REPORT

on the

5TH INTERNATIONAL CONFERENCE on PRECISON AGRICULTURE

JULY 16-19, 2000
BLOOMINGTON, MINNESOTA

By

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The 5th International Conference on Precision Agriculture* was held in Bloomington, Minnesota from July 16 – 19, 2000. This conference brought together 698 delegates from around the world including representatives from commercial companies, researchers, farm managers, consultants and growers. The conference highlighted that an expanding number of companies are becoming involved in the development and application of technologies specifically for use in site-specific management systems. Researchers are using this technology to develop more economically and environmentally sound farming systems for an increasing number of crops worldwide. We presented papers on establishing an opportunity index for precision agriculture and the variable-rate application of nitrogen fertiliser to Australian cotton fields, which are included as Appendices 1 and 2 respectively. Full proceedings from the conference are now available. The following report summarises the advances in technology and the latest research that will be of interest to the Australian Cotton Industry.

Natural Resource & Yield Variability

Ping and Green (Texas Tech University, jping@ttu.edu) studied the spatial variability of yield and soil parameters in two irrigated cotton fields over two years in Texas. The coefficient of variation for lint yield was 22% and 25% respectively for Field 1 and 18% and 16% for Field 2. Growing season rainfall varied between the two years with elevation influencing the yield variation in the wetter year and soil calcium, potassium and water characteristics having the bigger influence in the drier year.

Van Es et al., (Cornell University, hmvl@cornell.edu) conducted a five year study on nitrate leaching in the New York area. Using different N rates on soil classified by drainage class the results showed strong yearly variations apparently related to early season precipitation. During the wetter years soil N availability was reduced by up to 50kg per hectare independent of soil type. These losses were attributed to leaching in the coarser soil types and denitrifcation in the fine-textured soil types. It is expected considerable gains may be obtained from side-dressing N based on early season weather conditions.

Ward and Cox (Mississippi State University, bward@pss.msstate.edu) studied cotton yield variation in two fields in Mississippi. The coefficient of variation in lint yield was 42% for the north field and 32% for the south field. Soil sampling of both fields determined that soil texture, phosphorus, potassium, magnesium and elevation were having the greatest influence on cotton yield.

Johnson and Barrow (Texas Tech University, rjohnson@nola.srrc.usda.gov) investigated the spatial pattern of yield and soil properties for a cotton field in

* Funding for conference travel and attendance kindly supplied by the Cotton Research & Development Corporation

Louisiana. The coefficient of variation was 43% (2 bales) and this occurred in some areas of the field over just 40 metres. All soil properties (nutrients and texture) had some spatial relationship at a sufficient range to benefit from site-specific management except pH. Soil organic matter was positively correlated to yield.

Managing Variability

Shapiro et al., (University of Nebraska) investigated alternate row irrigation and alternate row nitrogen fertilisation to combat an increase in nitrate contamination in groundwater in Nebraska due to leaching caused by furrow irrigation of crops. The nitrogen fertiliser in the alternate rows was applied at different rates based on spring soil nitrate and soil organic matter levels as well as at the traditional uniform rate. Alternate row irrigation reduced yield in cases of low rainfall (< 500mm) while both the uniform and variable-rate nitrogen application yielded the same. It was concluded that the algorithm for nitrogen application is too general for estimating site-specific requirement.

Bradow et al., (USDA, jbradow@nola.srrc.usda.gov) studied the possibility of using zoned management to improve lint yield and quality in upland cotton in South Carolina within a single field. A grid sampling strategy was used to measure soil fertility indicators and quality characteristics such as micronaire, fiber yellowness and whiteness and maturity. In the first season 26% of the fiber was outside the micron AFIS penalty range and 22% in the second season. Higher phosphorus and soil organic matter levels was associated with increased maturity and micronaire and with decreased fiber yellowness and increased fiber whiteness. Both these properties were negatively correlated with yield. It was concluded that zone management of this field had the potential to increase the end-use value of the cotton.

Campanella and Hood conducted a variable-rate seeding experiment based on within-field zones to reduce seed costs for cotton farmers. Similar geographic zones were identified within a field using remotely sensed data. The lowest seeding rate (39000/acre) produced the highest yield in all zones compared to seeding rates of 52000 and 65000 seeds per acre. When compared to these rates this represented 2 – 10% more yield, saved 31 – 66% in seeding costs and increased profit margins by 7 to 13%. Further investigation is required to determine if these rates can be further modified for each zone.

Li et al., (Texas A & M, ho-li@tamu.edu) studied the affect of field heterogeneity on cotton yield and nitrogen uptake in center irrigated cotton fields in Texas. Irrigation and nitrogen fertiliser rates were varied throughout the field. Each year yield increased significantly with increasing irrigation while N input had no effect on yield in a dry year but was significant when wet during the early vegetative stage. Lint yield was most related to soil water content, clay content and elevation.

Engineering Technology

Searcy and Beck (Texas A & M, s-searcy@tamu.edu) discussed the development of two cotton plant height systems that have been developed to allow the site-specific application of chemicals such as growth regulators and defoliants. As biomass is strongly correlated with plant height from emergence to full bloom, determining plant height throughout a field would allow varying amounts of chemical to be applied according to local variation in plant height. One sensor uses mechanical fingers that are activated when coming in contact with the plant. The second sensor system uses an optical arrangement of forty infrared beams. Both sensors were mounted on a toolbar and pulled behind a tractor through the field. The optical sensor had an accuracy of +/- 3cm while the contacting sensor had an accuracy of +/- 5cm both suitable for chemical application.

Sui et al., (Mississippi State University, rsui@abe.msstae.edu) have developed a laboratory system to simulate the pneumatic flow system found in pickers to examine yield monitor accuracy. The system is used to test the accuracy of yield monitoring techniques by varying cotton flow rate and airflow rate. Results to date have shown that sensor position in both direction of flow and cross-sectional direction is very important for sensor accuracy. An advanced optical sensor and non-optical sensor system is being developed for use in cotton yield monitors.

Remote Sensing

Seal et al., (ITD/Spectral Visions, mseal@iftd.org) investigated using remote sensing technology in Mississippi cotton fields to reduce chemical application costs by applying insecticides more efficiently throughout the field. Remote sensing was used to identify the most vibrant cotton plants, usually the most infested by Heteroptera Miridae, from which a variable-rate application map was produced. This approach resulted in 30-40% average reduction of insecticide applied with no negative impact on yield. Further experiments are being conducted.

Lough and Varco (Mississippi State University, jlough@pss.msstate.edu) used spectral reflectance and chlorophyll concentration in an attempt to determine plant nitrogen and potassium status in the early growth of cotton plants. Different rates of nitrogen and potassium fertiliser were applied prior to sowing. The plants were measured using aerial multispectral imagery and a spectroradiometer to calculate a number of vegetation indices. Utilising these techniques it was possible to diagnose the N status of cotton as deficient providing no other nutrients were limiting.

