2 summarises the important features of a number of guidance systems that are on the market in Australia. Prior to purchase, the buyer should consult the dealer for a full list of the capabilities of each model.
Table 2. An overview of the types of guidance systems currently available in Australia. (October 2004)

<table>
<thead>
<tr>
<th>Company</th>
<th>Visual Guidance (VS) or Assisted Steering (AS)</th>
<th>Type of GPS Single Frequency (S); Single Frequency carrier phase (SF); Dual Frequency Carrier Phase (DF)</th>
<th>Claimed accuracy (metres) .90 CEP 24hours</th>
<th>Approximate price range inclusive of GST (see dealer for actual pricing)</th>
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<td>Beeline Arro HP</td>
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<td>$7 500</td>
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<td>1.00</td>
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<td>0.10</td>
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<td>S</td>
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<td>$14 500 + GPS</td>
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<tr>
<td>John Deere</td>
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<td>DF</td>
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<td>DF</td>
<td>0.02</td>
<td>$29 000 - $60 000</td>
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<tr>
<td>AutoTrak SF2 or RTK</td>
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<td></td>
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<td>VIS</td>
<td>S</td>
<td>1.00</td>
<td>$3 800 + GPS</td>
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<td>0.02</td>
<td>$16 000 + GPS</td>
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<tr>
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<td>VIS</td>
<td>S</td>
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Elevation Profiling

While the use of high-accuracy GPS units for assisted guidance systems has been well publicised, there are a number of other applications in which this technology may be utilised. Most notably is the creation of field-scale digital elevation models (DEM)s. The term DEM is used generically to mean the digital cartographic representation of the earth’s elevation. DEM may also be used interchangeably with digital terrain model (DTM). Essentially DEM’s represent elevation in various formats such as grids, lattices and triangulated irregular networks (TIN) to create an elevation model of the earth’s surface. The accuracy obtainable with most assisted steering GPS units in modelling elevation means that it is possible to create DEMs with higher levels of accuracy than is possible with traditional laser techniques.

These field-scale DEM datasets, recorded easily during routine guidance activities, may then be utilised in a number ways for agricultural purposes. Of particular interest to irrigated cotton production in Australia would be the ability of a RTK GPS survey to generate a DEM capable of identifying areas within the field of localised waterlogging or water-shedding caused by poor laser-levelling or years of erosion. Such information will enable growers to prioritise their laser-levelling programmes according to need and should lead to the more efficient application of irrigation waters. Furthermore, yield patterns within the field may be linked back to localised micro-elevation.

Figure 7 shows an example of a DEM collected by a RTK GPS unit on a guidance system. It is evident in this cotton field that there is a local watershed running diagonally through the middle of the field and that there are regions of possible waterlogging.

![Figure 7. A DEM created for an irrigated cotton field from a RTKGPS used for guidance.](image-url)
Real-Time Yield Monitoring Systems

Yield mapping is an essential component of any SSCM system. Grain yield monitors were released commercially onto the global harvester market in the mid-1990s and have been a standard attachment to 90% of harvesting machines sold in Australia since 2000. Real-time yield monitors have been developed for grain, cotton, horticultural and forage crops that are designed to record the harvested portion of a crop. These systems gather georeferenced yield data by measuring the mass or volume of a harvested crop per unit area, by location, within a field. The resulting maps are a spatially referenced graphic illustration of crop yield variability per unit area for a field or a user defined region constructed using the calibrated data from the yield sensors.

To produce a yield map, the harvester must be equipped with a GPS receiver and a yield monitor. Yield data is then sent to an onboard computer where measured yield is matched with its appropriate field position and the data are stored on a memory card. Data on the memory card are then transferred to a computer equipped with yield mapping software to produce a yield map.

Yield maps provide useful information to producers. These maps can identify areas of high and low productivity, so future inputs can be adjusted to maximise the productivity or profitability of a field. Yield maps document both natural and man-made sources of production variability. Natural variability is caused by weather within a growing season, and from year to year. To correct for this, a producer may need to acquire data from several years to determine consistent yield trends that can be related to soils or topography. In comparison, man-made yield variability may be easily identified and corrected with data from a single year. Examples of man-made variability include poor irrigation water distribution, or the effects of past production practices.

Development of a Cotton Yield Monitor

The development of a yield monitor for cotton has lagged behind that of grain crops. There have been three types of cotton yield monitor investigated. One type which operates by weighing the cotton as it accumulates in the picker basket and determines yield from the changes in the weight as the picker proceeds through the field; a second type which is based on the sound seedcotton makes as it travels along the picker chute; and a third type which uses a light attenuation set-up to measure light interference as the cotton travels along the picker chute (Wallace, 1999). To date, only cotton yield monitors that use the light attenuation technique to estimate yield have been released commercially. These monitors are based on the design of Wilkerson et al. (1994) in which cotton flow was measured using an array of NIR light beams and detectors dissecting the flight path of cotton within a cotton chute.

Currently there are four cotton yield monitors that have been commercially released onto the worldwide market. These are the Agleader, Farmscan, Micro-Trak
and Agriplan (formerly Zycom) cotton yield monitoring systems. Agriplan also has a cotton stripper model. Each of these systems uses a light attenuation technique set-up in a similar fashion to measure cotton yield. Sensors consisting of a number of sets of eyes are placed on each side of a cotton picker chute directly opposite each other. An optical signal (beam of light) is sent from each of the eyes to the other set of eyes and when cotton breaks the beams of light, the sensor detects it. The number of times the light beam is broken every second is then correlated to the weight of cotton by a calibration algorithm. Cables attached to the sensors on the ducts lead into the cab of the picker where a user interface console is installed. The console receives and processes data from the sensors and a DGPS storing the data for later use. Yield information and data relevant to the operation of the sensors is displayed on the console as the cotton is picked.

Two initial obstacles were faced by the developers of cotton yield monitors using the NIR light beam array to measure cotton flow. It was found difficult to keep the light emitting diodes clean for long periods of time and developing algorithms to identify periods when the information returning from the sensor was of questionable integrity in order to warn the operator.

![Figure 8. Light attenuation technique used in optical cotton yield sensors (from Wilkerson et al., 1994).](image1)

![Figure 9. The original Zycom (now Agriplan) light emitting diodes.](image2)
The Accuracy of Cotton Yield Monitors

In 1997 when research into the accuracy of cotton yield monitors was initiated at The University of Sydney, there were two cotton yield monitors undergoing pre-release testing in Australia, the Zycom and the Micro-Trak cotton yield sensors. During the 1998/99 season Farmscan initiated extensive field testing of a cotton yield monitor as did Agleader during the 1999/2000 season. Each season has seen these monitors upgraded via various product improvement programs. Often this involves only the upgrading of the in-cab controller firmware however occasionally it has involved more serious physical improvements such as changes to sensor designs and sensor mounting apparatus. Likewise, similar research into the accuracy of these monitors has been conducted in the United States over the same time period. A summary of the findings from all this research is presented in this document.

Table 3 summarises the average absolute error of the yield sensors tested in experiments conducted in Australia and those reported around the world. Details of these investigations can be found in reports by Gvili, 1998; Perry et al., 1998; Searcy and Rhodes, 1998; Durrence, 1998; Durrence et al., 1999; Khalilian et al., 1999; Sassenrath-Cole et al., 1999; De Tar, 1999; Wolak et al., 1999; Wallace, 1999; Thomasson et al., 1999; Perry et al., 2001; Sui and Thomasson, 2001; Wilkerson et al., 2002; Vellidis et al., 2003 and Boydell, 2003. These experiments encompass all 4 of the yield monitoring systems. They are classed into groups of increasing sample size.
These results indicate that there are imperfections in the yield monitoring sensors at both the small and large scale. Particularly, these errors are evident at small scales (less than 16 kg). Best management to minimise these errors is the averaging of a few individual measurements to increase the confidence one has in them. However, significant larger scale precision problems do exist. Most commonly these errors are caused by either an accumulation of dust blocking the sensor eyes or from stringers (cotton lint caught on the sensor housing) repeatedly recording yield measurements. Early sensors also had the propensity to malfunction due to an electrostatic charge created by the lint been blown up the picker chute. This problem has since been rectified in most systems.

### Recommended Operation of Yield Monitors

There are two main factors which influence the accuracy of yield estimates from cotton yield monitors which are commercially available. Firstly, the sensor’s sampling frequency and flow estimation method will have a large and constant influence on its ability to accurately measure flow. Secondly, the sensor sampling method (analogue or digital) and its mounting location will affect how the estimates react to gradual dust build-up and the mounting location to acquire stringers. This second factor will affect the yield monitoring systems reliability when operating in the field under non-ideal conditions. The more impervious a system is to typical problems such as dust build-up and stringers, the greater the confidence that one will be able to place in the yield estimates. With this in mind, great care should be taken when installing cotton yield monitors to remove any “burrs”, such as may be created when drilling into the cotton chute, to prevent possible stringer problems.

Great care should also be taken to ensure that for all monitors the sensor “eyes” are kept clean. The frequency of this maintenance will be determined by the field conditions in which the picker is operating and by the flow estimation method implemented by the cotton sensor. Digital sensors should be more tolerant of dust build-up with analogue area sensors being totally intolerant. All sensors have a self-diagnosis mechanism to warn the operating when the sensor eyes may be getting dirty or are otherwise malfunctioning. The picker must stop and sensors be cleaned immediately when this warning is given if confidence in the yield estimates is to be maintained.

<table>
<thead>
<tr>
<th>Actual Cotton Mass (kg)</th>
<th>5</th>
<th>9</th>
<th>16</th>
<th>500</th>
<th>1500</th>
<th>2500</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sensor Error (%)</td>
<td>10</td>
<td>11</td>
<td>2</td>
<td>3</td>
<td>3</td>
<td>3</td>
</tr>
</tbody>
</table>

Table 3. The average error in yield monitors for different cotton sample sizes from testing both in Australia and around the world.
Recommended Handling of Yield Data

The results from experiments conducted in Australia and those from publications around the world indicate that the errors of yield estimates are relatively large (about 10%) for small sample sizes (about 5 kg) through to samples of around 16 kg where the error is approximately 3%. Subsequently, a suitable method of reducing these errors is to group into a block a number of neighbouring (both down the row and neighbouring rows) instantaneous yield estimates for averaging. A likely size of this block is one which would include enough estimates to reach a summed value of about 16 kg producing an estimate with an error of less than 3%. The geographic size of this block would be dependant on the sampling density and on the yield of the crop but would typically include 8 to 10, 1-second yield estimates from an 8 bale/ha crop. A four-row picker travelling at five kph will normally generate these estimates in a block with approximately 5m x 5m sides. At this size, confidence in the quality of the yield estimate is maximised as is the spatial resolution of the resulting yield estimate map. An example of a cotton yield map generated using a Zycom cotton yield monitor is illustrated in Figure 11, where the map to the left is the raw Zycom yield estimate, and the map to the right is the map created using the block averaging method to maximise yield estimate accuracy.

Figure 11. Cotton yield maps illustrating the difference between a raw yield map (left) and a yield map where points within a 5m x 5m block are averaged.
Future Developments in Cotton Yield Monitoring

Progress in cotton yield sensing technology should see further significant developments over the next 12 months. The current optical yield sensing systems will be joined on the market by systems that utilise different techniques to measure yield. There may be up to 3 new systems commercially available. The accuracy and robustness of these new systems remains unknown at this stage.

Queensland based company AgGuide, in conjunction with the National Centre for Engineering in Agriculture, has recently developed a cotton yield monitor for use in Australia. Their cotton yield monitor is designed to link into their other guidance products.

Mississippi State University (MSU) have developed an acoustic cotton yield sensor (Figure 12). This ultrasonic cotton yield monitor is designed to be less susceptible to contamination from debris and other irregularities which have afflicted some current optical-based systems. Researchers at MSU have come up with a simple calibration procedure without the need for picker scales.

John Deere has recently introduced the Harvest Doc Cotton System based on their GreenStar components. This mass flow sensor utilises microwave technology that is a modification of a groundspeed sensing Doppler radar. The Harvest Doc Cotton System contains a microwave-transmitting and receiving antenna, circuitry, a digital signal processor and a controller area network bus interface (Figure 13). A sensor mounted in each duct records the portion of microwave energy that reflects off the moving pieces of cotton as they are blown up the picker chute. This information is combined with velocity and a signal-processing algorithm to estimate yield.

Figure 12. Ultrasonic cotton yield monitor developed by Mississippi State University (photo from www.asta.msstate.edu).

Figure 13. Microwave yield monitoring system developed by John Deere (from, Breaking Ground Spring/Summer 2004).
GROWER PERSPECTIVE

Using Yield Mapping Technology

By Anne Sullivan, Border Rivers Cotton Industry Development Officer
Australian Cotton CRC / Department of Primary Industries, Qld

Ian Burnett, 'Barkool', Emerald, along with his sons Craig and Nigel, have been using yield mapping technology for the past 3 years to monitor variability within fields. In this time they have been able to gather some baseline data that should assist with land management decisions in the future. Ian has his yield maps produced through Queensland Cotton, who have provided excellent technological assistance, and help calibrate the pickers each year.

Ian believes that at least 3 years data is needed before he would significantly change any management practices. The data needs to be examined over time to determine what is causing the differences in yield. He has been able to use yield maps to decide upon soil sampling sites, and in some cases this has confirmed what he had already been thinking - that is, there are some areas producing lower yields, and they are on a sandy, hard duplex soils type. Ian will be able to accurately add gypsum to rectify this problem.

Ian also has variety trials on his property, and differences in yields between the different varieties have shown up in the yield maps. This season’s maps also showed some areas where waterlogging occurred. This was mostly due to rainfall, so Ian won’t be making any changes based on just the one-year’s data. If, however, there was a recurring problem showing up over a few years, it may be an area that would require some adjustments to the drainage of the field.

QC SciAg also provide Ian with vigour maps prior to defoliation. In the 2001/02 season, Ian picked up a boundary effect around the paddock, which was an area of low vigour, and Ian believes this may have been as a result of whitefly.

Ian believes he will see a major benefit in the next few years when he installs GPS guidance systems on his tractors. He will be able to use the yield maps to test soil fertility in areas of lower yields, and follow up with the use prescription fertiliser treatments. This will allow him to alter his rates of fertiliser across a paddock, giving a more accurate and cost saving fertiliser application.
Remote Sensing

Remote sensing is the term used to describe the acquisition of information from far away locations such as satellite-based and aircraft-based sensors. Interest in remote sensing for broadscale crop management can be traced back to the late 1970s and early 1980s when a great research effort was focused on the use of multispectral images for crop inventory and crop production (Moran et al., 1997). The advantage of using multispectral data collected in this manner is that large areas can be covered rapidly and repeatedly throughout the entire growing season of a crop. Two types of sensors exist for the remote sensing of objects on land. Active sensing systems (e.g., radar) which measure the characteristics of a reflected signal generated from an object bombarded with a signal from the sensor and passive sensors which receive the naturally-emitted and reflected signals from sensed objects. By examining the reflectance values at certain regions of the electromagnetic (EM) spectrum it is possible to differentiate between various targets (e.g., crops and soil) and relate these to a variety of applications (Lillesand and Kiefer, 2000).

Collection of remotely sensed data for the intention of identifying within-field soil and crop variability for SSCM purposes has some crucial considerations. These include the spatial resolution (i.e. minimum object size), the temporal resolution (frequency of coverage), spectral bands and the spectral resolution (spectral band width).

Spatial resolution is probably the most significant for SSCM and is a measure of the number of image forming pixels per unit of area. Increasing the spatial resolution of an image will come as a trade-off with the size of area captured by an image. Selecting a desirable spatial resolution will depend on the intended use of the information. For monitoring weed and pest outbreaks a very high (< 1 metre) resolution will be necessary whilst for monitoring soil type boundaries a 30 metre resolution may prove adequate. The cost of purchasing imagery over a desired area is usually governed by the spatial resolution.

Remotely-sensed data can be collected by either orbiting satellites or from sensors mounted in aircraft. Both methods offer different advantages. Aircraft offer much more operational flexibility as satellites are constrained by system spatial and spectral resolution, a set temporal resolution and the reliance on cloud-free targets. However, the orbit of commercially available satellites means they are able to capture much greater areas. Generally it is conceded that aircraft-based sensors offer the advantages of time-specific imagery at an increased spatial resolution while satellite-based sensors are more cost-effective as the region of interest expands. Common satellite providers include the NASA launched Landsat Series, the French launched Spot Series, a cooperative effort between NASA and Japan’s Ministry of Economy Trade and Industry called ASTER, the Ikonos satellite launched in 1999 and the Quickbird satellite launched late in 2001. A summary of the potential applications of these satellites for SSCM purposes is given in Table 4.
Table 4. Potential use of optical satellite-based sensors for SSCM purposes.