Campanella and Hood calculated 23 normalised difference vegetation indices (NDVI) (similar to Far Site) from airborne multispectral imagery over two years in two cotton fields. The results revealed that the lowest 20% and highest 20% of the NDVI's consistently yielded less than the middle 60%. Remedial action during the growing season could possibly include pix application to the higher NDVI values, associated with too much vegetative growth, and side-dress N for the lower NDVI values where there is not enough vegetative growth.

Li et al., (Texas A & M, ho-li@tamu.edu) conducted a two year study in Texas to determine cotton plant spectral response and relate this to cotton lint yield. The measured soil/plant reflectance was significantly affected by water input level and interaction between water and N inputs. Generated vegetation indices showed that crop-N and soil moisture varied spatially and considerably within a single field. The vegetation indices, lint yield and water stress in plants was strongly associated with topographical features. It was concluded that plant spectral response could be used to quantify the impact of natural landscape variability on crop water and N status.

Hendrickson and Han (CNH, larry.hendrickson@chn.com) examined the use of remote sensed imagery to detect mid-season N deficiency in corn. The aim was to make conservative N applications pre-sowing and then variably apply nitrogen as required latter in the season. Three different rates were applied pre-sowing as well as the traditional uniform application rate. N stress was quantified using one metre resolution aerial imagery and a side-dress of fertiliser applied. Grain yield and quality was generally increased using this map-based approach with large yield responses to mid-season N application. Supplemental N applications had little effect where N was in plentiful supply according to the imagery.

Beatty and Johannsen (Purdue University-LARS, beattym@purdue.edu) conducted an experiment in a corn crop grown under four different nitrogen fertiliser application rates to determine if airborne multispectral data could be used to identify nitrogen sufficiency levels throughout the growing season. A SPAD chlorophyll meter and corn leaf nitrogen samples were collected as a means of testing how well the airborne data was predicting nitrogen sufficiency. Excellent correlations were achieved between he SPAD meter and the original N rate and leaf tissue N. The airborne data was correlated with both the SPAD leaf chlorophyll and leaf tissue N. Preliminary results suggest that it will possible to assess nitrogen sufficiency levels throughout the season using this sort of technology.

Weeds

Biller and Schicke used an optoelectronic system that made use of sunlight radiated from the ground under the spray boom to apply herbicide only where weeds were present in the field. This was possible because of the spectral response radiated from the sunlight is different between weeds and useful crops even when they are randomly mixed within a field. Developing this technology offers the potential to significantly reduce the cost of herbicide application although more research is required.

Varner et al., (ITD/Spectral Visions, bvarner@iftd.org) discussed the use of multispectral and hyperspectral (100+ wavelengths) imagery to detect weeds in soybeans in Illinois. This was was conducted on three levels: identification of weeds from bare soil, identification of weed types and identification of individual problem species. Data was collected using both a hand held radiometer and remote sensing technologies. Results were promising for use as part of a variable-rate herbicide system.

Cole et al., (South Dakota State University, ccole@itetel.com) delineated weed management zones using elevation as previous studies have shown a correlation between certain weed species and landscape position. Weed grid sampling data collected over three seasons was used to compare mean weed densities in each of the zones. The results indicated that for three of the five weeds measured, elevation zones influenced weed densities.

Luschei et al., (Montana State University, eluschei@montana.edu) tested three methods of herbicide application in grain farming systems for controlling wild oats; no spray, broadcast spray and site-specific spray. On 4/5 of the sites the site-specific application of herbicide was the most economical method of controlling wild oats. Further research aims to incorporate varying dosage levels.

Dalsted et al., (South Dakota State University) used remote sensing to identify weed species in a 60 hectare corn field. Grid weed sampling of the field indicated that the remote sensing classification accuracy was greater than 70% when weed populations exceeded 20 per $0.1m^2$. Further methods are being investigated to improve the accuracy.

LaMastus et al., (Mississippi State University, llamastus@msstate.edu) examined the use of multispectral imagery to differentiate four weed species growing at different densities. Initial results indicate classification of weeds using spectral response properties is possible, although more research is required to develop classification parameters.

Poppen et al., (South Dakota State University) conducted greenhouse experiments to evaluate the spectral reflectance of six weed species as compared to corn and soybean spectral reflectance. The results indicated that using specific filters or hyperspectral data collection it may be possible to identify weed outbreaks within a field which could then be treated site-specifically.

Conclusions

The focus on site-specific management is being expanded to encompass many more aspects of the cotton farming system. This has been stimulated by the availability of more reliable cotton yield monitors and advances in technology that can be adapted to a number of agricultural industries. The major issues to come out of the conference concerning the cotton industry was:

- Greater use of 'management zones' to determine site-specific fertiliser requirement.

- Recognition of the potential for site-specific weed control. The research in this area while very encouraging is still in a very preliminary stage which requires much more research.

- Expansion of research on cotton farming systems from site-specific nutrient management strategies to also include:
  - water-use efficiency
  - variable-rate herbicide application for weeds
  - variable-rate insecticide application to combat pests
  - variable-rate application of defoliants and growth regulators
  - variable-rate seed application
  - preliminary investigations into the variability of cotton fibre quality within a single field

- Nitrate leaching is a major problem in many of the irrigated cropping systems. To combat this:
  - Alternative irrigation practices are being tried
  - More precise methods of estimating site-specific nitrogen requirement are being investigated
  - Side-dressing nitrogen fertiliser by predicting areas of deficiency within the field in season using remote or hand-held sensors

- Remote sensing techniques are being adapted to a greater number of uses in site-specific management. These include:
  - Detecting in-season cotton nutrient deficiency, especially nitrogen
  - Predicting pest numbers within a field
  - Controlling the amount of rank growth in cotton plants

- A significant cause of yield variation in cotton fields may be attributed to changes in elevation within the field.

APPENDIX 1

A MANAGEMENT OPPORTUNITY INDEX FOR PRECISION AGRICULTURE

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ABSTRACT

Many farmers are employing emerging technologies to characterise the variation in their production systems. The most common of these technologies are real-time yield sensors. Farmers, however, are often left wondering how the subsequent yield maps can be used to justify a change to a Precision Agriculture management philosophy. The Opportunity Index is an attempt to provide a pragmatic solution to this problem.

The Opportunity Index for Site-Specific Crop Management (SSCM) is conditional on three components: i) the magnitude of variation (CV_a) present in a yield map, relative to a given threshold; ii) the spatial structure (*S*) of yield variation, relative to the minimum area within which variable-rate controllers can reliably operate; and, iii) the economic and environmental benefit (*E*) of SCCM relative to uniform management.

Methods for assessing the magnitude and spatial structure of variation in yield maps are proposed. These methods are then incorporated into an Opportunity Index to predict the potential for SSCM. Results are encouraging however further research especially into the economic and environmental impact of SSCM is required before the Opportunity Index can be considered complete.