<table>
<thead>
<tr>
<th>EM Region</th>
<th>Approximate Spectral Range (nm)</th>
<th>Potential Applications for SSCM</th>
<th>Satellite Provider</th>
</tr>
</thead>
<tbody>
<tr>
<td>Visible Blue</td>
<td>400 - 500</td>
<td>Differentiation of soil and vegetation</td>
<td>Landsat 7, Ikonos, Quickbird</td>
</tr>
<tr>
<td>Visible Green</td>
<td>500 - 600</td>
<td>Assessment of vegetation vigour</td>
<td>Landsat 7, Spot 4, Ikonos, Quickbird, ASTER</td>
</tr>
<tr>
<td>Visible Red</td>
<td>600 - 700</td>
<td>Chlorophyll absorption for vegetation differentiation</td>
<td>Landsat 7, Spot 4, Ikonos, Quickbird, ASTER</td>
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<tr>
<td>Near Infrared</td>
<td>700 - 1000</td>
<td>Biomass surveys for crop yield, differentiation of soil properties</td>
<td>Landsat 7, Spot 4, Ikonos, Quickbird, ASTER</td>
</tr>
<tr>
<td>Short Wave Infrared</td>
<td>1500 - 1800</td>
<td>Vegetation and soil moisture measurements</td>
<td>Landsat 7, Spot 4, ASTER</td>
</tr>
<tr>
<td>Short Wave Infrared</td>
<td>2000 - 2350</td>
<td>Hydrothermal Mapping</td>
<td>Landsat 7, ASTER</td>
</tr>
<tr>
<td>Thermal Infrared</td>
<td>8000 - 14 000</td>
<td>Soil moisture studies and plant heat stress management</td>
<td>Landsat 7, ASTER</td>
</tr>
</tbody>
</table>

- not included is the panchromatic band of each sensor
- Landsat 7 - Spatial resolution of 30 metres for all bands except thermal infrared which is 60 metres
- Spot 4 - Spatial resolution of 20 metres for all bands
- Ikonos - Spatial resolution of 4 metres for all bands
- Quickbird - Spatial resolution of 2.5 metres for all bands
- ASTER - Spatial resolution of 15 metres for Green, Red and NIR bands, 30 metres for short-wave infrared Bands and 90 metres for thermal infrared bands.

Figure 14. A Landsat image displaying the fields cropped to cotton (green areas) over a 210km² region near Moree.
Cotton Yield Estimates

The use of remotely sensed data to generate yield estimates and estimates of crop areas is not new. Typically, yield estimates based on remotely sensed imagery are accepted as qualitative unless supported by significant ground truthing (calibration) in the form of meteorological records and yield data.

Variation in the reflectance response of vegetation in the red (600 – 700nm) and near infrared (800 – 1100nm) wavelengths is influenced by crop properties such as leaf area index (LAI), plant health and crop biomass. A number of indices have been developed which utilise this information to form crop yield estimates. The most widely used has been the normalised difference vegetation index (NDVI) based on the ratio of NIR minus red reflectance, divided by NIR plus red reflectance. This index measures plant photosynthetic activity and thus crop growth potential which is then converted into crop yields based on various calibration models. Figure 15 illustrates the basic procedure for transforming reflectance data into cotton yield estimates. The accuracy of these estimates will vary from commercial provider to commercial provider based on the parameters used in the calibration model and the amount of ground truthing they have undertaken.

Figure 15. A method for transforming remotely-sensed data into cotton yield estimates.

In 1998 IAMA began actively marketing “Farsite”, a cotton yield-estimate map as a means of collecting cotton yield data prior to picking. Although the exact means of deriving these yield estimates is proprietary, the basic method involves the collection of satellite images for cotton fields in January when a large part of the crops yield potential is already determined. Lush and healthy crop canopies reflect light differently to poorly established, water stressed or diseased crops. This difference in reflection is then combined with a proprietary calibration to generate
a yield estimate on a 25m x 25m cell basis. This product, initially called “Farsite” and currently known as “Precision Cotton” is delivered by a joint venture between the company AGRECON (Button, 1998) and the University of Canberra. Precision Cotton provides farmers with raw imagery, yield estimates in map form, in text/tabular form and images displaying relative within-field vigour.

In 2002 a Perth based remote sensing company, Specterra Services, launched an aerial 4-band image acquisition service with a variable spatial resolution ranging from 10 metres x 10 metres down to 0.25 metres x 0.25 metres. A key deliverable of this company is within-field cotton yield estimation which is distributed in Eastern Australia by the Narrabri-based Precision Cropping Technologies. Likewise, Terrabyte Services based in Wagga Wagga, also provides the cotton industry with high resolution imagery ranging from 3 metres x 3 metres down to 0.5 metres x 0.5 metres. This geo-registered imagery provides yield and quality assessment based on vegetation indices at certain stages of the growing season.

Figures 16 and 17 illustrate how yield data can be obtained from remote sensing. Figure 16 is a false colour image which is used to differentiate cotton cropping areas over a region and Figure 17 shows the results of a transformation algorithm that has been applied to turn the crop biomass data into cotton yield estimates.

Figure 16. A false colour image from the Landsat ETM+ satellite differentiating cotton fields (red) from other landuse.
Figure 17. Cotton yield estimates derived from Landsat ETM+ satellite data.
Advantages of Remote-Sensed Yield Data

There are two main advantages of remotely sensed yield estimates over yield monitor data. Firstly, it is available to growers earlier in the growing season (2-3 months prior to harvest). Depending on the end use of this information, this timeliness may add value over that collected during harvest. The obvious application to benefit from these early yield estimates involves the ability of an informed grower to more confidently refine his/her forward selling and market position to most accurately match the probable production. A second major advantage is that it is available as a historic record for previous seasons. Derived from Landsat data collected in mid-January through February, and stored in a central data archive since the mid-1980s, this data could be drawn on to generate yield estimates for seasons of interest from the past. This in itself is a major advantage for use in operations such as the generation of management zones which may require multiple years of yield data to accurately approach a stable yield zone estimate. Whilst proximal data sources are totally reliant on future seasons for this information, the archive allows the manager to choose past seasons to include in the dataset or wait for future seasons. Added to this is the fact that the whole acquisition procedure is extremely clean with very little hands-on labour required by the farm operators at what is perhaps the most stressful and intensive management time of the year, picking. With current resolution, the benefit of remotely sensed yield estimates is largely centred on the ability to acquire massive areas of data and process this rapidly at a relatively cost effective level. Future satellites with new sensors and greater spatial resolution are also planned which should close the gap between the yield monitor and remote sensing spatial resolutions.

Advantages of Yield Monitor Data

Yield monitor measurements have consistently been proven to be superior in quantitative (more accurate) and spatial terms relative to that generated from remotely sensed yield estimates. Based on the superior spatial and quantitative capabilities of cotton yield sensing systems, other information advantages may involve mapping and recording yield data as individual rows instead of as a 2,4,5,6-row average across the machine. This approach, available on the Farmscan and AgriPlan yield monitors may offer opportunities to manage not just the spatial variability across a field caused by natural soil type and environmental interactions, but also to approach some issues actually created by farm operations. These may include the effect of wheel tracks and high traffic rows where the opportunity to quantify the difference of yield between traffic and non-traffic rows may prove enlightening and prompt managerial changes. Additionally the inter-row differences in yield may be used to identify features such as reduced yield along a row, which may result from imperfect irrigation in a furrow system or possibly to identify sub-optimal individual head operation on a picker at harvest.
Remote Sensing of Soil Properties

Remote sensing techniques have been applied in soil science for many years, in particular to aid soil surveyors to reduce the time and costs associated with discrete sampling. With the development of new sensors utilising a greater portion of the reflected spectrum and delineating a greater number of bands at ever increasing spatial resolutions, there is now many possibilities for its use in SSCM. Its main benefits are due to the fact that it permits estimation of many significant soil properties over large areas and also provides the ability to monitor temporal changes through repeated observations over time. The spatial resolution of the data source is critical to how well fine scale soil variability can be estimated, an important consideration for SSCM purposes.

The spectral reflectance of the soil is generally related to the weathering of the parent material over time and to cultural practices that effect the organic matter content. Thus, the resultant spectra will depend on the mineralogical features of the parent material, soil texture the amount of organic matter present in the soil as well as the soil moisture content when the image is captured. This has enabled spectral reflectance to be correlated to many significant soil components (Zheng and Schreier, 1988; Post et al., 1994) using different wavelengths or bands of wavelengths.

Figure 18. An aerial image illustrating bare soil colour differences within a cotton field.

Some of the more useful ways in which remote sensing can be used for the identification of various soil properties include:
Soil Moisture: can be measured by a number of ways. In images that measure the reflectivity of the soil surface, areas of higher moisture content appear as darker since water lowers the reflectivity of an object. Thermal infrared bands can be used to measure the diurnal changes in temperature of the soil which can be correlated back to the moisture status. Ground penetrating radar systems that measure the amplitude of a reflected signal may also be correlated to soil moisture.

Soil Mineralogy: can be measured as the spectral reflectance of the soil, is partially dependent upon its chemical composition. Generally minerals that reflect the most from soil are those which are produced from alteration, for example, iron oxides and clays (Drury, 1990).

Other Soil Characteristics: as soil is related to more than just soil moisture and mineralogy. These include soil texture (sand and clay content) and organic matter content. When there is no water, sandy soils have a lower reflectance than clay soils. Similarly, large amounts of organic matter has also been found to lower the reflectance of a soil (Lillesand and Kiefer, 1994). Further information on soil-related issues specific to the Australian cotton industry where remote sensing will be a useful tool can be found in SOILpak for cotton growers (McKenzie, 1998).

Remote Sensing of Pest and Weed Infestations

Pesticides and herbicides are the two of the most expensive controllable costs of cotton production. Rapidly improving remote sensing technology and image processing means there is the potential to significantly reduce these expenses. Research is currently being undertaken on using multispectral imaging and various analysis algorithms to distinguish and treat within-field weed and pest infestations.

Mapping weeds using multispectral imagery prior to crop emergence is relatively straightforward as in many instances weeds are not randomly distributed across a field, but are found in patches. Weed patches can be detected by the presence of biomass where normally there would be bare soil. This information may be ground-truthed to identify the species and processed into an on/off prescription map to spray weeds with a minimum amount of herbicide. This process is dependent on adequate image resolution to identify the weed patches. At resolutions less than 0.5 m, it has been demonstrated that it is difficult to distinguish moderate populations of a weed from soil (Lamb, 2000). The characteristics of most current remote sensing satellites like Landsat and Spot are very effective for monitoring general vegetation health, but are unable to monitor weed species due to their spatial resolution. Therefore, such applications require aircraft-based multispectral sensors to obtain the necessary spatial resolution.

Once a crop cover is present, separating crop plants from weed plants becomes a significant challenge. Hyperspectral imagery, with a large number of narrow and contiguous channels, should be able to exploit small differences in reflectance among weed species, and between weeds and crops. It is anticipated that the high spatial and spectral resolution (improved number and placement of spectral bands) of
hyperspectral sensors will allow for the unique detection, definition, and recording of multiple weed species in crops. This is due to each plant species possessing a unique spectral “fingerprint” based on the biochemical make-up of the species. From this information relevant herbicide application maps could be generated. However, determining weed species via multi- or hyperspectral imagery continues to be difficult and remains the focal point of current agricultural research.

Figure 19. NDVI image showing patches of wild oats (Avena spp.) Red against a background of bare soil (blue) in a seedling triticale (X. Triticosecale) crop. Image coverage, 111 ha; resolution, 1.5 m, (From, Lamb, 2000).

Likewise, remote sensing techniques have the potential to guide spatially variable pesticide applications. Pest and disease infestations often change leaf pigment content, which can be detected with a hyperspectral sensor. Measurements which may be relevant to monitoring crop disease and insect damage include maps showing variation of leaf chlorophyll, leaf area index and biomass. During the cotton growing season, plant bugs are likely to target vibrant cotton plants first and then radiate out as the plants mature and produce flower buds. Using remote sensing, these areas of development may be identified by biomass or leaf indices and developed into an on/off map for spot-spraying, eliminating most insects with a minimal amount of pesticide before serious infestation occurs.

Additionally, the early detection and mapping of disease may reveal the extent and magnitude of a problem. Temporal data could show the origin and progression of the disease or pest infestation. This may lead to the implementation of a more cost effective mitigation strategy that will also result in benefits to the environment through more judicious chemical use.

The use of remote sensing techniques to aid in pest management is still in its
infancy and more research is required to demonstrate the full capabilities of this technology. The mobility of insects makes their site-specific management considerably more challenging than less mobile species. Whereas weeds and nematodes can be found in a fairly narrow layer just above or just below the soil surface, flying insects may occupy vast three-dimensional areas in and around the crop.

GROWER PERSPECTIVE

An “eye in the sky” helps irrigation scheduling

By Julie O’Halloran, Gwydir Valley Industry Development Officer, Australian Cotton CRC / NSW Agriculture

In limited water seasons, opportunities for improving water use efficiency are keenly sought. At “Caroale” in the Gwydir Valley, Chris Humphries has found thermal imaging data valuable in irrigation scheduling. Chris first became interested in thermal imaging technology in 1997 and believes that one of the most important benefits it has is in optimising irrigation in a limited water season.

Thermal imagery data is gained from aerial photographs of a crop taken with a digital thermal camera that measures crop canopy temperatures to an accuracy of 0.1°C. This temperature reading is compared with that of a well-watered crop and the atmospheric water content to estimate the reduction in crop transpiration - termed the Crop Water Stress Index (CWSI). A CWSI is calculated for each field or management unit at the time the images were taken. These are used to rank fields from driest to wettest to set up an appropriate watering schedule. A colour image of the property is generated indicating the spatial variation of temperatures over the farm. To use thermal imaging as a scheduling tool, multiple passes are required to measure changes in stress and project them forward to time the next irrigation.

Chris has been able to use this technology to delay some irrigations, increasing water use efficiency and minimising waterlogging. Similarly, yields have been increased by timing of irrigation events after rainfall. For example, some heavy rainfall events were thought to be equivalent of a full watering until the thermal imaging data indicated watering was warranted.

An advantage of thermal imaging for irrigation scheduling is the spatial information provided (for every 2-4 metres) compared with probe data that give measurements at 2 or more points in a field. This allows any problems in watering such as missed syphons or incomplete irrigation runs to be identified which may otherwise not have been detected. There are significant advantages in scheduling and variability information on large multi-field properties and after variable rainfall events. While the results do not show moisture throughout the soil profile the data does reflect the plant’s response to moisture in the profile.
There are some limitations of the technology, including:

- best results require cloud free conditions so that an even solar load is placed on the crop,
- timing of flights can be delayed for various reasons,
- an even or full canopy is required.
- Cost – this has been the main obstacle to widespread implementation to date. Chris feels the technology can be economical with multiple passes over large farms or areas.

In addition to scheduling irrigation, thermal imaging has other potential applications including:
- early detection of fusarium,
- accurate yield variation maps in the growing crop to identify crop and soil factors that affect yield,
- defoliation information with rank and late maturing crop areas identified for variable rate and product selection,
- hail damage assessment,
- agronomist overview and precision mapping overlay with EMS,
- contours and farm maps.
- ideally suited to trickle irrigation systems to monitor distribution and design.
- to help explain the sources of loss or gain in picker yield maps and relate them back to a dollar value.

Chris feels that the best way to use thermal imagery for irrigation scheduling would be to use it initially in conjunction with existing decision making systems and if possible site probes as well.

Figure 20. Thermal imagery showing cotton evapotranspiration rates.
### On-the-Go Proximal Sensing Systems

Excluding yield monitoring, most data collected for SSCM is performed by manual sampling and laboratory analysis. Ground-based sensors offer the opportunity to automate the collection of crop, soil and pest data at a spatial resolution that is not economically feasible with manual sampling methods. Increasing the intensity of sampling will result in a more accurate characterisation of the within-field variability. A number of sensors that provide real-time georeferenced data have been developed or are in the progress of being developed for SSCM purposes. It is envisaged in the future that some of these sensors will be mounted on the front of farm machinery during cropping operations to permit the instantaneous variable-rate application of crop production inputs such as herbicides or gypsum based on the real-time sensor readings.

### What Soil Properties can be Measured using Sensors?

At present there exists a number of soil sensors which operate using a variety of measurement techniques (Table 5). These sensors are used in conjunction with a GPS receiver to provide geo-referenced measurements throughout a field. Of particular interest to the cotton industry will be the ability to measure soil texture, moisture and nutrient concentrations. Most of these sensors provide a measurement that is affected by more than one agronomic soil characteristic. Investigations have commenced on sensors for measuring soil organic matter, soil moisture content, electrical conductivity, soil nutrient levels including soil nitrate, salinity and soil physical properties. Although there are only a few of these sensors commercially available at present, it is anticipated in the future that the development of many of these sensors will lead to a rapid improvement in crop modelling and site-specific estimation of crop production inputs. For a detailed summary of the research conducted to date on soil sensing technology for precision agriculture the reader is directed to Adamchuk et al. (2004).

### Advantages of Soil Sensors

- Immediate Results.
- No need for expensive and tedious sampling and analysis.
- Minimises handling and removes transport and storage costs.
- Removes laboratory induced variability.
- Not much expertise to operate.
- Potentially cheaper than sampling.
Table 5. Soil sensors and the measurement technique they employ.