Keywords: Precision Agriculture, Opportunity Index, uniformity trials, yield variation

INTRODUCTION

From a farmer's perspective, a barrier to adoption of SSCM is deciding whether or not a crop displays enough variation, both in terms of magnitude and spatial structure to justify the cost of a shift from traditional (uniform) to site-specific (differential) management. A farmer's database of yield maps should provide the most significant clue towards the opportunity for SSCM. However while methods for quantifying yield variation do exist (discussed below), a way of quantifying the opportunity for SSCM has yet to be defined. This paper presents a first attempt.

Co-efficient of Variation

Perhaps the easiest and most common method currently employed is a 'Co-efficient of Variation' (CV) analysis. The relative magnitude of yield variation *could* be found by comparing CVs to a median value, however, we disagree with the use of a standard CV in this situation. Firstly, the CV is non-spatial and therefore potentially misleading when dealing with different sized areas (as illustrated by Fairfield Smith's work). Larger fields will, on average, have larger CVs for the same crop. Secondly, the CV tells nothing of the difference between autocorrelated yield variation (which is manageable), and uncorrelated ('nugget') variation (which is *not* manageable). The CV is therefore undesirable, and a better method of describing the magnitude of yield variation is needed.

Fairfield Smith's (1938) empirical law of yield heterogeneity

Secondly, the search for management opportunity through crop variation pointed to the work of Fairfield Smith (1938).

Fairfield Smith's empirical law of yield heterogeneity was derived from many uniformity trials. A uniformity trial is simply a field (or part thereof) treated with blanket applications of all agronomic inputs and subsequently harvested in small plots as if there were an experiment over the area (Mercer and Hall, 1911). These uniformity trials served as investigations into the resolution at which to perform effective agronomic management. Extending this concept into modern times, any uniformly managed field which is harvested with yield monitoring technology can be seen as a uniformity trial from which the opportunity for SSCM can be investigated. Fairfield Smith found that as the logarithm of area increased the logarithm of yield variation per unit area decreased linearly. The gradient of this relationship (*b*') was used as a heterogeneity coefficient that applied across all areas: the lower the absolute value of the gradient, the more heterogeneous the crop. It can also be thought of as relating to a fractal dimension (McBratney et al, 1997). It was reasoned that once *b*' was established for a field it could be used as an opportunity function for deciding future experimental plot sizes.

While useful for ranking crop yield variation, Fairfield Smith's methodology has some shortcomings if used as a measure of the potential for SSCM. The aggregation of individual 'plots' in a yield map is cumbersome and inefficient when applied to dense yield data. Furthermore, Fairfield Smith's empirical law cannot be expected to fully describe the variation present in crop yield because *b*' only relates the rate of change of variation with area. No consideration is given to either the magnitude of yield variation or the economic/environmental impacts. Thus on it own Fairfield Smith's empirical law is not ideal in describing the opportunity for SSCM.

The Variogram

Since the rise of geostatistics within the environmental sciences, the variogram has become another popular method of describing yield variation (*e.g.*, Perrier and Wilding, 1986; Mulla, 1993; Lark *et al.* 1999), mainly because it shows how variation *changes* (usually) through space. Variograms model variance as a function of separation distance between pairs of points. Pairs of points that have a greater lag should generally have a greater semivariance than those that are closer together. The reader is referred to Webster and Oliver (1990) and Isaaks and Srivastava (1989) for detailed explanations of the concept.

There are two primary problems with the use of variograms in explaining yield variation. As with the Fairfield Smith analysis, variograms do not give any indication of the magnitude of variation in relation to the mean or the economic/environmental impact. Furthermore variograms only represent distances not areas; thus they may not necessarily reflect the 'areal' structure of the variation.

AIMS

This paper aims to improve on the shortcomings of Fairfield Smith's method, the CV and the variogram by developing a SSCM Opportunity Index (O_c) based on yield monitor data. We propose that this O_c must account for three parameters of the production system:

- the *magnitude* of yield variation relative to some threshold;
- the area within which yield variation is autocorrelated (i.e. the *spatial structure* of variation) relative to the minimum area within which variable-rate controllers effectively operate; and,
- the *economic and environmental* benefit of SSCM relative to uniform management.

METHODS

Data Preparation

To establish a SSCM Opportunity Index, yield monitor data were gathered for 5 types of crop grown in Australia: wheat, grapes, cotton, lupins, and sorghum. Data from 20 harvests were recorded for 16 fields in the period 1995–1999 (some fields are represented more than once). All crops were managed using the traditional, uniform approach to ground preparation, sowing rates, and fertiliser and pesticide applications.

As much as possible, output from the various yield monitors has been trimmed of doubtful data, *e.g.*, distribution and spatial outliers, and crop headlands. Although dependent on the crop and yield monitor, generally data outside ± 3 standard deviations from the mean yield were regarded as distributional outliers and eliminated. Spatial outliers (arising from the loss of differential correction signal to the GPS) and crop headlands (where the harvester changes direction, leaving an undesirable artifact in the yield map) are more problematic and, as such, usually removed according to one's enthusiasm for the task. This illustrates the need for the development of automated yield correction procedures (*e.g.*, those presented by Blackmore and Moore, 1999; Lars and Antje, 2000)

Definition of Components

It is proposed that the opportunity for SSCM will be a function of i) the magnitude of variation present in a yield map, relative to a certain threshold; ii) the spatial structure of yield variation, relative to the minimum area within which variable-rate controllers can reliably operate; and, iii) the economic and environmental benefit of SCCM relative to uniform management. The following section gives a detailed description of how these components have been quantified.

Magnitude (*M*)

Obviously one of the main constraints to SSCM is the magnitude of the variation within the field. If variation ranges from 2.4 to 2.6 Mg/ha, with a mean of 2.5, there is little opportunity for differential management (unless the crop is of very high value). If however another field with a mean of 2.5 Mg/ha has a variation in yield from 0.5 to 4.5 Mg/ha there would seem to be a strong case for SSCM. A large magnitude of yield variation should allow greater differentiation between input applications, hence greater economic and environmental benefits in comparison to uniform management.

The method for quantifying this magnitude of variation presented here is an 'Areal coefficient of variation' (CV_a). This is a method of standardising the previously non-spatial CV to an area and is based on the double integral of the yield variogram. In this case, because we are only interested in autocorrelated variation, the C_0 parameter was excluded from the integration. The CV_a procedure is outlined here.

Variograms were made of the raw yield of each field and fitted, weighted by *m* at each lag (McBratney and Webster, 1986), exponential, spherical, double exponential, double spherical and power models. If there was a trend in the variogram (*i.e.*, no obvious sill), the maximum range was constrained to 1000 m, which thereby forced a sill upon the variogram. The fit of the models was assessed using the Akaike Information Criterion (AIC) (after Webster and McBratney, 1989). The parameters from the model with the best fit (lowest AIC) were (numerically) double-integrated (minus the C_0 parameter) to the standardising area (*V*). This area was selected as 1000ha and considered the upper limit of field size. The numerical definition of the double integration is (after Journel and Huijbregts, 1978: Goovaerts, 1997):

$$\bar{\gamma}(V) = \approx \frac{1}{N^2}\sum_{i=1}^{N}\sum_{j=1}^{N}\left[\gamma(\mathbf{x}_i - \mathbf{x}_j) - C_0'\right], \qquad (1)$$

where: $\bar{\gamma}(V)$ = average autocorrelated yield variation within the block of size V
N = number of points that discretise V;
$\mathbf{x}_i$ = a discrete point in V; and,
$\mathbf{x}_j$ = any other discrete point in V.
C0 = nugget variance of yield variogram

The square root of $\bar{\gamma}(V)$ was then divided by the field's mean yield and multiplied by 100 to obtain the CV_a:

$$CV_a = \left(\frac{\sqrt{\bar{\gamma}(V)}}{\bar{Y}} \right) 100, \qquad (2)$$

where: $\bar{Y}$ = mean yield

The 50% quantile (q_{50}) or median CV_a of all the fields was found, and used as the quantity against which to compare the magnitude of autocorrelated yield variation. Therefore the magnitude of yield variation can be expressed as:

$$M = \left(\frac{CV_a}{q_{50}(CV_a)} \right) \qquad (3)$$

In Equation 3, the division of CV_a by its median effectively states that the opportunity for SSCM will be increased if a crop is more variable than what is usually observed. Using $q_{50}(CV_a)$ as a value against which to make comparisons is the 'best guess', given present knowledge. It is assumed that 50% of the fields in the study will display enough variation for SSCM. With more experimentation into within-field variability, site-specific input response and experience in variable-rate technology, $q_{50}(CV_a)$ will be replaced by $q_\alpha(CV_a)$, a minimum CV_a. This $q_\alpha(CV_a)$ will define the magnitude of variation below which uniform treatment is advisable

Spatial structure (*D*)

The second consideration when evaluating the potential for SSCM is the spatial distribution of yield variation. A strong spatial structure is desirable because variable-rate controllers, which physically implement SSCM, operate at maximum efficiency when proposed application patterns are smooth and broad. While trended yield maps may be highly desirable for SSCM, problems do arise when trying to analysis such data. The manifestation of trend in a yield map's variogram will imply that the average autocorrelation area of yield is infinite, which will lead to extremely large (and potentially unrealistic) opportunities. To reduce this effect a trend surface was fitted to the data to calculate the average area within which yield was autocorrelated and the resultant residuals used for analysis. Although dependent on the size of the field, yield monitor data is usually so abundant that a reasonably complex trend model can be afforded; hence a fourth-order model was used here.

$$Y(E,N)=\begin{pmatrix}\text{Int.}+E+N+E^2+N^2+EN+E^3+N^3+E^2N+\\ EN^2+E^4+N^4+E^3N+E^2N^2+EN^3\end{pmatrix}+\varepsilon, \qquad (4)$$

where, E = Easting coordinates of yield (with minimum subtracted to prevent numerical overflow);
N = Northing coordinates of yield (again, with the minimum subtracted);
$Y(E,N)$ = yield as a function of its Eastings and Northings;
Int. = intercept of regression;
ε = error term (residuals).

Empirical variograms were made of the trend surface residuals, and fitted with the four *bounded* theoretical models, exponential, spherical, double exponential and double spherical. The best-fitting model was again found by the AIC. This model of spatial variation was then used to find the 'areal scale' in hectares of the yield residuals (J_a). Russo and Bresler (1981) employed this 'integral scale' concept to determine the spatial dependence of soil hydraulic properties. We have adapted Russo and Bresler's (1981) idea to approximate the average area within which the residuals of a yield trend-surface are autocorrelated:

$$J_a \approx \frac{\left\{2\int_0^\infty\left(1-\frac{\gamma(h)}{(C_0+C_1+C_2)}\right)hdh\right\}}{10000}, \qquad (5)$$

where: $\gamma(h)$ = theoretical variogram of yield residuals;
C_0, C_1, and C_2 = parameters of the residual theoretical variogram (if the best fitting model was not a 'double', C_2 was equal to zero);
A divisor of 10000 is used to standardise J_a to a hectare.

Equation 5 converts the best-fitting residual variogram model into an equivalent correlogram. This procedure requires that the variogram have a sill (hence the use of residuals from the trend surface and theoretical models with finite sills).

The proportion of total yield variance explained by the quartic trend-surface (P_t) is calculated. Because a trend-surface is theoretically autocorrelated to an infinite area, a limit must be employed; this was chosen as the area of each field (A). Multiplying P_t by A gives the contribution of the trend surface to the average area within which yield is autocorrelated. Multiplying J_a by (1- P_t) provides the contribution of the residuals. Adding these two terms together produces the average area within which yield is autocorrelated (S)

$$S = (P_t A) + (1 - P_t) J_a. \quad (6)$$

Now let s be an estimate of the minimum area (in hectares) within which variable-rate controllers can reliably operate. It is calculated as:

$$s = \frac{(\beta v \tau)}{10000}, \quad (7)$$

where: β = width of application swath (m);
v = speed of vehicle (m/s);
τ = time required to alter application rate (s).
A divisor of 10000 is used to standardise s to a hectare.

Values of these parameters are given in Table 1 and are based on personal experience with variable-rate applicators. It was necessary to distinguish between grapes and the four other crops used in this study because viticulture operates within much smaller areas than broadacre cropping.

Table 1. Parameter values for the determination of *s*.

Parameter	Grapes	Other crops
β (m)	6	20
ν (m/s)	3	6
τ (s)	3	3

The contribution of the spatial structure of yield variation to the potential for SSCM can therefore be calculated as,

$$D = \frac{S}{s}, \quad (8)$$

Equation 8 effectively states that the opportunity for SSCM will be increased when farm machinery can operate within the average area within which yield is autocorrelated; if this is not the case then SSCM is hardly feasible.

Economic/environmental benefit (*E*)

At present, little is known about the nature of parameter E, and it has therefore been assumed constant (= 1) in this study. Future studies into the opportunity for SSCM will benefit from knowledge of E but it is a topic that requires further research. Some of the factors that E must consider will be short- and long-term economic goals, the on-farm and off-farm environmental impact of management practices, government legislation and a changing consumer preference.