<table>
<thead>
<tr>
<th>Attribute</th>
<th>Measurement Technique</th>
<th>Attribute</th>
<th>Measurement Technique</th>
</tr>
</thead>
<tbody>
<tr>
<td>Organic Matter</td>
<td>Visible and NIR reflectance</td>
<td>Nutrient</td>
<td>Ion-selective electrode</td>
</tr>
<tr>
<td></td>
<td>Electromagnetic induction (EMI)</td>
<td></td>
<td>Ion-selective field effect transistor (ISFET)</td>
</tr>
<tr>
<td></td>
<td>Electrical resistivity (ER)</td>
<td></td>
<td>Electrical conductivity</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Electrical resistivity</td>
</tr>
<tr>
<td>Texture</td>
<td>Visible and NIR reflectance</td>
<td>pH</td>
<td>Ion-selective electrode</td>
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<td>Electromagnetic induction (EMI)</td>
<td></td>
<td>Ion-selective field effect transistor (ISFET)</td>
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<tr>
<td></td>
<td>Electrical resistivity (ER)</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Ground penetrating radar (GPR)</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Acoustic sensors</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Moisture</td>
<td>Electromagnetic induction (EMI)</td>
<td>Salinity</td>
<td>Electromagnetic induction (EMI)</td>
</tr>
<tr>
<td></td>
<td>Ground penetrating radar (GPR)</td>
<td></td>
<td>Electrical conductivity</td>
</tr>
<tr>
<td></td>
<td>Electrical conductivity (EC)</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Electrical capacitance Time-domain reflectivity (TDR)</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>NIR reflectance</td>
<td></td>
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</tr>
<tr>
<td></td>
<td>Nuclear magnetic resonance (NMR)</td>
<td>Topsoil</td>
<td>Electromagnetic induction (EMI)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Depth</td>
<td>Electrical conductivity (EC)</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Ground penetrating radar (GPR)</td>
</tr>
</tbody>
</table>

The greatest activity currently occurring in the on-the-go sensing of soil types and soil attributes revolves around the measurement of soil electrical conductivity either by non-contacting electromagnetic induction (EMI) or by means of direct contact. EM sensors obtain a measure of soil conductivity by creating a magnetic field which generates an electrical current as it passes through the soil profile, which in turn generates a secondary magnetic field whose strength is dependant upon the soil conductivity. Contact methods utilise electrodes which are in direct contact with the soil. These systems contain one set of electrodes which emit current into the soil while the other set of electrodes measures the voltage that results.

Figure 21. Veris 3100 direct contact soil electrical conductivity sensor from Veris Tech.
Soil electrical conductivity is a measure of the electrical properties of the soil determined by a complex interplay of numerous soil attributes including clay content, moisture content, salinity, soil mineralogy and cation exchange capacity (CEC). As crop yields are predominately influenced by soil nutrient status and water-holding capacity, using soil conductivity techniques as the basis of a real-time sensing system is invaluable.

One application of measuring soil electrical conductivity in the cotton industry is that it can assist in identifying regions within a field of varying soil texture. Using the instrument when the moisture content is uniform (i.e. after heavy rainfall or irrigation) and in fields where salinity is negligible, then most of the response of the instrument is directly related to clay content and mineralogy. As heavy textured soil (clays) have a high conductivity and light textured soil (sands) have a low conductivity, mapping the soil electrical conductivity shows how yield variability may be influenced by spatial patterns of potential water stress. This relationship is highlighted in Figure 23 where higher cotton yields correspond to the lower conductivity measurements. Information such as this can then be used to guide agronomic practices such as determining planting density, irrigation scheduling and fertiliser application.

Another application in which measuring soil electrical conductivity has been demonstrated to offer considerable benefits is the mapping of irrigation channels. Using an EM 31 instrument, apparent soil EC can be measured down to a depth of 4 metres. This information can be used to identify areas of potential seepage in the subsoil of irrigation channels. Work to date has shown that on some farms 80 per cent of irrigation water lost by seepage is caused by just 5 per cent of the channel area.
The continuous monitoring of soil moisture content may also offer a means of identifying areas susceptible to waterlogging and aid in the determination of soil textural variation. Soil electrical conductivity measurements can also be utilised for this purpose as well. There also exist a number of other sensing techniques including microwave attenuation, capacitance probes, nuclear magnetic resonance (NMR), near-infrared reflectance (NIR), microwave reflectance and ground-penetrating radar (GPR) for the sensing of soil water content.

An area which has also received considerable research interest has been technology for the direct on-the-go measurement of soil chemical characteristics, such as soil nitrate, potassium and pH. Ion selective probes and Ion Selective Field Effect Transistors (ISFET), which use ion-selective sensors mounted on computer chips in conjunction with specific membranes to measure soil solution ion concentrations, have been investigated (Loeto and Morgan, 1996; Birrell and Hummel, 2001; Viscarra Rossel et al., 2004). Research is continuing with the aim of commercialising these systems.

Soil optical and radiometric sensors which determine the amount of energy reflected from the soil surface within a particular spectral range are also gaining popularity. These sensors are based on the same measurement techniques as those mounted in satellites or aircraft. Sensors of this design are usually mounted on tillage or spraying equipment in close proximity to the soil. A number of researchers have been able to use NIR reflectance to estimate a number of agronomically significant soil properties including organic matter, soil moisture, CEC, clay, pH, organic carbon and total nitrogen (Sudduth and Hummel, 1996; Reeves et al., 2002; Fytso, 2002; Christy et al., 2003).
Other On-the-Go Proximal Sensing Systems

The development of other proximal sensing systems has focused primarily on systems that measure the crop canopy to variably apply fertiliser or sensors that detect weeds from a crop or the soil to apply a herbicide in real-time. Most ground-based plant detection systems use either machine vision or optical sensors to identify and remedy problems. Machine vision utilises advancements in computer technologies that recognise shape, texture or colour features of objects. This technology is used predominantly to discriminate weeds from soil and crops. Optical sensing systems measure variations in spectral reflectance to distinguish growing plants from background soil and crop residue or to delineate spectral differences within the same crop species. These differences are used to estimate the plants' nutrient needs. Figure 25 shows the set-up of a typical proximal sensing system for weed control. A sensor located at the front of a tractor measures spectral reflectance which is then transmitted to a processor in the cab. A rate of herbicide is determined and this information is transmitted to a sensor behind the cab that activates the sprayer when it reaches the weeds. The whole process of determining the amount of weeds and application of the correct herbicide rate happens instantaneously, with no time delay.

Most proximal sensors are still in a developmental stage however a few products have been commercially released. These include two patented systems from NTech Industries. WeedSeeker® uses sensor optics to sense and treat weeds and GreenSeeker® is an integrated optical sensing system that measures crop nitrogen status and variably applies the crop's nitrogen requirements. Nitrogen requirement of the crop is determined by the NDVI (normalised difference vegetative index) and an environmental factor. A similar nitrogen sensor is the Yara-N-Sensor, formerly called the Hydro-N-Sensor, which is increasingly being used for nitrogen fertilisation.
in grain production. This optical reflectance sensor is mounted on the roof of the tractor cab and uses a biomass index based on plant reflection characteristics to calculate the recommended fertiliser rate to be applied. It is anticipated that a wider range of sensors with greater applications for broadscale agriculture will be released in the near future.

![Diagram of a proximal sensing system for weed control](image)

**Figure 25. The set-up of a proximal sensing system for weed control.**

### Discrete Soil and Plant Sampling

This refers to the manual sampling of variables within a field using either a grid-based or statistically based random sampling strategy. In the cotton industry, this technique is predominately applied to the observation of soil attributes but could be applied to monitoring pest levels. Ideally for SSCM purposes, discrete sampling should supplement a dynamic spatial information system that stores all relevant data collected within each cotton field. This additional information should result in an increasing understanding of the field and improved management over time. There is currently a number of strategies that could be employed to produce an efficient sampling plan that should addresses knowledge gaps, rather than exhaustively generating redundant data.

### Traditional Composite Sampling

Traditional composite sampling has generally being implemented by the cotton industry over the past several decades, especially for nutrient testing. Generally the aim of such a sampling scheme is to obtain an estimate of an attribute to represent the whole field. It involves randomly taking cores throughout a field, bulking them, then thoroughly mixing and sub-sampling for analysis as a single sample. In most cases whole fields are represented by a single soil sample. There is no set procedure, although a composite soil sample should consist of a number of randomly selected
sample sites within a field based on knowledge of the field variability and the attribute to be measured. Furthermore, it is advisable to avoid sampling obvious sources of unusual variability and within close proximity of field borders. With the use of GPS, traditional random sampling locations can be located at the same coordinates each year to reduce year-to-year sampling variability.

Such an approach to sampling has some serious limitations for uniform crop management and is unsuitable for SSCM. A significant shortcoming of composite sampling is that it does not provide any indication on the extent to which variability is occurring within a field. High and low values are generally averaged out by the bulking process. When adopting this approach for estimating field average applications of nutrients there is the potential for serious miscalculations. Small areas of very high nutrient levels, that are included in composite samples, may cause the “average” reported value to be artificially inflated, resulting in the average fertiliser requirement of the field to be underestimated. Conversely, regions of very low nutrient concentrations may cause the estimation of the field average fertiliser requirement to be excessively high. This frequently occurs with temporally unstable nutrients such as soil nitrate or with nutrients which may be inherently higher or lower in certain soil types. For SSCM purposes such a sampling approach is inappropriate as it does not provide any measure of the spatial variability that is present in the field.

Grid Sampling

A grid sampling system uses a systematic method to select sampling points but assumes there is no logical reason in the way patterns may vary within a field. The rigid shape of the grid means that sample density does not depend on actual variability within the field. Sampling by grid is at present a laborious procedure if large areas such as cotton fields are to be tested.
The first step in grid sampling is to divide the field into small areas or blocks (Figure 27). From this a sample location is identified within the grid. Most commonly this will be the point at the centre of the grid cell, which becomes the sample point. Each sample may represent a composite of samples taken within a radius of the centre location of that grid. Modification to the sampling pattern by randomising sample placement within the grid, may help to reduce bias caused by the regular row and column sample alignment. For the production of accurate soil maps, the appropriate grid size must be determined. The greater the sampling intensity, the greater the likelihood of identifying fertility patterns, however this comes as a trade-off between accuracy and cost. Sampling at a too wider sample spacing may still provide useful information on the magnitude of field variability, but may be too inaccurate for variable-rate management.

**Grid Sampling for SSCM**

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 about 40 metres.

Grid schemes are convenient to locate and can be easily inputted in geographic information systems (GIS), but like traditional random sampling schemes they may be inefficient when there is prior information. In Australia, the dense grid sampling required to effectively reveal fertility patterns can be prohibitively expensive and in fields with complex soil patterns there is a risk of not identifying all the variability. Grid sampling may be the best option where there is little or no prior knowledge of the within-field variability.

**Stratified or Directed Sampling**

Directed or stratified sampling is based on spatial patterns defined by some prior knowledge or observation from a field. There are many data sources which can be utilised for directed sampling purposes. The most efficient sampling design involves the incorporation of all data layers that can provide information on the local spatial variability of an attribute in question. Aerial photographs, satellite imagery, yield monitor maps, soil survey information, digital elevation models and grower experience have all been demonstrated to be useful in directed sampling schemes for measuring soil and crop production variation.

Directed sampling requires the identification of zones (polygons) within a field with similar soil and crop conditions. For cotton, the boundaries of management zones are most easily delineated with the aid of yield maps, soil survey maps or remotely-sensed images. Boundaries may be adjusted with further data and experience of the farming system. Once the zones have been identified, there should be less variability within each zone than between zones. There is no firmly established protocol as to the sampling density and the location of the samples that should be
used within each zone. This will be governed by local variability and costs. If the zones within each field were totally homogeneous, one sample would characterise the entire zone, but in reality these zones are not homogeneous. Options are to take a number of samples per zone or to take a composite sample to represent the entire zone. New samples may be taken in areas of the field where yield variability or crop response to variable management departs from expectation.

Figure 28 shows a directed sampling scheme based on soil colour. In this field there are 3 zones, representing 3 soil types, in which 6 - 8 sample locations has been randomly selected.

Figure 28. A directed soil sampling scheme based on soil colour.

Figure 29. Field navigation equipment for discrete soil and plant sampling, including: (a) program control (b) moving map display (c) data entry keyboard (d) GPS and correction satellite antenna mast (e) backpack containing the GPS (f) handheld computer running navigation software.
Once data on spatial variability has been collected it is necessary to establish whether the observed variability is significant enough to warrant some form of differential treatment. A model is required that relates the degree of field variation in an attribute or number of linked attributes to an expected yield outcome based on treating the variation in a uniform or differential manner. An assessment may then be made regarding the implementation of differential or uniform management of the field based on economics and environmental considerations. Advancements in computing technologies has lead to the development of software that is capable of processing spatial data for this task.

**Geographic Information Systems (GIS)**

GIS are computer-assisted systems for the acquisition, storage, analysis and display of data that are geographically referenced, or related to real-earth coordinates. Most GIS consist of hardware and software used for the storage, retrieval, mapping, and analysis of geographic data. Central to the system is the database which is compromised of two elements. A spatial database, that records the location and an attribute database, that describes the characteristics or qualities at each of the locations. Each measured variable from a field that is georeferenced becomes a unique data layer that can be overlaid and visually and mathematically correlated or interpreted. For example, a GIS for SSCM may contain information on cotton yield, topography, soil nutrient concentrations and soil textural properties at the same point for numerous locations throughout a field.

The highly complex procedures required to operate some GIS packages has led to the development of a range of less capable but more simply operated precision agricultural GIS (PAGIS). Typically aimed at the farmer or agronomist level, PAGIS are capable, to varying degrees, of importing PA spatial information, storing and organising it into an intuitive hierarchy, manipulating it through the application of models and transformations and outputting the resultant information via the screen, as a printout or as an exported data file onto a removable storage media (Usery et al., 1995).
Before a decision is made to purchase a GIS for precision agriculture purposes a number of issues should be considered. If your initial aim is only yield monitoring, then the mapping software that comes with the yield monitor is probably adequate. However, when there is desire to utilise this information for management purposes an agricultural GIS with the ability to view, manipulate and interpret a variety of data sources will be necessary. The complexity of the GIS software will depend on the intended use of the software, the expertise of the operator and the cost. Table 6 summaries the results of a study conducted at The University of Sydney into the functionality of a number of agricultural GIS for SSCM. These results are intended only as a guide as GIS software is being constantly improved and updated. During this study it was not possible to review all available software as a few companies were preparing to release new products. The study found that in all cases, cost is very representative of the capabilities of the software.

**Some Considerations when Selecting a GIS for SSCM**

- Is the system compatible with current computer hardware?
- Does the software link to other business software?
- Can the GIS process and output data formats used by yield and variable-rate application equipment?
- Can the GIS process remotely sensed data from the sources that you obtain data?
- Can the software read data inputs from a number of input devices, e.g. PCMCIA or flash ram cards?
- Does the software only create maps or can it analyse multiple layers of data?
- Does the software give a number of options for interpolating point data into continuous map data?
- What level of expertise is required to operate the package?
- Does the software create application maps that are compatible with your variable-rate controller?

**Coordinate Systems**

An important aspect of working with spatial data in a GIS environment is the coordinate system used to represent geographic position. Generally, GPS receivers pinpoint the location on the spherical surface of the Earth using latitude and longitude. This data should then be transformed from GPS-derived coordinates (representing a curved surface) to a map (flat surface). This is done by a feature of GIS called map
Table 6. A summary of the features of a number of agricultural GIS for SSCM. (August, 2004)

<table>
<thead>
<tr>
<th>Company</th>
<th>Mapping For Precision Agriculture</th>
<th>Other Features</th>
<th>Analysis of Precision Agriculture Information</th>
<th>Reporting Capabilities</th>
<th>Import/Export Features</th>
<th>Comment</th>
<th>Approx. Price inc GST</th>
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<td>Elevation Data</td>
<td>EM Data</td>
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</tr>
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<td>SSToolkit</td>
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<td>yes</td>
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</tr>
</tbody>
</table>

* During this study it was not possible to review all available software.
projection. Fundamentally, the map projection process results in the map’s spatial representation being distorted according to some model. A rectangular grid coordinate system is associated with every map projection with the coordinates described in terms of Easting and Northing. These referring to the distances to the East and North of an origin and usually expressed in units of metres.

The most common projection system used within Australia is Universal Transverse Mercator (UTM). This is a global implementation of the Transverse Mercator projection in which the earth is divided into 60 zones, each being bounded by meridians of longitude. Each UTM zone is restricted to a width of six degrees of longitude. In Australia, the standard projection system used in mapping since the year 2000 has been the Geocentric Datum of Australia 1994 (GDA94). It is recommended that all data be converted to this system and that growers purchasing satellite or mapping data demand that it is delivered in this projection.

The Department of Lands in NSW has made available a software package called GEOD for converting between various coordinate systems currently in use in Australia. This package can be obtained as a free download from their web site (http://www.lands.nsw.gov.au/Records/Surveying/GDA/GEODSoftware.htm).

There are significant differences between GDA94 and the AGD66/84 geodetic coordinate systems which were commonly used throughout Australia before 2000. They are NOT interchangeable.

Figure 30. The concept of a GIS - overlaying a number of data layers to relate variables at the same geographic location.
What Methods can be Used to Measure Variation?

Before any management decisions about the variability of an attribute can be made, we have to quantify the amount of variability that is present. There exists a number of methods of statistically describing spatially variable data contained within most GIS packages. A very basic review of some common statistical measures found in GIS software relevant to precision agriculture is given. The interested reader can find more thorough descriptions in works by Burrough and McDonnell (1998) and Webster and Oliver (2001).