By combining the three parameters and applying a square root function to remove skewdness in the data, (logarithmic transforms were tried but proved too powerful), an interim continuous Opportunity Index is produced:

$$\mathrm{O_c} = \sqrt{\left(\frac{CV_a}{q_{50}(CV_a)}\right)\left(\frac{S}{s}\right) E} = \sqrt{M \bullet D \bullet E} \qquad (9)$$

RESULTS AND DISCUSSION

Descriptive details of the 20 yield-monitored fields are given in Table 2. The CV_a and J_a values of the 20 fields are shown in Table 3. Also shown are the proportions of total yield variation that is contributed by the quartic trend-surface (P_t), the average area within which yield is autocorrelated (S), the limitation of variable-rate technology (s), the SSCM Opportunity Index (O_c) and finally the Fairfield Smith b' value. Fields have been sorted in order of decreasing O_c.

The values of O_c in Table 3 range from 2.8 to 47.2, with the median equal to 19.3. A range of parameter combinations for CV_a, $q_{50}[CV_a]$ J_a, P_t, and A, with resultant O_c, were simulated in an 8^6 factorial arrangement (results not shown) to determine the probable range of O_c values. The median O_c of this factorial trial was 16.6, with 90% of the distribution being less than 95; it takes an extraordinary combination of parameter values to gain an O_c above this.

Scaled yield maps for ten of the studied fields are shown in Figure 1. They are ranked in decreasing order of opportunity. Fields with the largest O_c had significant magnitudes of trend in the yield data. As O_c decreases, so does the contrast between high and low yielding sub-regions of fields, such that C9-11 (a grape field), with the lowest O_c of all the fields, exhibits something akin to white noise.

Temporal fluctuations in O_c size are worth noting. The 1996 and 1998 seasons at West Creek (Fig. 1f-g) displayed less opportunity than in 1997 (Fig. 1e). The differences in these yield maps, which are reflected in their O_c, have been attributed to rain – both 1996 and 1998 recorded above normal within-season rain, whereas 1997 experienced little. In drier years crop production is dependent on stored soil moisture thus soil texture/available soil moisture become important yield determining factors. The large triangular feature on the left of Fig. 1e is a red ridge of lighter textured soil running through a field of predominantly heavy clay. In wetter years (1996 and 1998) there was sufficient within season rain to continually replenish soil moisture thus the effect of texture is not as dominant. This field illustrates an important point in determining management zones and opportunity: it is unlikely that a single season's yield maps will characterise the expected variation in most crop fields. Single seasons have been used here just to illustrate the method.

Figure 1 is an interesting case because, while it has the largest magnitude of O_c, it presents one of the pit-falls of this method: the effect of natural disasters. The yield of Maidens in 1995 was severely affected by frost. The low mean yield lead to a very large magnitude of CV_a (74.7%) which, when coupled with a trend (which is strongly correlated to topography and frost damage), has given the illusion of a large opportunity for SSCM. Spatial catastrophes – such as frost, waterlogging, and insect damage – may appear disguised as spatial opportunity. Local knowledge is necessary for correct interpretation of the O_c value.

The point-to-point accuracy of yield monitors is also acknowledged as a significant contributor to the validity of the O_c assessment procedure. As with any analysis the outcome is dependent on the quality of the data that is entered into the model. Noisy or poorly calibrated monitors will produce erroneous values.

The last column of Table 3 presents each field's *b*' value The range of *b*' is from 0.44 (Rowlands 5) to 0.89 (C9-11). Interestingly, the three grape fields recorded the three largest *b*' values. Fairfield Smith reported *b*' values for wheat of 0.44–0.72; our values of *b*' for wheat, even though from much larger fields, are very similar and range between 0.44–0.76. When the O_c and *b*' are compared, a moderate negative correlation is found (r = -0.43).

As mentioned in the Methods, $q_{50}(CV_a)$ is currently a 'best guess' of the minimum magnitude in yield variation ($q_\alpha CV_a$) that is needed for SSCM to be viable. Differences in both crop type and production systems will require that $q_\alpha(CV_a)$ be determined for each unique production area. For example wheat growers in Western Australia with yields of 1 Mg/ha may consider 0.4 Mg/ha a significant increase whilst European growers, averaging more than 7 Mg/ha may not. Similarly minimum threshold values for a winegrape crop yielding 25 Mg/ha will differ from the wheat growers in Western Australia. Further research needs to be conducted to determine ($q_\alpha CV_a$) for a range of crops and production systems.

Ultimately, it is envisaged that limits will be set to the O_c, whereby one can decide whether there is a 'high', 'medium' or 'low' opportunity for SSCM. At this stage, any proposed limits are only tentative, however subjective appraisal of the yield maps in Figure 1 suggests that an O_c of 20 represents a threshold above which SSCM is more viable than uniform management.

In the future, as our database of information grows, a number of years of data may be analysed to provide a mean O_c. It is also envisioned that different layers of information (*e.g.* yield estimates from remote sensing (Boydell and McBratney) will be combined to form an 'integrated variation map' that may be analysed for the opportunity of SSCM. Thus opportunity may be judged on the variability of the entire production system and not just yield. This may allow the O_c to shift from a retrospective to a predictive assessment of production variation.

Finally, having established that there *is* an opportunity for a change in field management practices, the next step is to ask what component(s) of management can be changed. This requires a more detailed investigation of site-specific crop variation that can only be achieved through field-scale experimentation (Gotway Crawford *et al.* 1997; Cook *et al.* 1999) and continued crop monitoring.

CONCLUSIONS

Without the backing of information, many farmers may feel reluctant to change their traditional agronomic practices. A database of yield maps contains a vast amount of information that can be utilised to assess the opportunity for Site-Specific Crop Management.

While searching for a method to quantify the opportunity for SSCM, the empirical law devised by Fairfield Smith (1938) was initially applied to yield monitor data, but was found lacking. The SSCM Opportunity Index offers greater possibilities.

The Opportunity Index calculated for 20 fields showed that no particular crop is suited to SSCM over another. There is evidence of temporal instability in the values of O_c for a given field. Perhaps several seasons of crop data are needed before stability in O_c is found. This is a subject that requires more work, but unfortunately, at this stage of SSCM's development, very few fields have more than five years of yield maps.

A tentative proposal is that an O_c greater than 20 suggests a good opportunity for changing one's management practices to SSCM, although further research is needed to justify this recommendation.

Further information on the application and development of the O_c can be found in a paper by Pringle *et al.* (submitted).

ADDENDUM

A Management Zone Opportunity Index

As defined above, O_c is a 'continuous' management index. It does not imply management zones. Since current PA technology may be more effective when applied in a management-zone rather than a continuous context, a management-zone opportunity index (O_{zs}) should be defined.

Briefly, an index based on statistical parsimony (Lark, in press) derived from the Akaike Information Criterion could be used:

$$AIC = n \bullet \ln(RMS) + 2p \quad (10)$$

where:
- n = the number of observations
- RMS = the residual mean square for the model fit
- p = the number of parameters in the fitted model.