Classical Statistics for Describing Populations

The Mean

The arithmetic mean (also known as the average) is the sum of all of the data points within a sampled population divided by the number of points in that population.

$$m = \frac{\sum_{i=1}^{n} x_i}{n}$$

Where: $m$ is the population mean  
$x$ is the value for each of the sampled data points  
and $n$ is the total number of data points in the population

The mean is typically a good indicator of the usual values within a population. However, with highly diverse populations and relatively small populations the mean...
can be somewhat misleading because it can be greatly influenced by extreme scores. Subsequently, additional statistical methods that describe the population spread are important supplements to the information carried by the mean.

**Variance and Standard Deviation**

The variance ($\sigma^2$) is a measure of the degree of spread in values within a sampled population. It is calculated as the average of the squared deviation of the difference between each value and the mean. The square root of the variance, the standard deviation, provides a more meaningful measure as it corresponds to the same units as the mean.

\[
\text{variance} \quad \sigma^2 = \frac{\sum_{i=1}^{n} (x_i - m)^2}{n-1}
\]

\[
\text{standard deviation} \quad \sigma = \sqrt{\frac{\sum_{i=1}^{n} (x_i - m)^2}{n-1}}
\]

Where: $m$ is the mean  
$n-1$ is the number of independent data values in the sample  
and $x$ is the value of each data point.

**Coefficient of Variation**

The coefficient of variation (CV) is a measure of relative dispersion and is simply the standard deviation of all samples divided by the overall mean of all samples. It may be expressed as a percentage.

\[
\text{Coefficient of variation} \quad CV = \frac{s}{m}
\]

\[
CV\% = CV \times 100
\]

Where: $s$ is the standard deviation  
and $m$ is the mean of a population.

When the CV is small < 10%, it says that a particular attribute is occurring over a very small range of values, something you would expect if within-field variability is very low. CV will usually increase as the sample area increases. If the CV is used as a preliminary assessment of yield data variability, then any value higher than 10 per cent can be considered above average for cotton. However this value should serve only as a guide as it has no direct relationship with the potential to manage a field site-specifically.
Correlation

Correlation \((r)\) is a measure of the linear association between two sets of data. It is effectively a measure of how well a simple linear model will describe the relationship between two variables.

\[
\text{Correlation} \quad r = \frac{\sum_{i=1}^{n} z_x z_y}{n}
\]

Where: \(z_x\) is the variable \(x\) converted into \(Z\) scores and \(z_y\) is the variable \(y\) converted into \(Z\) scores. The \(Z\) scores are computed following equation below.

\[
Z = \frac{X - m}{\sigma}
\]

Where: \(X\) is a score from the original normal distribution, \(m\) is the mean of the original normal distribution and \(\sigma\) is the standard deviation of original normal distribution.

The correlation coefficient will range in value from plus to minus one with a value closer to one indicating greater similarity/correlation. A negative correlation suggests that as one variable increases the other will decrease. Alternatively, a positive correlation indicates that as one variable increases, so will the other.

When investigating the within-field variability of a number of variables, the mean, standard deviation (s.d.) and correlation coefficient will all be useful statistical methods to describe the variability observed. However, none of these statistics model the spatial relationship between each of the data points. The following section on spatial statistics is a brief introduction to geostatistics and will be of interest to readers who wish to pursue more advanced data analysis such as the variants of kriging. Simpler spatial interpolation methods are described from page 51.

Spatial Statistics

Spatial statistics are based on the premise that data points within a field can be related to other data points by considering their respective geographic locations. The most widely applied scientific technique for describing this relationship is geostatistics. Fundamentally, the idea behind geostatistical techniques is the presumption that neighbouring points in a field will be more similar than points a
greater distance apart, thus the separation distance between points should be useful to model the rate of change expected for a given distance across the field. By modelling this rate of change it is possible to predict attributes at unsampled locations and use this information to guide future sampling schemes.

The difference between points in a field, separated by the distance \( h \), is measured by the semivariance \( \gamma(h) \)

**Semivariance**

The semivariance is a calculation of the variance between two points and is calculated by the equation below.

\[
\gamma(h) = \frac{1}{2N(h)} \sum_{i=1}^{N} [Z(x_i) - Z(x_i + h)]^2
\]

Where: \( Z(x) \) and \( Z(x+h) \) are the two points \( h \) distance apart and \( E \) is the expectation.

By analysing all of the pairs of points within a dataset, and arranging them in order of separation distance, the degree of spatial variability can be illustrated. Simplification of a plot of this kind can be achieved by calculating the average semivariance steps or lags of separation distances. For instance, over a range of 100 metres, ten 10 metre lags could be calculated to summarise the semivariance into 10 data points. This average semivariance is calculated as followed:

\[
\gamma(h) = \frac{1}{2N(h)} \sum_{i=1}^{N} [Z(x_i) - Z(x_i + h)]^2
\]

Where \( N(h) \) is the total number of pairs fulfilling the segregation criteria of the lag range \( h \).

In order to use the spatial trend information contained within the semivariance calculations, a model may be fit to the lags of progressively longer (separation) distances and used to predict semivariance at any separation distance. Graphing separation distance against semivariance is commonly known as the semivariogram which can then be utilised for describing spatial variability and in particular as a weighting factor for an interpolation technique known as kriging. A theoretical spherical semivariogram model is presented in Figure 32, highlighting the important structural features of all semivariograms. These are the nugget \( (C_0) \), sill \( (C_0 + C_1) \) and the range \( (a) \). The nugget variance is due to inherent variability at scales less than the sampling interval and measurement errors. From \( C_0 \) the value increases with distance between the samples until the semivariance flattens out at the sill variance.
At the range $a$, semivariance remains constant with increasing distances between samples as they achieve independence.

![Spherical Semivariogram](image)

**Figure 32.** A spherical semivariogram highlighting the important structural features.

There a number of models which can be used to represent the relationship between the semivariance and distance. Common models which may be utilised for SSCM data include the spherical and exponential models. To date there is no objective manner for selecting the most appropriate model, however, Webster and McBratney (1989) suggest the use of the Akaike information criterion (A.I.C.) for choosing the most suitable model where a lower value represents a good compromise between goodness-of-fit and parsimony of the model.

**Spatial Interpolation Methods**

Much of the data collected for use in SSCM is arranged in irregularly spaced datasets. While increasing sampling intensity is the best way to improve spatial prediction, logistically and financially it is impossible to measure at a high enough density to create continuous surfaces, especially at the within-field scale. Therefore, spatial modelling techniques have to be utilised for creating continuous maps of soil and crop attributes for SSCM purposes. Secondly, where the intention is to compare two datasets, it is often necessary to estimate or interpolate values from each dataset onto coincident points. Most GIS contain the following capabilities for the spatial interpolation of precision agricultural data.

**Nearest Neighbour**

Nearest neighbour is the simplest of the interpolation methods whereby the predictions of attributes at unsampled points are provided by the single nearest data point. The region is divided into polygons or tiles by perpendicular bisectors determined by the configuration of the sampling points, with one observation per polygon. Thus, the unknown value is set equal to the nearest point and that all change
occurs at the borders as demonstrated by the example below. As this method uses just one measurement to make a prediction it tends to result in a continuous surface which consists of a series of steps.

**Local Moving Average**

Local moving average estimates an unknown value by taking the average of a selected number of points around the desired location as demonstrated below. The weighting is the same for all observations within the search neighbourhood. Either a fixed number of known points or all the known points within a fixed radius of the unknown value can be used to make an estimate. Increasing the number of sample points in estimating an unknown value will produce a smoother transition between points. This method generally provides a better representation of the spatial continuity than simple nearest neighbour interpolation. It is particularly useful for dense data sets such as yield monitor data.
Inverse Distance Weighting

The method is based on the premise that the unknown point is more likely to have a value similar to points closer to it than those further away. Weights for each prediction are dependent upon a power, where points progressively further from the grid location to be estimated have progressively less influence on the prediction. Normally, inverse distance is an exact interpolator in that if a point is exactly coincident with a grid point, the values will be the same. In this method weights are defined by the equation below, and sum to give one.

\[
Z_j = \frac{\sum_{i=1}^{n} \frac{i}{h_{ij}^\beta}}{\sum_{i=1}^{n} \frac{1}{h_{ij}^\beta}}
\]

where:
- \(h_{ij}\) is the separation distance between grid node \(j\) and the neighbouring point \(i\);
- \(Z_j\) is the interpolated value for grid node \(j\);
- \(Z_i\) are the neighbouring points;
- \(d_{ij}\) is the distance between the grid node \(j\) and the neighbouring point \(i\);
- \(\beta\) is the weighting power.

Although the selection of a value for \(\beta\) is arbitrary, the most popular choice for \(\beta\) is two so that data are inversely weighted on square distance.

Figure 35. Unknown points interpolated using inverse distance.

Each of the interpolation methods discussed should be available for the interpolation of point data to a continuous surface in most agricultural GIS. Advanced
GIS software will contain the option to perform kriging based on the previously discussed geostatistical model. Geostatistical methods have the advantage of providing a direct estimate of the quality of the predictions made at unsampled locations.

**Kriging**

Kriging is a group of generalised least-squares regression algorithms pioneered by South African Danie Krige in 1951, that make predictions at unsampled sites by appropriately weighting the known values at the sample sites through the use of the previously described semivariogram. As a general rule, kriging will create the most accurate interpolations when there is sufficient data to estimate the semivariogram (at least 80 data points). Typically, kriging will use a single (called global) variogram model as the basis for all predictions however, it is also possible with large datasets (such as yield data) to calculate semivariograms for smaller parts of the field (local variogram) and then through kriging apply this local variogram to prediction locally. Although this method of spatial interpolation can be quite complex, the kriging method of interpolation has as an advantage in that it has the ability to calculate estimates of the error of prediction at each unsampled site. As the theory behind kriging and its application is complex, interested readers are directed to Isaaks and Srivastava (1989) and Webster and Oliver (2001).

The Australian Centre for Precision Agriculture (ACPA) has developed new spatial prediction software which is capable of performing kriging with both local and global variograms on data sources associated with SSCM. This PC-Windows program is called VESPER (Variogram Estimation and Spatial Prediction with ERror) and can be obtained as shareware from the ACPA web site (http://www.usyd.edu.au/su/agric/acpa).

This program is ideal for growers or consultants who wish to perform this type of analysis without wanting to purchase an advanced GIS system. Applications of the program include the generation of yield maps, interpolation of discrete soil sample data, interpolation of DEM data and the production of EM survey maps. The user-friendly interface permits the creation of a field boundary and generation of an interpolation grid.

**Before any interpolation procedure is undertaken all unrealistic data values (outliers) should be removed from the dataset. This includes the removal of zero values from yield data and any values which are clearly associated with machinery malfunction.**
A popular approach for discerning spatial and temporal patterns in data associated with SSCM is by cluster analysis. Cluster analysis is a repertory of statistical methods that encompasses a number of different algorithms for grouping data of a similar kind into respective groups (clusters). Its objective is to create groups so that the degree of association is strong between members of the same cluster and weak between members of different clusters. Each cluster thus describes, in terms of the data collected, the class to which its members belong: for example, a cluster could be points in a field where high cotton yield and low soil conductivity occur together.

An important question that needs to be answered before applying a clustering
algorithm is the type of algorithm. For SSCM, research has shown the k-means clustering algorithm to be the most beneficial as it will produce exactly k different clusters of greatest possible distinction. The ACPA has also developed new software which is capable of performing this type of clustering on SSCM data sources. This PC-Windows program is called FuzME (Fuzzy k-Means with Extragrades) and is particularly useful for making within-field management zones. This program can be obtained as shareware from the ACPA web site (http://www.usyd.edu.au/su/agric/acpa).

Figure 36. FuzME interface for cluster analysis of SSCM data.

If it is used for research or commercially please cite the following reference: Minasny, B. and McBratney, 2002. FuzME version 3. Australian Centre for Precision Agriculture, McMillan Building A05, The University of Sydney, NSW 2006. (http://www.usyd.edu.au/su/agric/acpa).

Clustering for SSCM

To develop within-field management zones with FuzME the following procedure should be followed. The benefits of delineating management zones within a field are described in Chapter 4. An example with cotton yield monitor data, satellite yield data and soil electrical conductivity data is used here. Prior to clustering, each raw dataset had all unrealistic values removed and was then interpolated onto coincident grid points using one of the spatial interpolation procedures described in this chapter.
Click on the 'Files' tab and input a text file containing geographic coordinates and the attribute datasets into the Data File box (e.g. easting, northing, yield monitor data, satellite yield data, EC data).

Click on the 'Fuzzy Clustering' tab

Choose the number of classes k (potential management zones in a field), with $1 < k < n$ you wish to investigate. In most scenarios it will best to test between 2 and 5 zones for a single field.

Choose a value for the fuzziness exponent $f$, with $f > 1$. A value of 1.1 should suffice.

Choose a definition of distance in the variable-space - mahalanobis.

Choose a value for the stopping criterion $e$ ($e = 0.001$ gives reasonable convergence).

Select the Fuzzy k-means algorithm

Click on the random start box.

Click on the 'Save' tab to retain the settings (Figure 36 shows these settings) and then run the problem by clicking the 'FuzME' tab.

In the output file examine the class means for each set of clustering (for 2, 3, 4, 5 zones etc.) to assess how distinct our $k$ clusters are.

Ideally, we wish to obtain very different means for most, if not all the datasets, used in the analysis. Following the clustering process, we check the average value of the yield monitor data, satellite yield data and soil electrical conductivity data for all tested classes (i.e. when there is 2, 3, 4 and 5 zones or classes in the field). We then select the classification scheme for the field which gives zone averages suitability different enough to warrant some form of differential action.

Figure 38 illustrates the results of clustering the yield monitor data with satellite yield data and soil electrical conductivity data. For this field, it was decided that 4 zones made the most sense from an agronomic perspective based on the averages. Each zone has considerable yield and soil electrical conductivity differences. Zone 1 represents the high yielding coarse-textured (sandier) areas of the field; zone 2 represents the high yielding heavy-textured (clayeyer) areas of the field; zone 3 represents the low yielding medium-textured areas of the field and zone 4 the very low yielding sandy areas. This zone map from clustering can then be used to apply different rates of crop production inputs to each zone based on these properties. A description on how zone management can be applied to cotton farming is given in Chapter 4.
Figure 38. A zone map derived using k-means clustering with the zone averages provided in the lower right table.

**Decision-Support Systems (DSS)**

Decision-support systems (DSS) are a key component of the site-specific management wheel. Their role is to integrate data sources with expert knowledge and decision models to aid in making strategic decisions for both the short- and long-term. Basically they operate by combining a crop model, which contains technical knowledge on crop growth, with economic and environmental considerations. Ideally a DSS will provide the user with a number of possible courses of action in response to some hypothetical scenarios.

Although considerable progress has been made in the development and use of tools for the other components of a SSCM system, developing software for deciding on remedial measures in the cotton industry is still in its infancy. There are however a couple of DSS which have been developed for cotton in Australia to use on a whole-field basis. These are CottonLOGIC (ACCRC Staff, 1999) and OZCOT (Hearn,
1994), both of which were developed by the CSIRO Division of Plant Industry in Australia as a practical means to solve crop management problems. The integration of these models into a GIS environment to permit their use at the within-field scale will prove invaluable in the future. Figure 39 highlights the role these models will play in the entire data gathering/decision-making process. Having collected enough spatial data to determine a management size (e.g., management zones), these models can then be applied to estimate the amount of a crop production input or the effects of alternate management strategies on these different regions within the field.

Figure 39. An outline of the complete decision-support process. Current crop models used by the industry could be used to make management decisions once the optimal management size for a field has been determined.
By Brendan Griffiths, Agronomist, Griffiths Agronomy Pty. Ltd.

Turkey Lagoon is a mixed cattle farming enterprise this year producing 500ha irrigated cotton, 80 ha irrigated corn, dryland wheat, chickpeas, and cattle. The property has been producing irrigated cotton for approximately 20 yrs.

**Background on move towards GPS/GIS technology.**

- If yields were to be significantly increased it is unlikely to occur through dramatic changes in insect management.
- It was decided that the two main areas over which we had control were those of irrigation efficiency, and soils – through nutrition, and management of soil physical structure.
- There are large variations in soil types both within farm and within fields on Turkey Lagoon. The challenge is how to best manage these soils, from the perspectives already mentioned.

**Identification of in-farm / in-field variation**

- We need to identify where these soil variations exactly are and use tools to identify the extent of the variation, and the relative impact on yield, and ultimately gross margin.
- Last year some fields were yield mapped, and this year the entire farm has been mapped via near infrared photography.
- It is important to note that we are not attempting to predict yield but to identify the relative differences between strong and weak areas within the field.
- Airborne remote sensing was chosen as it can be done well before picking and can be ground truthed while the crop still has leaf on it.

* Ground truthing will involve anything from simply looking at the crop, to boll counting, and perhaps even petiole testing, obviously picker yield monitor data would also further validate the photographs.

**Cost/ Prioritise program to address problem areas/fields**

* Once we have identified the relative differences in crop performance, both within the field, and within farm we then need to actually put a value on what the
weaker areas/fields are costing. From this we will then develop a program of identifying soil management zones, and then the weakest/most costly areas and look at identifying what is actually causing the problem.

**Tools available to identify problems**

- GPS/GIS equipment is costly, and often quickly superseded. We need to carefully select how we intend on identifying problem areas and the tools that we use to take the required measurements to identify, and correct, the cause.
- I see five broad tools that we may use:

  1. **Topographical Mapping** - Turkey lagoon has machines equipped with Autofarm GPS equipment capable of mapping topographical (up and down) variation within the field. This will be obviously the first point of call and will allow us to identify whether inefficient, or uneven slope, or slumping, is causing our problems. Various tricky software is available to model the irrigation efficiencies of various fields.

  2. **EM surveying** - an EM survey, perhaps overlaid on a cut and fill map, can identify whether it is simply soil type variation that is causing variations in crop performance.

  3. **Measurement of soil/plant nutrition** - Obviously variations in soil fertility will cause variations in crop performance. It is also important to measure plant fertility levels as soil nutrient levels do not always reflect plant nutrient status.

  4. **Soil physical structure** - Compaction/ poor soil structure is well documented as having a significant impact on yield. This may be simply measured by digging a hole in the ground, i.e. a soil pit, and having a look at the physical soil structure.

  5. **Soil water holding capacity** - This will relate to a couple of other measurements that may also be taken. Obviously the ability of the soil to hold water is likely have a significant impact on the performance / yield of the crop sticking out of it. There are many different methods of measuring soil water holding capacity - Turkey Lagoon uses enviroscan, however a portable tool such as a diviner may be a useful tool to measure variations within field.

**Tools available to correct the problems**

- **Topographical Variation** - The extent to which inefficient slope is damaging yield and perhaps a re-levelling program may be developed and prioritised based on the cost/effect of the measurements taken.
GROWER PERSPECTIVE cont.

- **EM Surveying** - In conjunction with a cut/fill map, and some soil tests, may be an avenue for a variable rate gypsum program. Rather than applying gypsum to the whole field, applying beneficial amounts only to problem areas may be an option.

- **Soil/Plant Testing** - This is the avenue through which variable rate fertilizer will be implemented. It may mean variable rate N through the field from head ditch to tail drain through to correction of specific nutritional disorders in weaker areas.

- **Physical Structural Problems** - Are often difficult to correct and may be handled in a number of ways.

- **Soil Water Holding Capacity** - It is identification of this problem that be cause for actually applying lower inputs to these particular areas, as the water holding capacity may not be able to be improved and these areas may be destined to never be higher performing, thereby requiring lower inputs to achieve their potential.

**Summary**

GPS/GIS type of equipment and techniques prior to now, have, in my opinion, been time consuming, impractical, and often once a problem was identified it was difficult to correct it anyway. The equipment was expensive, and quickly superseded. I think now we are able to use it as a real management tool to both lift yields, and maximise the effectiveness of our inputs. There are many tools available to identify problem areas and also to correct them, but it is critical that problem areas are prioritised and a logical approach is followed in implementing a program for correction of problem. Also, it is important that the changes implemented can be quantified, so a program of yield mapping or airborne remote sensing or the like is used before, and after the changes have been made.
The technology is now available to use spatial information to manage the effects of inherent soil heterogeneity on plant growth. Instead of applying a single rate of input throughout an entire field, lesser amounts of input can be applied where they are not needed and saved for regions within the field that require greater amounts of input. Consequently, this will be economically beneficial and also limit the unwanted release of chemicals into the environment. Such governing operations occur at nearly all phases of the crop-growth cycle.

**Variable-Rate Technologies (VRT)**

The concept of the site-specific application of crop production inputs is dependent on machinery with the capacity to accurately vary application rates within a field. Different technical solutions has enabled manufacturers to refine existing machinery and develop new machinery so that seed, fertiliser, agricultural chemicals, irrigation water and tillage can all now be applied variably within-field. VRT differs in complexity, ranging from the simpler manually controlled systems to the more complex automated systems. The central component of any applicator is the computer/controller which receives information from several sources and in turn it uses this to control the application equipment.

For the most part, manually controlled systems are only suitable when there are very few rate changes in a field and the boundaries where these changes occur can be easily identified. These systems rely on a human operator to adjust the rate, commonly by changing the hydraulic control valve, as the machine moves through the field. Alternatively, the more complex automated systems adjust the rate by either a preset map (determined by the user from the integration of yield, soil and plant data) or from information gathered by sensors as the machine moves through the field. The hardware and sensors that make automated variable rate application possible include the controller, the microprocessor, actuators, pressure sensors, flow sensors, speed sensors and DGPS technology. It is automated systems which are of interest to growers wishing to pursue SSCM.
How can VRT be used by the grower?

The additional equipment needed to perform variable-rate applications (VRA) will vary according to type of VRT system you wish to implement. There are two ways in which automated VRT can be utilised for SSCM purposes. These are sensor-based and map-based systems. There are advantages and drawbacks to both application systems. Table 7 summarises the benefits of both forms of VRT. Generally, map-based variable-rate applicators will require more components than a sensor-based applicator, however, this is offset by the fact that these components can be used for multiple inputs.

Table 7. A comparison of the benefits of sensor- and map-based VRT.

<table>
<thead>
<tr>
<th>Sensor-Based VRT</th>
<th>Map-Based VRT</th>
</tr>
</thead>
<tbody>
<tr>
<td>* Does not require a DGPS</td>
<td>* Product application amounts are determined prior to entering the field</td>
</tr>
<tr>
<td>* Measurement and product application is completed in a single pass</td>
<td>* Product application rates can be based on a much wider range of factors</td>
</tr>
<tr>
<td>* No need to collect, store and analyse sample data</td>
<td>including grower knowledge</td>
</tr>
<tr>
<td>* Continuous application maps should be more accurate as there is no need for</td>
<td>* There is the potential to modify rates to expected growing conditions</td>
</tr>
<tr>
<td>the spatial interpolation of data between sampling points</td>
<td>* Currently map-based VRT systems are able to apply a much wider range of</td>
</tr>
<tr>
<td>* No need for the purchase of specialised software</td>
<td>production inputs</td>
</tr>
<tr>
<td>* Are suitable for the treatment of ephemeral problems such as insect outbreaks</td>
<td>* Processing of sample data permits the removal of erroneous data points</td>
</tr>
<tr>
<td></td>
<td>* Rate changes can be anticipated and compensated for by the equipment</td>
</tr>
<tr>
<td></td>
<td>* Is capable of performing on-farm field trials</td>
</tr>
</tbody>
</table>

Sensor-Based VRT- these systems create application maps by processing field data collected from real-time sensors as the implement moves through the field to alter an input, on-the-go. There is no requirement for detailed maps or extensive decision making prior to application. Machinery of this type can be easily integrated into any farming system, as there is no prior need for any data records or detailed maps.

Sensor-based VRT may apply inputs by either directly measuring a particular attribute and adjusting the input rate or by correlating the requirement of a particular input with some other easier to measure property such as soil conductivity. There are currently automated sensors being used or in developmental stages designed to apply crop production inputs based on soil organic matter, soil moisture, soil conductivity, presence of weeds, soil pH, soil nitrates, crop nitrogen status, soil texture and compaction. These sensors will not only allow controllers to vary application rates, but they will also create maps indicating what was being applied.
at that coordinate and the amount. Currently, most sensor-based systems are only capable of performing a single function, however in the future, sensors will be available that will allow the direct sensing and treatment of multiple attributes as the equipment moves across the field.

An example of detect and treat technology are the WeedSeeker® and GreenSeeker® sensors detailed in Chapter 2 which measure plant reflectance to adjust herbicide and nitrogen rates respectively. There also exist sensors capable of varying nitrogen fertiliser rates in response to soil type variations, soil cation exchange rates (CEC), top soil depth and soil nitrate levels, sensors for varying the seeding rate based on CEC, and sensors for varying the herbicide rate in response to soil organic levels. Figure 41 is the Soil Doctor® from Crop Technology Inc. which is a commercially available system currently in use in the United States that varies nitrogen in response to changes in CEC and topsoil depth as measured by soil electrical permittivity.

Figure 40. WeedSeeker® controller from NTech industries (photo from www.ntechindustries.com).

Figure 41. Soil Doctor® sensor-based nitrogen applicator by Crop Technology Inc (photo from www.soildoctor.com).
Map-Based VRT – these systems consist of a controller, sensors, and actuators (devices that respond to signals from controllers) to adjust inputs based on a pre-made electronic map of the input using a differentially corrected positioning system to determine the applicator position in the field. Application maps may be constructed from yield, topography, soil, plant or weed data as described in Chapter 3. Map-based systems allows the grower to make decisions based on knowledge of the field before they are in the field. This also gives the grower precise control over how much of an input is applied to specific region in a field.

Map-based variable rate controllers are attached to standard farm equipment and can be used to control the rate of liquid fertilisers, dry chemicals (granular fertiliser, granular pesticides, gypsum, lime), anhydrous ammonia, herbicides, pesticides and seeds. These systems incorporate specialised features such as direct injection, thermal equalisers and on-the-go product blending to permit VRA. In many instances, a single controller can be used to vary liquid, dry or anhydrous products. Centre pivot irrigation systems can also be modified to apply varying amounts of water and liquid fertiliser (Perry et al., 2003).

Variable applicators for granular fertilisers come in the form of either spinner spreaders or pneumatic applicators. Spinner spreaders are normally used for adjusting one input via spinning discs located at the rear of the applicator, while pneumatic spreaders use metering controls on centrally located bins to vary single or multiple products. There are a number of methods available for applying liquid chemicals variably. These commonly include changing the system operating pressure for fine adjustments and altering travel speed or nozzle size for coarse adjustments. Anhydrous ammonia is varied using a regulator valve to control the flow as vapour pressure varies with the amount and concentration of the ammonia in the tank and with temperature. As measuring flow rates of ammonia gas is difficult, a thermal transfer unit is used to convert vapour to liquid for metering and application. Seeding rates can be varied by adjusting the speed of the seed metering device. Irrigation waters can be variably applied by centre pivots which use a controller in conjunction with a GPS to activate and deactivate sprinklers to create a spray pattern based on a pre-made application map.

Figure 42. Kee Technologies variable-rate seeder control box (photo from www.kee.com.au).
Figure 43. Mid-Tech single control system for liquid, dry or anhydrous products.

Figure 44. A spreader setup for variable-rate anhydrous applications with a Raven control system.

Figure 45. A spreader applying variable-rate anhydrous ammonia using a DICKY-john thermal equaliser to meter the gas.
Using SSCM to Improve Crop Management

Equipped with an ability to measure, record and analyse spatial information and also equipped with the ability to vary agronomic inputs on-the-go, there is a number ways in which SSCM can be applied to improve the cotton farming system. There are four courses of action which can be undertaken based on this data. These are:

(i) to stop farming a field or small region of a field entirely based on its poor production and high input costs.
(ii) to continue with current whole-field management practices.
(iii) to decide whether some form of differential action is warranted based on the spatial and/or temporal variability present in the cropping system. This could be either a form of zone or continuous management.
(iv) to gain a greater understanding of the crop system by using the technology to conduct experiments on-farm.

The remainder of this chapter focuses on the implementation of the last two options.

Zone Management

Initially it was believed by most that PA management techniques would be applied on a site by site basis. However, as detailed maps of many field attributes were collected it became obvious that there was corresponding patterns of spatial variability in many of these maps. This lead to the use of spatial classification techniques to integrate these maps into a single map of the field highlighting a number of quasi-homogeneous zones. These are commonly termed ‘management zones or management classes’ (Larson and Robert, 1991) and the aim behind their construction is to represent regions in the field of similar yield potentials for the uniform application of inputs within each zone. In many ways this can be viewed as interim
Determination of these management zones may be difficult due to the complex combination of factors that may affect crop yield. Failure to construct meaningful zones may be no better than uniform management of the field. Some of the more common data layers used to construct zones includes yield maps, topography, field history, soil type, soil electrical conductivity, soil nutrient levels, soil colour, soil organic matter, remote sensing measurements and moisture content. The appropriateness of each data layer and the amount of data required depends greatly on the environment. The optimal number of zones in a field will be related to the magnitude and pattern of yield variability and the probable agronomic requirements. Initially, two to five zones would be a sensible starting point. These zones may be developed into true “management units” if some beneficial differential treatment can be identified to increase the effectiveness of management.

Research conducted at The University of Sydney over the last six years has examined whether meaningful management zones can be identified within Australian cotton fields. In one study, cotton yield estimates for 3 fields were generated for 11 consecutive years from 1988 to 1998 using a satellite based yield estimation method. Potential management zones were delineated using the FUZME software described in Chapter 3. Analysis indicates that the fields described in this study exhibited a strong degree of temporal stability and thus, stable yield-zone patterns were present from multi-year yield estimates. It was concluded that 4-years of yield data (±2 years) seems to give reasonably stable estimates of yield zones. Further analysis indicated that the water management from year to year (dryland vs. irrigated) had a significant effect on the yield magnitude and spatial pattern of yield within the
fields. Furthermore, there appears to be a differential yield-response to water application (irrigation) between potential management zones. The improvement on the stability and efficiency of generating potential management zones using datasets comprised of years with exclusively dryland or irrigated management was investigated for each field. Irrigated and 'dry' years show quite different behaviour and should be separated when defining zones depending on the kind of water-management proposed, i.e., dryland or flood irrigation. The use of historical cotton yield estimates essentially short circuits the 3-5 year wait for picker-mounted yield maps and provides producers with an alternative and more immediate management option. Of course, we need to test whether the yield zones identified have sufficient biophysical differences to allow them to be used as management zones.

![Figure 48. 11 seasons of yield estimates for a 200 ha field continually sown to cotton in the Gwydir Valley (1991, 1994 and 1995 were dryland years).](image)

A second study defined management zones based on soil colour using multispectral data collected by the Landsat-7 satellite from cotton fields that were essentially bare of crop cover. Figure 49 shows the bare colour soil image, the optimal number
of management zones generated using the soil colour classification method and a yield map for the 1999/2000 season. The optimal number of zones was based on a criterion that there was at least 100 kilograms per hectare difference in yield between the zones.

Figure 49. A management zone classification based on soil colour. The yield map shows that yield is influenced by soil type throughout the field.

Subsequent soil testing was used to classify each of the soil type derived management zones. The red coloured soil type was classified as a Red Dermosol (Isbell, 1996) covering 30 hectares, whilst the darker coloured soil belonged to suborders of the Vertosols (Grey - 70 hectares and Black - 50 hectares). The major difference between these profile types is that the Vertosols are strongly self-mulching whereas the Dermosols exhibit very little cracking due to an absence of shrink/swell clay minerals. For the 1999/2000 season the average yield of each zone in this field was 10.1, 8.5 and 9.1 bales per hectare for the Red Dermosol, Grey Vertosol and Black Vertosol respectively. It can be concluded that cotton lint yield in this field is very much a reflection of soil type contrarieties. In economic terms, this equates to a difference in gross returns of nearly $700 per hectare between
the highest and lowest yielding soil types.

Soil testing also revealed that there exists an enormous opportunity to examine the merits of managing each zone uniquely. Table 8 lists a comparison of the soil properties between each of the zones.

**Table 8. Average nutrient levels for each soil management zone (Different letters indicates mean is significantly different at 95 % C.I).**

<table>
<thead>
<tr>
<th>Field Property</th>
<th>Red Dermosol</th>
<th>Black Vertosol</th>
<th>Grey Vertosol</th>
<th>Recommended Range*</th>
</tr>
</thead>
<tbody>
<tr>
<td>Soil pH</td>
<td>8.74^a</td>
<td>8.87^b</td>
<td>8.84^b</td>
<td>6.5 - 8</td>
</tr>
<tr>
<td>Soil Nitrate (ppm)</td>
<td>3.5^a</td>
<td>6.2^b</td>
<td>5.1^c</td>
<td>20 - 25</td>
</tr>
<tr>
<td>C:N Ratio</td>
<td>12^a</td>
<td>13^a</td>
<td>13^a</td>
<td>15 - 20:1</td>
</tr>
<tr>
<td>Phosphorus (ppm)</td>
<td>14.4^a</td>
<td>6.6^b</td>
<td>2.7^b</td>
<td>10 - 20</td>
</tr>
<tr>
<td>Potassium +cmol(+)kg</td>
<td>0.76^a,b</td>
<td>0.71^a</td>
<td>0.81^b</td>
<td>1-5% of CEC</td>
</tr>
<tr>
<td>CEC cmol(+)kg/1</td>
<td>34.20^a</td>
<td>40.71^b</td>
<td>39.48^b</td>
<td>na</td>
</tr>
<tr>
<td>Sodium Percentage</td>
<td>3.2^a</td>
<td>5.17^b</td>
<td>5.26^c</td>
<td>&lt; 5</td>
</tr>
<tr>
<td>Ca/Mg Ratio</td>
<td>2.54^a</td>
<td>2.20^a</td>
<td>1.91^c</td>
<td>&gt; 2</td>
</tr>
<tr>
<td>Clay Percentage</td>
<td>50^a</td>
<td>55^b</td>
<td>58^c</td>
<td>na</td>
</tr>
</tbody>
</table>

*Recommended levels for cotton from NUTRIpak (ACCRC Staff, 2001).