In this context we can write it as:

$$O_{zs}(z) = 2z - n \bullet \ln(r^2) \quad (11)$$

where:
- z = the number of zones or spatial units in the field.
- r^2 = the fit of the model

In this situation z is not the number of classes that might be fitted by a (fuzzy) k-means algorithm but rather the number of discrete contiguous spatial zones. These contiguous spatial zones can be formed by including the spatial co-ordinates as well as the yield in the numerical classification. For this paper Eastings and Northings were added as variables to ensure zones were single entities. (N.B. these zones are not the same as treatment classes. While individual zones may be discrete treatment classes, other treatment classes may be composed of two or more zones (that are spatially discrete from each other). An additional 2 zone model determined "by eye" (E_2) was also added (discussed later). For the example we have chosen West Creek 1997 as it has a high O_c and the large feature on the left hand side indicates it is suitable for zone management. For this analysis the headland artifacts shown in Figure 1e were removed manually to the best of our ability.

The goodness of fit of the zone models (in describing yield variation) was determined from the r^2 of a one-way analysis of variance model. The use of n is problematic however, because it is the number of independent observations. For this discussion the method of Bishop *et al.* (in press) has been adapted to raw yield data to determine n using 5000 data points. The number of zones (z), which minimises O_{zs}, can be regarded as optimal.

From Table 4 we can see that O_{zs} becomes asymptotic after 7 zones indicating that there is little benefit in managing additional zones. The amount of variation accounted for in the management zones can be determined by comparing the yield variogram to that of the residuals. In this case a spherical model has been fitted to the yield data and the exponential model to the residual data. There has been no penalty imposed to models with more parameters, thus as the number of zones increases the amount of variance explained by the model increases and the sill decreases.

Figure 2 shows the variograms for the yield and residuals from the ANOVA for 5, 6 and 7 zone models. The area between the sills of the yield and the individual residual variograms can be considered representative of the amount of variation explained by the zonal models. Taking the variance at 1000m, the 5, 6, and 7 zone models explain 51%, 63% and 67% of the variation in yield respectively. These numbers are comparable to the r^2 derived from the ANOVA of the cluster means however they also include a spatial component.

Table 4. Estimates of Opportunity for managing different numbers of zones for West Creek 1997.

z	n	r^2	O_{zs}	O_{zi}
1	112	0	∞	-
2	112	0.002	389.51	2.99
3	112	0.061	189.67	6.70
4	112	0.181	158.87	9.54
5	112	0.484	140.09	13.64
6	112	0.582	124.57	13.63
7	112	0.616	49.86	12.98
8	112	0.660	48.82	12.56
9	112	0.692	49.33	12.12
10	112	0.700	48.84	11.57
E_2	112	0.257	156.17	15.73

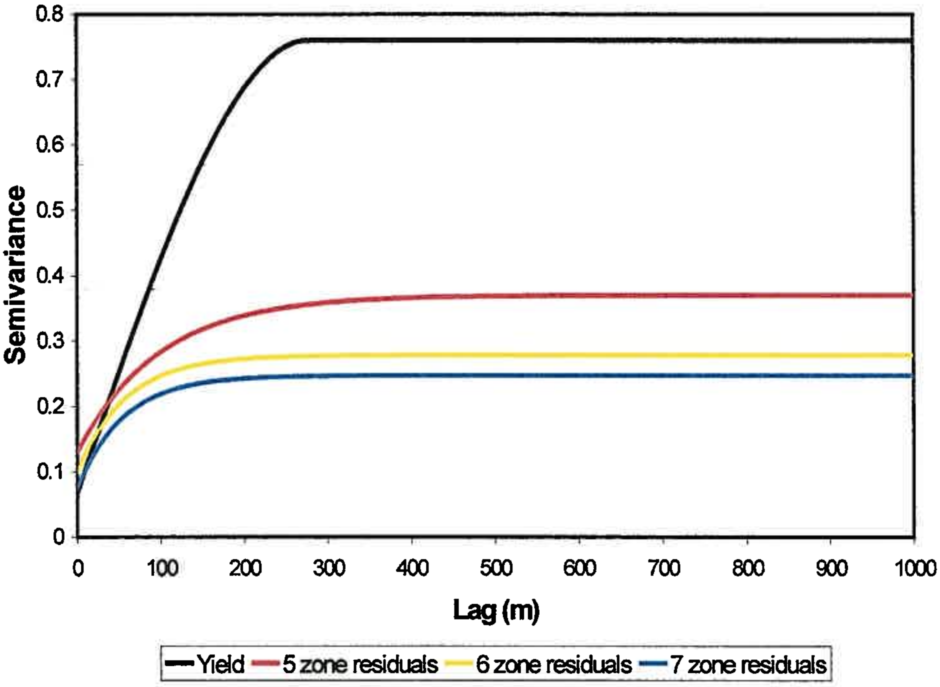

Figure 2: Variograms of Yield and Residuals from the ANOVA between management zones.

While determining which model best describes variation the calculation of O_{zs} does not take into account issues such as differences between means of zones, gross margins etc. Ideally a better opportunity index would be an economic one (O_{ze}), measured in dollars (per hectare):

$$O_{ze} = \sum_{i=1}^{z} \left[\frac{G_i}{A_i} \right] \tag{12}$$

where A_i = the area of zone i.

G_i = the gross margin for zone i which is calculated from;

$$G_i = P_i - C_i - F_i \tag{13}$$

Where: P_i = value of production

C_i = agronomic cost of production

F_i = environmental cost of production (which is still difficult to calculate).

Here the assumption is that the zones are suitable for PA. This time, the optimal z is the number that maximises O_{ze}.

Currently, it may be difficult to obtain all the data to calculate O_{ze} but developing methods to obtain these data should be an aim of further research. In the meantime, we might think of using a compromise between the statistical and economic indices, which is really what our O_c is. If we replace S in Equation 8 by

$$S(z) = r^2\left[\frac{A}{z}\right] + J_a\left[1 - r^2\right] \quad (14)$$

it is possible to calculate O_{zi}, which should be maximised. Results of this are presented in Table 4. O_{zi} values indicate that the optimal number of management zones in this field is either 5 or 6 (less than that indicated by the O_{zs} analysis). It should be noted that these values cannot be compared directly to the O_c values as they are situated on a different scale. From Figure 3, diagrams with only 3 and 4 zones are reflecting the heavy weighting of the spatial coordinates in the analysis thus have poor r^2 values when compared with the yield. When compared with the yield map, diagrams with 5, 6 and 7 zones highlight the main management zones in the field. Diagrams with 8 or more zones are starting to identify small areas in the field, which are probably not viable units with current variable-rate technologies.

In this field we would expect two management zones to have a reasonable opportunity due to the large feature on the left-hand side. However the heavy weighting with spatial coordinates in the numerical classification negates this in the 2 zone model. By applying expert knowledge we can segregate this feature into z_1 and specify the rest of the field as z_2 and analyse this model (E_2). The r^2 for the ANOVA between z_1 and z_2 is 0.257 significantly higher than the 2 and even the 3 and 4 zone model derived using yield and spatial coordinates in Table 4. Plotting the variogram of the residuals against the yield shows that this minimal segregation already accounts for 28% of the variation in yield.