There are a number of possible management options that could be applied to these soil-type-derived management zones from which economic and environmental benefits may be forthcoming. Such management options could include the variable-rate application of nitrogen and phosphorus fertilisers, the variable-rate application of gypsum and the shrewd scheduling of irrigation water. The higher yielding Red Dermosols have a significantly lower soil nitrate concentration than either of the Vertosols. This suggests that more of the applied nitrogen fertiliser is being taken up by the plant in the higher yielding regions, thus applying rates based on yield potential would be more beneficial. Despite uniform phosphorus applications, the available soil phosphorus concentration varied considerably indicating that only the Vertosols in this field require phosphorus application. Soil textural and mineralogical differences are also a major contributor to the yield disparity between the Dermosols and the Vertosols due to the role water plays in growing cotton. The more coarse-textured Dermosol will be better draining and less prone to waterlogging.
than the Vertosols. Of course, deep drainage can be an issue. Conversely, as the Dermosols hold less soil moisture, cotton plants grown on the Dermosol will be more susceptible to stress in hot or drought conditions. Based on the area of Red Dermosol in this field, management could be improved by basing irrigation scheduling around the moisture requirements of the Vertosols as they span a greater area of each field.

There is no one management zone model that is going to bring benefits in all circumstances. However, some general conclusions can be drawn. As the amount of data collected and variety of data sources increases, so will the likelihood of creating useful management zones for agronomic inputs; assuming that there are in fact distinct agronomic zones within a field. In most instances it appears that the accurate identification of zones will require yield data over a series of a few years in order to ensure that the zones are indeed similar from year to year. This process is improved by combining yield data with other attributes which affect the yield potential within the field. For cotton, yield potentials will vary based on moisture availability and this can be directly related to soil type and topography.

Once meaningful management zones have been determined, the amount of an input to be applied to that zone has to be decided. This can be done by expert knowledge, decision-support tools and/or on-farm experimentation. Figure 50 shows an example of a cotton field with four zones based on yield and soil EC. In this field, only nitrogen was applied at different rates to the four zones. Pesticide rates were varied between the highest and lowest two yielding zones while the same gypsum rates were considered necessary for the lowest two yielding zones.

Figure 50. A zone management strategy for 3 different inputs.
Continuous Management

The inaugural foray into SSCM began in the early 1990s in the United States, where variable-rate application began prior to the advent of yield mapping, based on a continuous management philosophy. Continuous management is the variation of crop production inputs on a point-by-point basis within a field. This may mean varying input rates over a region as little as 5 square metres, depending on the resolution of the information available to guide such decisions. Initially this approach was reliant on extensive soil sampling, most commonly conducted in a grid configuration, to measure soil nutrient variability. From this, most adopters used a uniform yield goal for the entire field to make predictions for agronomic inputs at each point. Application maps for the entire field were then generated by utilising spatial prediction methods (e.g., nearest neighbour, inverse distance and kriging) to provide estimates at unsampled locations within the field.

Figure 51 illustrates this concept for a cotton field in the Gwydir valley. A continuous nitrogen fertiliser map made by collecting one hundred soil samples taken 6 weeks prior to sowing and analysing each sample for soil nitrate. Fertiliser requirement at each of these sample points was estimated using the NutriLOGIC component of CottonLOGIC and the results interpolated over the entire field using the Vesper software.

![Figure 51. A continuous application map for nitrogen fertiliser.](image)

Unquestionably, the accuracy of the application map is fundamental to the success of any site-specific management plan. Whilst increasing sampling intensity is the best way to improve the accuracy of the maps, it became apparent that relying solely on extensive soil or plant sampling to create continuous input maps at the within-field scale would be both economically prohibitive and totally impractical from a labour point of view. This is particularly relevant in Australia due to the high
costs associated with sampling and analysis.

A second problem with early attempts to continuously vary inputs in this fashion was the assumption that yield response and yield potential are identical everywhere in the field. In most instances this has proven to be an incorrect assumption which has meant that calculating input rates based on a uniform yield goal is inappropriate. Thus, where crop production inputs are involved, some method of estimating yield potential across a field is required such as a series of yield maps or some measurement of soil moisture properties like clay content.

At this point in time, continuous management philosophies are best restricted to inputs that can be estimated by reliable on-the-go sensing systems such as herbicides or inputs highly correlated to soil EC. This currently precludes fertilisers for the cotton industry due to the unavailability of a sensor which measures specific soil nutrients on-the-go or can top-dress fertiliser based on the cotton canopy during the season. However, the near future should technology capable of doing this as well as sensors which will also allow for the continuous application of other chemicals such as gypsum, growth regulators and defoliants.

**On-Farm Experimentation**

Rarely have growers been encouraged by agricultural scientists to conduct their own experimentation due to the sophisticated designs that are often used to measure a response between treatments. The ease in which much of the new equipment associated with SSCM can be adapted to permit on-farm experimentation means that the opportunity exists for growers to conduct their own on-farm experiments. This will allow the grower to answer questions specific to the range of climates and environmental conditions typical of those found on that farm.

Firstly, these experiments should endeavour to answer whether a particular field will benefit from SSCM. An adequate characterisation of field variability can be provided by a uniformity trial, a form of experimentation which has no design associated with it. Any grower who is yield mapping a uniformly treated field is in reality conducting a uniformity trial. Although this does not does not indicate whether a field will benefit from SSCM, the ease of data collection allows the grower to make an informed decision on the variability present prior to selecting a field to trial some form of site-specific experimentation. Further experimentation would then lead to a direct comparison between variable-rate (VRM) and current whole field (WFM) management practices.

**Designs for Assessing SSCM**

Implementing experiments for the purpose of comparing SSCM to uniform management is relatively easy through the use of either systematic or randomised designs. Although systematic designs have generally been admonished for small plot experiments, many of the perceived problems with independence of errors are less
important when conducting the experiment over large areas. In can be as simple as randomly selecting entire fields to receive either VRM or WFM and comparing the results and then repeating this basic comparison at many different locations (Gotway Crawford et al., 1997). In this scenario, the field itself represents the experimental unit and thus the experiment has the advantage of being conducted on the same scale as the results are intended to be implemented at.

A more realistic comparison of the merits of both management strategies can be gained by subdividing fields in either a randomised or systematic fashion, as this will help to negate the effects of differences between and within fields. The most common form of experimental design for such purposes is the use of strip trials. Strips can be aligned in any direction (i.e. horizontal, vertical or diagonally) in order to spread treatments more evenly over the experimental area. An alternative to a strip trial is to the use some form of multiple plot approach such as the systematic design shown in Figure 52 (d). The benefits of this approach is that it reduces the bias caused by the shape of the strips in situations when this maybe of concern. Similarly, how the choice of treatments is most efficiently assigned to the plots is again down to the preference of the experimenter. All of these designs can be constructed by any GIS software and easily applied using VRA equipment.

![Figure 52 A range of designs for comparing whole field management (WFM) to variable-rate management (VRM).](image)

It should be stressed that the results of these experiments will be greatly influenced by the ability to characterise field requirement of inputs in the VRM areas. While providing an excellent starting point for SSCM, these designs are limited to testing whether VRM improves crop performance over WFM. These designs do not assess whether a failure to improve crop performance through VRM is due to imperfect knowledge of field conditions, inadequate recommendations, or a combination of both.
Designs for Calculating Site-Specific Requirement

Inevitably the aim of many experiments for VRM is going to be to quantify the requirement of a crop production input at a site-specific scale. This will mean implementing experiments in which many unique input levels (treatments) will need to be tested at many locations throughout a field to generate localised yield response curves. One method for performing such experiments in a spatially-variable environment is the use of embedded designs (McBratney, 1985). The 'embedded design' is based on classical experimental designs such as the randomised complete block design (RCBD) which have each treatment plot surrounded on all sides by a control treatment plot. For site-specific experimentation purposes, the control plot would simply be the current uniform rate while the other treatment plots would be levels of levels of an input above and below the field average. Such a design allows a predictive model to be obtained which accounts for spatial variation. Treatments in embedded designs can also be allocated in either a systematic or random form as shown in Figure 53. This approach would be adopted in the absence of no prior information on the field variability.

![Figure 53](image)

**Figure 53.** A randomised Latin-square embedded design with four treatments (red, green, aqua, and magenta) and four replications. A systematic embedded design with the same four treatments and six replications could also be used. Blue squares represent the field average rate.

If something is known of the field variability, then placing different treatments within potential management zones is the most efficient form of design. This permits any nominated zone rate to be compared to a theoretical optimum and to the field uniform rate. Traditional experimental designs, such as the randomised complete block and the Latin-square, can be placed in each management zone if permitted by spatial constraints. For the soil-derived management zones example, a fertiliser trial could be set up as shown in Figure 54. This would allow yields from different
fertiliser rates to be compared in a statistical manner and still permit the fitting of response curves to calculate the optimum rate of fertiliser. It is left to the experimenter’s discretion as to whether each potential management zone receives the field uniform rate (which the grower currently considers his best practice) or a specific zone rate.

Figure 54. The experimental design for a field-scale nitrogen fertiliser trial based on previously defined management zones. Response curves (on right) were generated to determine the optimal nitrogen rate for each zone.

For further discussion on experimental design issues refer to McBratney et al., (2002) who emphasise the importance of selecting cheap designs that potentially can be used in every field on every farm. They suggest for fields divided up into management zones, an efficient design would seem to be the “fleck” design where randomised block experimentation is done with spatial constraints and economic considerations. Figure 55 illustrates an example for wheat in Australia in which they selected a design in which there was a maximum penalty of 2.3 per cent of expected profit. The experiment takes up 8.22 ha of a 70 ha field, and costs around $20/ha in expected lost production per annum.

A significant problem that may afflict any type of experiment is a failure to select some sufficiently low rates for the generation of response functions. The impact of these suboptimal rates is that yield losses brought about by this form of experimentation will need to be recovered in the future. However, deliberately incurring a minor yield loss (<2.5 per cent of profit) in the year of experimentation may represent a very good decision for the long term good of the farm.
Figure 55. Simple random design with 5 levels of nitrogen and 2 replicates and three management classes. Note the rest of the field receives 100kg N/ha.

Prospective Management Options

In order to determine if there was sufficient variability to warrant SSCM managerial intervention in cotton fields, a study was undertaken at The University of Sydney to measure the degree of yield variability throughout three of the industries key growing regions. Yield estimates from both proximal and remotely-sensed origins were analysed across the Gwydir, Lower Namoi and Upper Namoi Valleys of New South Wales for the 1999/2000 growing season. The results presented in Table 9 summarise the survey which consisted of 273 individual fields covering approximately 27,000 hectares of these valleys.

In all three valleys analysis indicated an average cotton yield of just over 6 bales per hectare was likely to vary by ±1.7 bales per hectare over a range of only 267 metres. The range indicates the maximum distance at which you expect to find a relationship in yield at two different points. Therefore, you would expect to find this yield difference occurring within just a 9-hectare area of the field. These results are similar across each of the three valleys investigated. The average field in the Gwydir valley for 1999/2000 yielded an average of 7.12 bales/ha but could be reasonably expected to range from as high as 9.0 bales/ha to a low of 5.3 bales/ha over a distance of 295 metres. Likewise, the average field in the Lower Namoi valley for 1999/2000 yielded an average of 6.66 bales/ha but this may range from as high as 8.33 bales/ha and as low as 4.98 bales/ha over a distance of 285 metres. Whilst for the upper Namoi valley, the average field in the 1999/2000 season yielded 6.33 bales/ha but could be expected to range in yield from as high as 6.52 bales/ha to as low as 3.57 bales/ha over just a distance of 217 metres. When we consider this variation over an entire field it is not surprising that yield maps for an average size
cotton field can show up to an 8 bale per hectare difference between the lowest and the highest yielding parts of the yield.


<table>
<thead>
<tr>
<th>Valley</th>
<th>Average yield (bales/ha)</th>
<th>Spatially dependant variability (bales/ha)</th>
<th>Range of variability (m)</th>
<th>Lowest expected yield over this range (bales/ha)</th>
<th>Highest expected yield over this range (bales/ha)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Gwydir</td>
<td>7.12</td>
<td>1.89</td>
<td>295</td>
<td>5.23</td>
<td>9.01</td>
</tr>
<tr>
<td>Lower Namoi</td>
<td>6.66</td>
<td>1.68</td>
<td>285</td>
<td>4.98</td>
<td>8.33</td>
</tr>
<tr>
<td>Upper Namoi</td>
<td>5.04</td>
<td>1.48</td>
<td>217</td>
<td>3.57</td>
<td>6.52</td>
</tr>
<tr>
<td>all</td>
<td>6.33</td>
<td>1.70</td>
<td>267</td>
<td>4.63</td>
<td>8.03</td>
</tr>
</tbody>
</table>

This analysis confirms that there is considerable variability within cotton farming systems and this should provide further impetus for the industry to adopt SSCM practices to manage this variability. Important areas of managerial intervention should include:

**Planting**

Variable-rate seeders make it possible to vary plant population and variety within a given field. Matching the rate of sowing to reflect the changes in the potential productivity of different soil types within a field offers an opportunity to apply site-specific management. All soil types do not possess an identical ability to support a given plant population to reach its full potential. A likely factor in the soil type influence over plant establishment is soil texture, and its expression through seed soil contact. The presence of large clods in the seedbed will result in poor seed soil contact, lower establishment rates and possibly more variability in plant spacing intra-row. Coarser textured soil types are more resistant to “clodding” due to a higher sand content and are able to retain a seedbed capable of good seed soil contact. A study into plant establishment rates in two uniformly managed fields in the Gwydir valley found that plant densities were spatially related to soil type and could vary by ± 4.5 plants/m over 200 metres.

**Growth Regulators and Defoliants**

Considerable variation in plant growth throughout a field has implications for
the amount of growth regulators and defoliants that are applied. As crop biomass is strongly correlated with plant height from emergence to full bloom, determining plant height throughout a field would allow varying amounts of these chemicals to be applied according to the local variation or even to plant growth potential in each management zone.

Our initial investigations into plant height variations within Australian cotton fields found that on average plants will exhibit similar plant height traits out to a range of 230m where they vary by as much as ±17 centimetres compared to their neighbours which will be of virtually the same height.

**Crop Diagnosis**

Crop diagnosis in the form of field scouting is an essential part of SSCM just as it is in any conventional management system. Assessments of the cotton crop with a portable GPS unit makes it possible to identify and record the location of problems or events that will affect production such as soil differences, insect infestations, nutrient deficiencies and weed problems. Temporal monitoring may show the origin and progression of a disease problem. This process can be made more efficient by using remotely-sensed imagery to identify unusual occurrences or areas of maximum variation so that field scouts can seek out economically threatening problems. This imagery also makes it much easier to quantify the extent and magnitude of a field afflicted by a particular problem. Botched fertiliser applications or errant spray drift from pesticide applications can also be identified from the near-infrared region of the EM spectrum prior to being visible with the naked eye permitting early treatment.

**Water and Irrigation Management**

The variable-rate application of irrigation waters may not be feasible in a flood irrigation system at present, however, the investigation of superior methods of water application is becoming increasingly important on the basis of financial, social and environmental considerations. With appropriate controls, sensors and decision making tools, self-propelled centre pivot (CP) and linear move irrigation systems permit water to be applied to account for spatial variations in soil properties. They are an effective and economical means for the SSCM of water and agrichemicals. Additionally these irrigation systems may also provide a platform on which to mount sensors for the real-time monitoring of plant and soil conditions.

Our research has shown that considerable yield variations within single fields can be attributed to natural variations in soil texture, water holding capacities and infiltration rates. Managing a whole field to ensure that areas with the lowest water holding capacity maintain adequate water levels whilst simultaneously trying to avoid over-irrigation in the wettest areas is not possible based on average soil water depletions. Furthermore, an understanding of the soil spatial variation will enable the grower to be more judicious in selecting locations for the placement of tools for
measuring soil moisture to determine irrigation scheduling. This technology offers alternate solutions to an ever increasing number of water-use efficiency related issues.

Another tool to aid with irrigation scheduling is the use of continual logging plant monitoring sensors (PMS) that provide direct real-time measurements of crop physiological growth. Aerial PMS are possible with vision guidance, ultrasonics and/or infrared and give the added advantage of being a non-invasive technique of measuring part or all of a crop in a field. Aerial measurements with PMS could include crop indicators such as plant height, nodes above white flower, nodes above cracked boll and leaf area index. This would enable a real-time assessment of field variation in crop physiological growth.

With current pressures to improve irrigation use efficiency, the development of tools such as these to achieve further precision in the timing of irrigations by monitoring crop growth response is of significant value. An expected outcome from the adoption of PMS for irrigation scheduling is achieving a greater level of precision in irrigation scheduling and an increase in crop water use efficiency from the use of irrigation management strategies such as a deficit irrigation strategy.

**Compaction Management and Minimisation of Overlapped Inputs**

The soil compaction created by tractor wheels has been demonstrated to be a deterrent to growth of crop roots and often reduces crop yield as compaction increases soil strength, density, runoff and erosion while decreasing soil structure and porosity. Under conventional farming, machinery movements each season leave damaging wheel tracks over nearly the entire paddock. The use of GPS guidance systems to implement controlled traffic wheel tracks or ‘tramlines’ confines compaction to the wheel zone and maintains the soil in most of the paddock in an optimum state for plant development and growth.

Secondly, the use of very precise guidance technology to implement controlled traffic systems also minimises the potential for overlapping of crop production inputs during the application stage as is often a problem with conventional application equipment. Minimising the amount of overlapping will bring both economic and environmental benefits.

**Fertiliser Management**

Variable-rate fertiliser applications have the potential to improve fertiliser use efficiency, increase economic returns and reduce environmental impacts by adjusting rates of fertilisers to specific conditions within discrete areas of a field. Our research on a number of fields has highlighted that the degree of spatial variability of important soil nutrients is indeed substantial and can occur over very short distances. Table 10 shows the pre-sowing variation of four important soil nutrients within five irrigated cotton fields.
Table 10. Coefficient of variation (%) of soil nutrient concentrations within 5 irrigated cotton fields.

<table>
<thead>
<tr>
<th>Location and Field Size</th>
<th>Nitrate</th>
<th>Phosphorus</th>
<th>Potassium</th>
<th>Exchangeable Sodium %</th>
</tr>
</thead>
<tbody>
<tr>
<td>Collarenebri 140 hectares</td>
<td>47</td>
<td>66</td>
<td>21</td>
<td>38</td>
</tr>
<tr>
<td>Telleraga 80 hectares</td>
<td>41</td>
<td>70</td>
<td>23</td>
<td>70</td>
</tr>
<tr>
<td>Ashley 80 hectares</td>
<td>42</td>
<td>119</td>
<td>22</td>
<td>42</td>
</tr>
<tr>
<td>Ashley 100 hectares</td>
<td>44</td>
<td>88</td>
<td>22</td>
<td>36</td>
</tr>
<tr>
<td>Narrabri 100 hectares</td>
<td>46</td>
<td>18</td>
<td>15</td>
<td>33</td>
</tr>
</tbody>
</table>

* Sampling density equalled one per hectare.

The coefficient of variation ($C_v$) given in this table is a measure of relative dispersion and is simply the standard deviation of all samples divided by the overall mean of all samples. When the $C_v$ is small, it says that a particular nutrient is occurring over a very small range of values, something you would expect if applying both nitrogen and phosphorus fertilisers in uniform quantities. However, the values obtained for each of these fields are considered very large and indicate the supply of nutrients to the cotton plant is vastly different within different parts of the field. Further analysis showed the spatial variability of these properties is highly correlated with crop yield within each field.

Field experimentation was used in these fields to quantify the possible economic benefits from employing zone nitrogen management. Fertiliser response curves for applied nitrogen showed that economic benefits ranged from $1500 to $3000 per field excluding additional costs associated with gathering the necessary site-specific information, processing the data and applying the fertiliser. Furthermore, even if a zone fertiliser strategy fails to demonstrate definitive returns from site-specific fertiliser applications, it may still bring significant economic benefits from having a better understanding of the local growing environment.

Further investigations are required to economically quantify the benefits from variable-rate phosphorus and potassium applications.

**Soil Amelioration**

Another agronomic input, which may be more judiciously applied by using a site-specific strategy, is gypsum (CaSO$_4$) for soil structural problems. Soil structural problems are caused by sodic and highly sodic soil. Sodic soil is identified as soil containing exchangeable sodium levels (ESP) that contribute >6% to the total cation exchange capacity. A differential application regime could then be calculated and applied according to the varying sodicity mapped within a field. Soil sampling could
be used to calculate the average ESP for each management zone within a field with gypsum applied only to the zones that have levels of ESP >6%. Alternatively on-the-go soil sensors or yield maps could be used to identify potential problem regions which could be specifically targeted. This approach offers the potential for savings in chemical and physical application costs as well as improving the soil-crop environment.

Pest and Weed Management

Although still at an evolving stage of development, the site-specific management of pests and weeds holds clear potential to reduce pesticide and herbicide use within the industry. This will have considerable economic and environmental implications.

Weeds are not always randomly distributed across a field, but are often found in patches. This may be due to differences in soil characteristics that influence weed populations directly or indirectly. Weed species, just like crops, are better adapted to growing under certain soil conditions than others. Variations in pH, texture, organic matter and the mineral balance may have a significant impact on the weed species and their populations within a field. Utilising variable-rate herbicide technology may increase weed control efficiency and reduce herbicide use and residues, thereby avoiding excess applications that lead to increased costs, potential herbicide resistance in the field and runoff into the environment. With most yield monitors it is possible to use binary indicator switches to digitally record field areas where weedy patches exist. Such maps can then be used to guide spot-spraying of perennial weeds prior to the next seasons crop.

Although the mobility of insects makes their site-specific management more difficult, the ability to detect insect damage to focus pesticide applications in the areas of fields most infected will bring significant benefits. Preliminary research suggests that vibrant cotton plants are more likely to be infested with insects as they target these areas first and then radiate out. Mapping these areas within a field may be useful in identifying zones suitable for initial treatment to prevent further spread or for directing the differential application of the insecticide over the entire field. Another approach to insect management may see a whole field receive a minimum application rate with higher rates being applied to the outbreak zones or the highest yielding management zones throughout the season.

Cotton Quality

The colour, strength, length and the thickness of the cotton fibres (micronaire) are all important characteristics evaluated by cotton buyers. To reflect the values of these qualities, the market has developed a series of sliding payment scales consisting of premiums and discounts for delivery of cotton outside set grade acceptability limits. This is extended to growers through a premium and discount pricing scheme to
encourage the delivery of a quality textile. To remain competitive in world markets, it is essential that Australian growers produce the highest quality cotton.

Strategies for improving fibre quality and increasing quality uniformity within fields will be based on knowledge of the interactions between yield and quality influencing parameters and their spatial variability. SSCM makes it possible to identify regions within a field of similar environmental suitability which may be managed to the local optimum of vegetative versus reproductive growth to alleviate stresses during critical times. This will enhance the production of quality fibre. The relationships between yield, fibre quality and plant height suggest that these regions would not necessarily have the same response to managerial inputs. Instead, local responses may be discovered and applied to optimally manage the crop’s alternative vegetative and reproductive response to a changing growth environment. In some areas, a relatively small transition from vegetative into reproductive growth phase of little quality consequence and managerial interest may coincide with a significant shift within another region of the field. The ability to identify these regions early will greatly enhance the manager’s ability to manage cotton quality.

It has been demonstrated that opportunities exist to manage quality variability through the identification of similar production potential within a field, which then may be used as a guide to identify other regions which will experience similar levels of environmental stress throughout the season. Significant variability was observed in the plant properties within a number of our research fields. The local soil type around each of the sample sites and the local growth environment provided by it appeared to have a significant influence on the measured plant properties. Subsequently, these plant properties also displayed spatial structure. Quality variability and in particular the plant height vs. turnout/length parameters at these points indicated that there may be an opportunity to manage fields differentially based on soil type delineated zones where water holding capacity and yield potential are incorporated into decision making processes. This would allow the local stem elongation growth rates and thus ultimate plant height to be managed to maximise yield and quality.

**Product Tracking**

Consumers are increasingly demanding more information on the food and fibre products they purchase. This has been highlighted by the GMO issue especially in Europe. SSCM offers the possibility of product tracking through a system. The ultimate aim would be a label capable of being read by a consumer’s handheld computer/phone/organiser that describes the operations that have been undertaken to produce this product. There is a tiny amount of work on this (e.g., Nislon et al., 2004) but not from the perspective of SSCM. Future research will look to provide the tools on-farm to initiate the process.
BMP and Environmental Auditing

The industry’s Best Management Practices (BMP) program is designed to help growers identify and manage their farm operations, from pesticide application to land and water practices. SSCM technologies are one of the many tools growers can use to improve and monitor their farming practices. One of the main principles of the BMP program is to ensure cotton farms improve their environmental performance. This may be achieved by product-tracking techniques.

A simple consequence of product-tracking techniques is the ability for growers to demonstrate the operations and associated fertiliser/chemical rates that have been applied across a farm. This would allow environmental auditing compliance to be done effectively if, as foreshadowed, legislation is adopted on the right to use and apply chemicals. However, there are large institutional hurdles which have to be cleared before this can be achieved. Environmental regulations within the European Union, for example, focus on the means to achieve environmental objectives rather than on the environmental goals to be achieved. Rather than check the groundwater quality directly, emphasis is on arbitrary allowable fertilisation rates that have an unclear relationship to groundwater quality. This approach is associated with massive bureaucratic control mechanisms that are essentially built on distrust of farmers (McBratney et al., 2004). The challenge is to change this fundamentally by building on farmers’ expertise to achieve environmental goals that have been accepted by society. SSCM in the hands of modern, capable farmers is a powerful tool to achieve this different approach as it is based on trust rather than distrust. Using SSCM for environmental auditing creates a foundation for restoring trust as a basis for the interaction between governments, farmers and consumers.


**GROWER PERSPECTIVE**

**Variable-Rate Applications Targets Inputs**

*By Julie O’Halloran, Gwydir Valley Industry Development Officer,\nAustralian Cotton CRC / NSW Agriculture*

Auscott “Midkin” in the Gwydir Valley have been interested in precision agriculture for several years, firstly Beeline and yield mapping and more recently variable rate applications. The 2002-03 season is the first that they have used variable rate application technology. They have used this technology over all their cotton country to apply products including gypsum, phosphorus, potassium and zinc.

Auscott “Midkin” agronomist Justin Ramsay explained their interest in managing the soils on “Midkin” which are sodic at depth, resulting in patches exposed by leveling. Variable rate applications provide an opportunity to concentrate gypsum applications on the cut areas where it is most needed. Yield mapping, used on “Midkin” over the last couple of seasons, was related back to laser leveling and cut and fill maps to help identify contributing factors for low yielding areas. The cut and fill maps were used as the basis for the variable rate gypsum applications and soil tests were then carried out to assist with determining the appropriate rates. Similarly, phosphorus was also applied to cut areas, as due to the immobility of this nutrient, levels were low in the cut areas.

The main advantage of this technology is reduced application costs, which will then be put back into production e.g. a more balanced nutritional program. The initial costs associated with setting up variable rate application technology are quite high. However, these initial outlay costs should be recovered through use of the technology, through increased yields in previously lower yielding areas and reduced costs.

In the future they hope to use this technology to apply nitrogen at variable rates. The aim of this would be to hopefully reduce some of the in field variation in the crop between the head ditch and tail drain and reduce costs associated with growing an uneven crop.

Justin advises growers who are interested in variable rate application technology to be cautious and look into the various options available. There are many different units available so ensure that you shop around and speak to others that have used the technology. Ideally fields should be leveled and yield mapped. This technology has the scope to be used with many crops other than cotton, something “Midkin” would like to try on their dryland country in the future.
Our investigations have demonstrated the reality of variation of yields within fields and from season to season, and that there are potential economic and environmental benefits from this relatively easily obtainable information. Importantly, we found that the technology to measure variability is adequate, even for small areas or sample sizes. From a potential management perspective, these yield patterns are relatively stable and can be predicted using a number of different sources. With the continual development of a wide range of technologies there is an opportunity to optimise the management of many aspects of the cotton farming system. This will lead to the variable-rate application of fertilisers, herbicides, insecticides, defoliants, growth regulators and seed, all of which will potentially increase profitability and reduce negative environmental aspects associated with their application.

Furthermore, research to date has highlighted just some of the applications of using this technology. There are many other applications of this technology. Information obtained from yield mapping, remote sensing, soil sensing techniques and DEMs can be used to solve many problems. The applications of remote sensing are endless. These include the early detection of in-season nutrient deficiencies, pest outbreaks, water stress, problem sprays, rank growth, and defoliation efficiency. Soil electrical conductivity sensing systems have the potential to provide fine-scale high quality maps of soil properties such as texture, the cation-exchange capacity and soil moisture. Post-season, a yield map can be utilised for targeted sampling of problem regions within a field to correct localised deficiencies or take nonproductive areas out of cotton.

One of the most prominent arguments against SSCM is that the costs associated with the additional data collection and technologies are prohibitive. The validity of such an argument is questionable. Technologies associated with SSCM are being developed with greater capabilities at comparatively lower prices. If a grower wishes to pursue some form of SSCM, such as a zone management, this need not be a costly or prolonged process. Meaningful management zones can be established across farms using satellite imagery from which further investigations can commence. Costs
for this data could be further diminished by neighbouring growers purchasing the data as a consortium. We also suggest that an appropriate economic model is used to assess the benefits of SSCM. A complete criterion would encompass all aspects of the SSCM concept: spatial and temporal variability of yield, profitability of the agricultural enterprise, sustainability of the resource base (soil and water), environmental issues and the value of information (Ancev et al., 2004). These criteria may be designed specifically for different management hypotheses (e.g. uniform, zone and continuous management) and assessed.

The authors would urge the industry to consider developing the integrated system as a realistic and scientific method of optimising inputs and building further on the recent progress made by the industry in minimising the environmental impact of cotton farming. For growers considering the technology we offer the following advice:

**Best implementation strategy for precision agriculture (PA) in cotton**

The best implementation strategy for farmers looking to incorporate PA management techniques is possibly best separated into two categories. Firstly, those farmers who are aware of variability within their fields and are prepared to invest in PA immediately to manage the variability and secondly, the farmer who is unsure of the extent of variability within fields and is more interested in characterising the fields rather than moving directly into management.

**Immediate applications of PA would involve:**

**Field elevation mapping and analysis** to evaluate the quality of the level within a field. Analysis would involve the collection of high quality elevation data which would then be made into a digital elevation model (DEM). Analysis of this DEM could involve the creation of a perfect level/plane for a field and the calculation of the extent of local cut and fill which would be required to “brush” it back into a more evenly watering condition. These analyses, performed on multiple fields, may be used to prioritise re-levelling operations towards fields or parts of fields most warranting remedial action.

**Digitising and geo-referencing of development (cut and fill) records** to be used as a guide for directed soil sampling and potential soil ameliorative management zones where a clear relationship is identified between cut and gypsum requirements.

**Soil EC mapping** to identify soil electrical conductivity variability within a field to act as a guide to subsequent soil sampling surveys. This EC data layer, when calibrated, could then be used as an indication of soil type variability within the field and subsequently be included in data layers combined to create potential management zones.

**On-farm field experimentation:** Any ameliorative action or variable-rate application
of inputs applied as a result of these information layers should be applied in such a way that analysis of yield (or other important agronomic factor) may be used to assess the success or failure of the application. These field trials should include controls and alternative management strategies which will be of value to managers at the end of the season calculating the economic benefit of their actions.

**Cotton yield estimates:** In order to obtain the results of field experiments, the farmer will need to obtain cotton yield data. This could either be sourced from a properly calibrated proximal yield monitor or from a calibrated remotely sensed image of sufficient spatial resolution to identify the desired trials. If yield estimates are sourced from aerial imagery, the opportunity exists to explore the observed variability prior to the end of the growing season. Field scouting directed from the within field vigour map may be used to better direct agronomic inputs (such as plant growth regulator (pix) application or timing of cut-out/defoliation sprays), or as a guide to yield risk management whereby management effort is weighted towards areas of greatest yield potential. Under this methodology, insect checking would be allocated weighted on potential production (1 check to 100 bales) not simply on geographic spread (3 checks/100 ha).

**Evaluation of the variability observed within-fields as a guide towards the potential application of PA management techniques:**

**Yield Mapping:** Farmers interested in investigating the spatial variability of cotton yield within their own fields as a first stage to evaluating the potential suitability of PA to their farming system, should obtain yield maps for their most variable fields. These could be obtained by either buying or renting a proximal yield monitor for the picker harvesting their field, or by obtaining remotely sensed yield estimates. These yield estimates can then be evaluated by the farmer who can quantify in bales or dollar terms the impact that the within-field variability is having on their fields. If not significant, they can apply their management focus elsewhere, confident that their un-investigated but apparently less variable fields are likely to be less suitable to PA techniques than the variable ones. If the field investigated is variable then the manager can seek to apply the management techniques outlined above.

**Training in PA or employment of PA consultants:** Under both contingencies, it would be advisable for farmers wishing to adopt PA management techniques to either participate in PA training courses or employ consultants to assist with data gathering, analysis and interpretation thereby maximising the potential for appropriate management techniques to be applied.

**Future Research Priorities**

As the concept of SSCM is only embryonic in the cotton farming systems context, there are many potential areas of investigation that could significantly improve the profitability and long-term sustainability of the industry. Research needs to be undertaken to tackle some key agronomic questions site-specifically, especially weed control and irrigation management; and the whole area of lint-quality
mapping within fields needs to be opened up. Additionally, greater attention needs to be paid to the farm as a whole. Most precision agriculture studies reported to date have been done on single fields. Many studies consider several fields but almost always on different farms. The challenge for precision agriculture is to become an integral part of the normal farming process. Therefore we should like to see all fields on a farm managed in a precision way. Taking the example of zone management, we would like to be able to recognise the classes of soil and agronomic properties and their spatio-temporal expression across a whole farm. We need to be able to do this cost effectively at large scales. This is a research challenge. Once this is done, farmers can decide on those fields which are most suitable for precision management and the cropping regimes for the various parcels.

Finally, we would urge the industry to consider the following research objectives to expand on the current understanding and management of spatial variability in Australian cotton farming systems:

- Investigations into the variable-rate application of pesticides. Immense within-field variation in the vegetative growth of the crop canopy suggests that it will require different amounts of insecticides, defoliants and growth regulators. The large yield differences between the management zones in our research fields also intimates that some areas of the field may have a higher affinity for attracting pests.

- Field-scale trials into the variable-rate application of phosphoric fertilisers and gypsum. It was evident in several research fields that phosphorus and gypsum were required in vastly different quantities across the field.

- An investigation into the variable-rate application of herbicides as it has been documented that the behaviour of pre-emergence herbicides is strongly influenced by soil type.