The O_{zi} for this model (15.73) is the highest of any of the models due to S_z being weighted to minimise zones. As expected two large discrete contiguous zones provide a good opportunity for PA. Whether it should have a higher O_{zi} than a more complex model that better fits yield variation is a point for further research and discussion. The r^2 O_{zs} and O_{zi} values from E_2 highlight the need for a better algorithm for deriving the discrete contiguous zones.

The authors would like to emphasis that this is only a preliminary model and presented here as an example. Considerable work still needs to be done especially on the development of a zonal algorithm. Further we would like to reiterate that while this analysis has been done on a field for one year, data from several years will be necessary before a true indication of the opportunity will be known.

ACKNOWLEDGMENTS

We acknowledge the Australian Grains Research and Development Corporation (GRDC) and Australian Cotton Research and Development Corporation (CRDC) for supporting this research.

We should like to thank Dr. Simon Cook of CSIRO Land and Water in Perth Agriculture for permission to use the Wyalkatchem data, and Craig and Judy Boydell (at Moree), Doug and Noela Maitland (at Wyalkatchem), Peter Glennie (Norwood), Nick Barton (Telleraga) and Orlando-Wyndham (Cowra) for access to their fields.

Thanks to Broughton Boydell for his helpful discussion.

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Table 2. Summary statistics of the fields used for development of the opportunity index.

Crop	Location	Field	Year	~ Area (ha)	Mean yield (Mg/ha)	Std. dev. yield (Mg/ha)	CV (%)
Wheat	Moree, NSW	B4	1995	8	1.90	0.73	38.4
Wheat	Moree, NSW	East Creek	1997	77	3.86	1.45	37.6
Wheat	Moree, NSW	Maidens	1995	88	0.96	0.78	81.3
Wheat	Moree, NSW	West Creek	1996	80	5.40	0.67	12.4
Wheat	Moree, NSW	West Creek	1997	80	3.69	0.92	24.9
Wheat	Moree, NSW	West Creek	1998	80	5.58	0.95	17.0
Wheat	Wyalkatchem, WA	Home 1	1998	61	1.83	0.47	25.7
Wheat	Wyalkatchem, WA	Home 5	1998	40	1.09	0.38	34.9
Wheat	Wyalkatchem, WA	Rowlands 1	1995	75	1.49	0.52	34.9
Wheat	Wyalkatchem, WA	Shire 4	1997	64	1.09	0.24	22.0
Wheat	Wyalkatchem, WA	Shire 4	1999	64	2.25	0.45	20.0
Grapes	Cowra, NSW	C3-8	1999	14	21.76	7.02	32.3
Grapes	Cowra, NSW	C9-11	1999	2	24.13	4.98	20.6
Grapes	Cowra, NSW	D3-4	1999	6	20.37	6.97	34.2
Cotton	Moree, NSW	Norwood 28	1998	42	2.33	0.63	27.0
Cotton	Moree, NSW	Telleraga 10	1998	97	1.76	0.38	21.6
Lupins	Wyalkatchem, WA	Blackies 6	1998	51	1.08	0.35	32.4
Lupins	Wyalkatchem, WA	Home 8	1997	30	0.54	0.16	29.6
Sorghum	Moree, NSW	East Creek	1996	77	6.90	1.07	15.6
Sorghum	Moree, NSW	W80	1997	42	4.21	1.02	24.2

Table 3. Parameters used in the determination of the opportunity index.

Field	Crop	Year	CV_a (%)	J_a (ha)	P_t	S (ha)	s (ha)	O_c	b'
Maidens	Wheat	1995	74.7	0.074	0.330	29.101	0.036	**47.2**	0.57
Home 5	Wheat	1998	47.9	0.118	0.589	23.627	0.036	**34.1**	0.44
C3-8	Grapes	1999	36.7	0.038	0.293	4.135	0.005	**33.5**	0.88
D3-4	Grapes	1999	43.1	0.003	0.364	2.187	0.005	**26.4**	0.86
Blackies 6	Lupins	1998	26.2	0.301	0.491	25.174	0.036	**26.0**	0.65
Rowlands 1	Wheat	1995	30.4	0.108	0.251	18.927	0.036	**24.3**	0.60
Home 1	Wheat	1998	28.1	0.220	0.314	19.308	0.036	**23.6**	0.55
W80	Sorghum	1997	26.7	0.026	0.473	19.885	0.036	**23.3**	0.67
West Creek	Wheat	1997	21.7	0.300	0.266	21.489	0.036	**21.9**	0.52
Shire 4	Wheat	1997	20.1	0.050	0.287	18.397	0.036	**19.5**	0.70
Telleraga 10	Cotton	1998	18.3	0.112	0.202	19.702	0.036	**19.2**	0.70
East Creek	Wheat	1997	29.9	0.076	0.137	10.622	0.036	**18.0**	0.64
Shire 4	Wheat	1999	17.0	0.094	0.289	18.561	0.036	**18.0**	0.70
West Creek	Wheat	1996	10.6	0.074	0.245	19.632	0.036	**14.6**	0.76
East Creek	Sorghum	1996	29.9	0.076	0.204	15.866	0.036	**13.4**	0.77
West Creek	Wheat	1998	10.3	0.035	0.199	15.918	0.036	**13.0**	0.74
Home 8	Lupins	1997	24.9	0.054	0.183	5.548	0.036	**11.9**	0.78
Norwood 28	Cotton	1998	15.3	0.043	0.141	5.946	0.036	**9.7**	0.77
B4	Wheat	1995	37.2	0.019	0.271	2.178	0.036	**9.1**	0.62
C9-11	Grapes	1999	7.6	<0.001	0.068	0.136	0.005	**2.8**	0.89