- An investigation into how much cotton quality varies within single fields and how this can be managed to improve the overall quality.

- An examination of variable-rate irrigation technology for the industry.

- An exploration of remote sensing technologies to aid in site-specific cotton management. Remotely-sensed data can be utilised for: the early detection of in-season nutrient deficiencies, to identify pest outbreaks or water stress, correct problem or missed sprays, and to assess defoliation efficiencies.

- An examination of the EM, VERIS and other similar soil sensing systems for providing surrogate data for the creation of high-resolution maps of soil properties such as texture, cation-exchange capacity and soil moisture for SSCM.

- An investigation into the use of picker-mounted yield maps to guide targeted soil sampling within a field to correct localised deficiencies or take non-productive areas out of cotton.
REFERENCES AND RELATED READING

Chapter 1


Chapter 2


Development of an on-the-go soil sensing system for determinations of soil pH and lime requirement. On: CD-rom Proceedings of the 7th International Conference On Precision Agriculture and Other Precision Resources Management, Minneapolis 2004. ASA, CSSA, and SSSA, Madison, WI.


Chapter 3


Chapter 4

Cotton Cooperative Research Centre, Narrabri, NSW, Australia.


Chapter 5


Books, Journals & Popular Magazines

Those interested are urged to seek out more research information provided by the Australian Centre for Precision Agriculture (http://www.agric.usyd.edu.au/acpa/) and many others in the following journals and books.
The Leading Edge Supplement
Agricultural Engineering and Precision Agriculture Issues (inc. in Australian Grain/ Australian Cotton Grower/ Australian Sugar Cane)
Published by: Greenmount Press, P.O. Box 766, Toowoomba, Queensland, 4350, Australia.

@gInnovator
Popular On-Line Journal - Covers all areas of precision ag and moderates a wide ranging discussion forum
Published through: Successful Farming: @griculture Online.

Modern Agriculture (quarterly)
A Journal for Site-Specific Crop Management
Published by: Modern Agriculture Inc, 13741 E. Rice Place, Suite 200, Aurora, CO 80015.

AgroPrecise (quarterly)
An Independent Journal for Precision Agriculture
Published by: Herbert Daybell Publications, Devon Farm, 14 Grantham Rd, Bottesford, Nottingham, NG 13 ODF, UK.

Precision Agriculture (triannually)
An International Journal on Advances in Precision Agriculture
Published by: Kluwer Academic Publishers, Journals Department, P.O. Box 358, Accord Station, Hingham, MA 02018-0358, USA.

Computers and Electronics in Agriculture
An International Journal
Published by: Elsevier Science B.V., P.O. Box 1527, 1000 BM Amsterdam, The Netherlands.

Advances in Agronomy (Volume 67): Aspects of Precision Agriculture (84 pages)
A well referenced review of the developments in PA
Published by: Academic Press 525 B Street, Suite 1900, San Diego, California 92101-4495, USA.
Automated Agriculture for the 21st Century (540 pages)
Proceedings of the 1991 Symposium
Published by: American Society of Agricultural Engineers, 2950 Niles Rd, St Joseph, Michigan 49085-9659, USA.

Soil-Specific Crop Management (395 pages)
Proceedings of the 1st International Conference on Precision Agriculture (1992)
Site-Specific Management for Agricultural Systems (993 pages)
Proceedings of the 2nd International Conference on Precision Agriculture (1994)
Precision Agriculture (1222 pages)
Precision Agriculture (2 volumes, 1938 pages)
Proceedings of the 4th International Conference on Precision Agriculture (1998)
Precision Agriculture & other Resource Management (CD containing PDF files)
Proceedings of the 5th International Conference on Precision Agriculture (2000)
Proceedings of the 7th International Conference on Precision Agriculture (2004)
Published by: American Society of Agronomy, 677 South Segoe Rd, Madison, Wisconsin 53711, USA.

Precision Agriculture '97 (2 volumes, 997 pages)
Papers presented at the 1st European Conference on Precision Agriculture (1997)
Published by: BIOS Scientific Publishers, 9 Newtec Place, Magdalen Road, Oxford OX4 1RE, UK.

Precision Agriculture '99 (2 volumes, 987 pages)
Papers presented at the 2nd European Conference on Precision Agriculture (1999)
Published by: Sheffield Academic Press, Mansion House, 19 Kingfield Road, Sheffield S11 9AS, UK.

ECPA 2001 (2 volumes, 970 pages)
Papers presented at the 3rd European Conference on Precision Agriculture (2001)
Published by: agro Montpellier - Genie Rural, 2 place Viala, 34060 Montpellier cedex 2, France.
ECPA 2003 (783 pages)
Published by: Wageningen Academic Publishers, The Netherlands.

The State of Site-Specific Management for Agriculture (430 pages)
Invited chapters based on a 1995 symposium organised by the Soil Science Society of America and the North Central Regional Committee on Site-Specific Management.
Published by: American Society of Agronomy, 677 South Segoe Rd, Madison, Wisconsin 53711, USA.

Precision Agriculture in the 21st Century: Geospatial and Information Technologies in Crop Management (149 pages)
Report by the Committee on Assessing Crop Yield: Site-Specific Farming, Information Systems and Research Opportunities. National Research Council
Published by: National Academy Press, 2101 Constitution Avenue, N.W., Lockbox 285, Washington DC 20055, USA.

Precision Agriculture: Spatial and Temporal Variability of Environmental Quality (251 pages)
Papers presented at an International Symposium on Precision Agriculture, Wageningen, The Netherlands, 1997
Published by: John Wiley & Sons, Baffins Lane, Chichester, West Sussex PO19 1UD, England.

The Precision Farming Guide for Agriculturists (117 pages)
A general, well organised guide to the basics of Precision Agriculture
Published by: John Deere Publishing, 374 John Deere Rd, Moloine, Illinois 61265-8089, USA.

Precision Farming Profitability (132 pages)
Focuses on profitability assessment for PA management. Also provides succinct reference chapters for the enabling technologies.
Published by: Site-Specific Management Centre, Purdue University, 1150 Lilly Hall, Room 3458, West Lafayette, Indiana 47907-1150, USA.

Other papers and articles on Precision Agriculture in Australia can be found by searching the Australian Bibliography of Agriculture.
Glossary of Precision Agriculture Terms

- **Active Sensing Systems** - Remote sensing systems which measure the characteristics of a reflected signal generated from an object bombarded with a signal from the sensor. *e.g.*, radar.

- **Aerial Photography** - Remote sensing technique in which either an orbital satellite or aircraft records a photograph of a portion of the Earth’s surface.

- **Archive** - The storage of historical records and data collected over a number of years. *e.g.*, The Landsat data archive stored since the 1980’s.

- **ASCII** - (American Standard Code for Information Interchange). A standard coding system used for identifying alphanumeric characters within a computer.

- **Aspect** - The horizontal direction that a slope faces.

- **Attribute Value** - A numerical measure of a spatial element.

- **Band** - A discrete interval of the electromagnetic spectrum between two wavelengths measured by remote sensing systems.

- **Baud Rate** - A measure that describes how rapidly single digital elements are transmitted over a communications line.

- **Bit** - An abbreviated term for binary digit, the smallest unit of computer data.

- **Block Kriging** - A spatial interpolation method used to predict unknown values at unsampled sites by appropriately weighting the known values at sample sites based on grid cells.

- **Byte** - A unit of computer storage of binary data usually comprising eight bits, and equivalent to a character.

- **Carrier** - An encoded radio frequency signal in which information is transmitted.
- **Carrier-Phase GPS** - High accuracy GPS units which measures geographic position based on the L1 or L2 carrier signal as opposed to code-phase GPS which use the pseudo random code.

- **Centroid** - The position at the centre of an entity. e.g. the middle of a 2-dimensional object such as a polygon, but could also be the middle of a n-dimensional object.

- **Channel** - The necessary circuitry for a GPS receiver to receiver signals from a single GPS satellite.

- **Choropleth Map** - A map which shows regions or areas which have the same characteristics, such as a yield map, where quantitative spatial data is depicted by different colour variations of yield ranges.

- **Classification** - The process of assigning individual pixels of a digital image to classes based on spectral reflectance.

- **Clustering** - A number of different algorithms for classifying spatial and temporal data into groups of a similar kind.

- **Coarse Acquisition (C/A)** - A unique code for each GPS satellite that is accessible by the public for single and group use.

- **Continuous Management** - A management system in which agricultural inputs are applied to a field on a point-by-point basis.

- **Coefficient of Variation (CV)** - A measure of the relative dispersion of an attribute and is simply the standard deviation divided by the overall mean.

- **Contour Line** - A line drawn on a map connecting a set of points all of which have the same value.

- **Decision Support System (DSS)** - A system that is capable of integrating diverse data sources with expert knowledge and decision models to aid in the making strategic decisions.

- **Differential Correction** - The correction of the GPS signal to make it more accurate. This requires a secondary GPS receiver, called a base station, placed at a point of known position. The base station then measures bias errors that are used to correct bias errors at the location of interest. There are three common ways to access a correction signal from a base station.

  1. A marine beacon.

  2. A satellite provided by a specialised GPS operator.

  3. **Wide Area Augmentation System (WAAS)** used in the US.
- **Digital Elevation Model (DEM)** – A digital representation of the continuous variation of elevation over space.
- **Digital Terrain Model (DTM)** – A digital terrain model representing the continuous variation of ground-level land surface over space.
- **Electromagnetic Radiation (EMR)** – Energy that is reflected or emitted from objects in the form of electrical and magnetic fields.
- **Electromagnetic Spectrum** – All the wavelengths of electromagnetic energy including visible light, infrared light, ultraviolet light and radio waves.
- **Enhanced Thematic Mapper (ETM)** – A passive sensor carried on Landsat 7.
- **Expert System** – A computer program that uses techniques normally associated with a human expert such as knowledge, heuristics and inference to solve a narrowly defined set of problems.
- **Extrapolation** – The prediction of the value of a variable outside the measured range or an inference of the value of a variable.
- **Geocode** – A code representing a spatial element which describes its location incorporated into a GIS.
- **Geographic Data** – Data which records the shape and location of a feature as well as associated characteristics which define and describe the feature.
- **Geographic Information Systems (GIS)** – A computerised database designed to efficiently capture, store, update, manipulate, analyse, and display all forms of geographically referenced information.
- **Georeferenced Data** – Spatial data that pertains to a specific location on the earth’s surface.
- **Georeferenced System** – A coordinate system keeping track of specific points on the Earth's surface. An example of such a system is the Universal Transverse Mercator system (UTM).
- **Global Positioning System (GPS)** – A network of 24 radio-transmitting satellites developed by the US Department of Defence to provide accurate geographical position fixing.
- **Grid** – A data structure that uses a set of grid cells forming a regular, or nearly regular, tessellation of a surface to represent an area like a field.
- **Ground Control Point (GCP)** – An easily identifiable feature with a known location that can be used with other GCPs to geometrically correct an image.
- **Ground Truth** - The collection of information on the Earth’s surface at the same place and time as a remote sensor gathers data. This permits the interpretation and calibration of remotely sensed data sources such as a yield maps.

- **Guidance System** - A system of equipment for automatically guiding the path of a vehicle.

- **Hyperspectral Sensor** - A sensor capable of simultaneously measuring hundreds of individual wavelengths of the electromagnetic spectrum.

- **Image Rectification** - The process by which an image or grid is converted from image coordinates to real-world coordinates.

- **Interpolation** - The process of predicting unknown values between neighboring known data values.

- **Inverse Distance Weighting** - A spatial interpolation method that assigns greater influence to known samples closer to a desired location.

- **ISFET** - Ion-selective field effect transistor. A semiconductor sensor integrating an ion selective electrode with a field effect transistor to measure membrane voltage changes caused by fluctuations in different ions.

- **Kriging** - A method that interpolates data from a known set of sample points to a continuous surface by assigning a set of weights to the samples based on a semivariogram model, the locations of the samples relative to each other, and to the point or block being estimated.

- **Landsat (Land Satellite)** - A series of unmanned earth-orbiting satellites used to study the earth’s surface.

- **Latitude/Longitude** - A polar coordinate system that specifically describes a position on the earth. Latitude is the north to south position. Longitude is the east to west position. Locations are described in units of degrees, minutes and seconds.

- **Map-Based Variable-Rate Application System** - A system which adjusts inputs based on a pre-made electronic map of the input using a differentially corrected positioning system to determine the applicator position in the field.

- **Map Projection** - A systematic transformation of locations on the spherical globe to locations on a flat plane while maintaining spatial relationships.

- **Mean** - The average of a set of data in which the values of all observations are added together and divided by the number of observations.

- **Mosaic** - The process of joining database files for adjacent areas into a single file or image.
- **Multispectral Sensor** – A sensor that obtains imagery from several different portions of the electromagnetic spectrum at one time.

- **Nearest Neighbour** – A spatial interpolation method whereby the predictions of attributes at unsampled points are provided by the single nearest data point.

- **Near Infrared (NIR)** – Portion of the electromagnetic spectrum lying near the red end of the visible spectrum. Wavelengths between 700-2500 nm.

- **Noise** – Random variations or error in a data set.

- **Normalised Difference Vegetation Index (NDVI)** – An index of vegetation biomass commonly used to estimate the potential yield of a cotton plant.

- **Nuclear Magnetic Resonance (NMR)** – A measurement technique capable of estimating volumetric soil moisture content.

- **Panchromatic** – A film sensitive to all or most of the visible spectrum, between 0.4 and 0.7 micrometres. Landsat 7 has a panchromatic band.

- **Passive Sensing System** – Remote sensing systems which receive the naturally emitted and reflected signals from sensed objects.

- **PCMCIA Card** – A removable card that is able to hold large quantities of data and able to withstand the harsh environmental conditions used by most yield monitors.

- **Pixel** – A term used in remote sensing which is an abbreviation for “picture element”. A pixel is simply the smallest picture element of a digital image. The smaller the pixels, the higher the resolution of an image.

- **Polygon** – A multisided figure that represents area on a map such as a similar yields range, land use or soil type.

- **Precise (P) Code** – Is a confidential pseudorandom code transmitted by GPS satellites.

- **Pseudorandom Noise (PRN)** – It is a regular binary sequence of code that has noise-like properties. It is merely measuring the distance to a satellite.

- **Pseudo Range** – It is a measurement of the true distance of a GPS receiver from a satellite.

- **Raster Format** – These are images that are represented by a matrix of row and column data points whose values which when taken together, describe the display of an image on an output device.
Real-Time Correction - The practice of correcting the GPS signal by immediately sending the differential correction information to a mobile receiver in use.

Real-Time Kinematic (RTK) - A procedure where carrier-phase corrections are transmitted in real-time from a reference receiver to a user's receivers.

Remote Sensing - The collection of information about an object, series of objects or landscape without being in physical contact with the object or event.

Scale - The ratio or fraction between the distance on a map, chart, or photograph and the corresponding distance on the ground.

Selective Availability (SA) - Adopted by the US Department of Defence to introduce some error into the GPS satellite signals to reduce their accuracy for civilian users. This policy was discontinued as of May 2000 and is now turned off.

Semivariance - A measure of how much neighbouring data points differ in value. Equal to half one-half the squared difference, it is used by the spatial interpolation technique of Kriging.

Semivariogram - A line fit to a graph plotting the semivariance against distance for Kriging.

Sensor-Based Variable-Rate Application Systems - Systems which create applications maps by processing field data collected from real-time sensors as the implement moves through the field to alter an input, on-the-go.

Site-Specific Crop Management (SSCM) - A management systems that takes into account the variability of crop and soil parameters to make decisions on the application of production inputs.

Spatial Prediction - This refers is any prediction method that incorporates spatial dependence.

Spatial Resolution - Refers to the size of the smallest object on the ground that an imaging system, such as a satellite sensor, can distinguish.

Spatial Variability - Is the differences in field conditions from one location to another in the same field.

Spectral Resolution - The capability of a sensing system to distinguish between electromagnetic radiation of different wavelengths.

SPOT - The name of a series of French satellites used to study the earth's surface.
Standard Deviation – A statistical term that tells how spread out numbers are from the average, calculated by taking the square root of the average of the squares of the deviations from the mean.

Temporal – Pertaining to time, such as temporal variation (variation over time).

Temporal Resolution – The time taken for a satellite to revisit the same location.

Thermal Band – The infrared wavelengths of the electromagnetic spectrum.

Thematic Map – A map depicting selected kinds of information relating to one or more specific themes such as yield or soil type.

Universal Transverse Mercator (UTM) – A commonly used planar coordinate system that uses a set of transverse mercator projections to divide the globe into 60 zones, each covering 6 degrees longitude.

Variable-Rate Application (VRA) – The adjustment of crop production inputs such as fertiliser to match conditions within a field.

Variable-Rate Technology – Instrumentation used for varying the rates of application of fertiliser, pesticides and seed as a spreader moves across a field.

Variance – A measure of dispersion of a set of data points around their mean value. The square root of the variance is the standard deviation.

Vector Format – A format where positional data is represented in the form of points, lines and polygons where each of these units is composed of a series of one or more coordinate points.

Yield Monitor – A system that gathers georeferenced yield data by measuring the mass or volume of a harvested crop per unit area, by location, within a field.

Zone Management – A management system in which a field is divided into different zones, based on production potential, for the application of agricultural inputs.