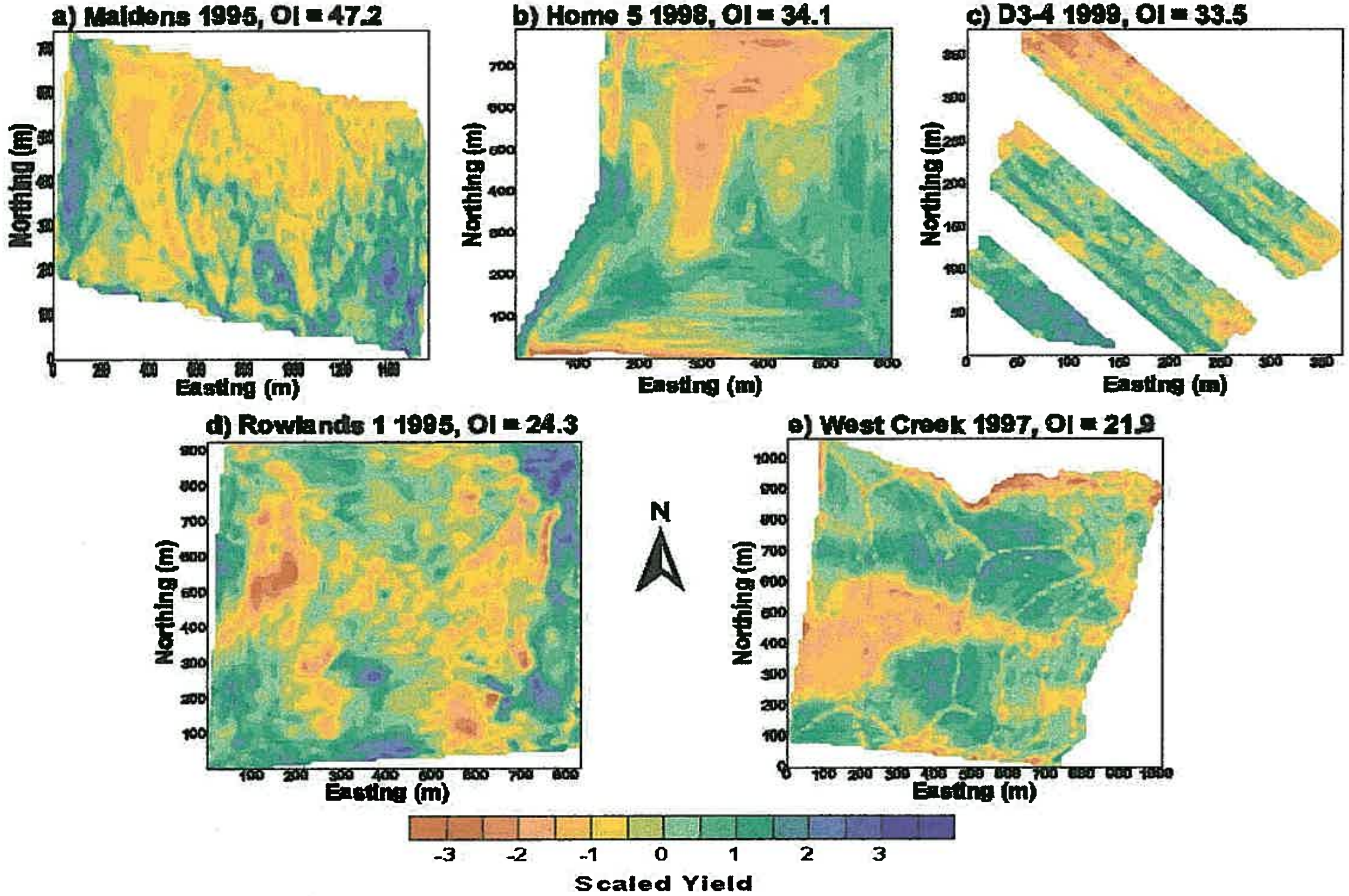

Figure 1(a-e). Scaled yield maps of fields used in the determination of the O_c.

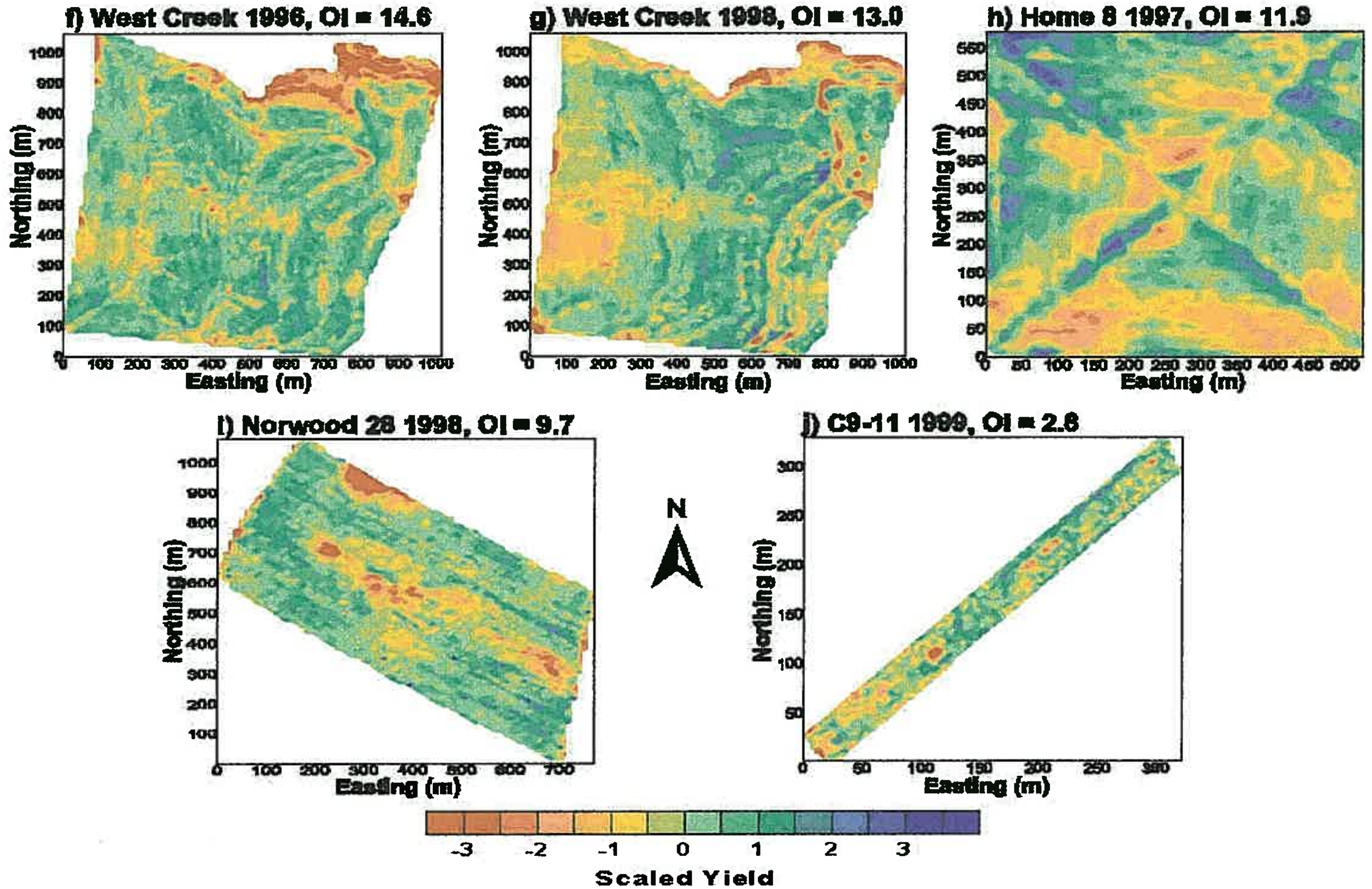

Figure 1(f-j). Scaled yield maps of fields used in the determination of the O_c.

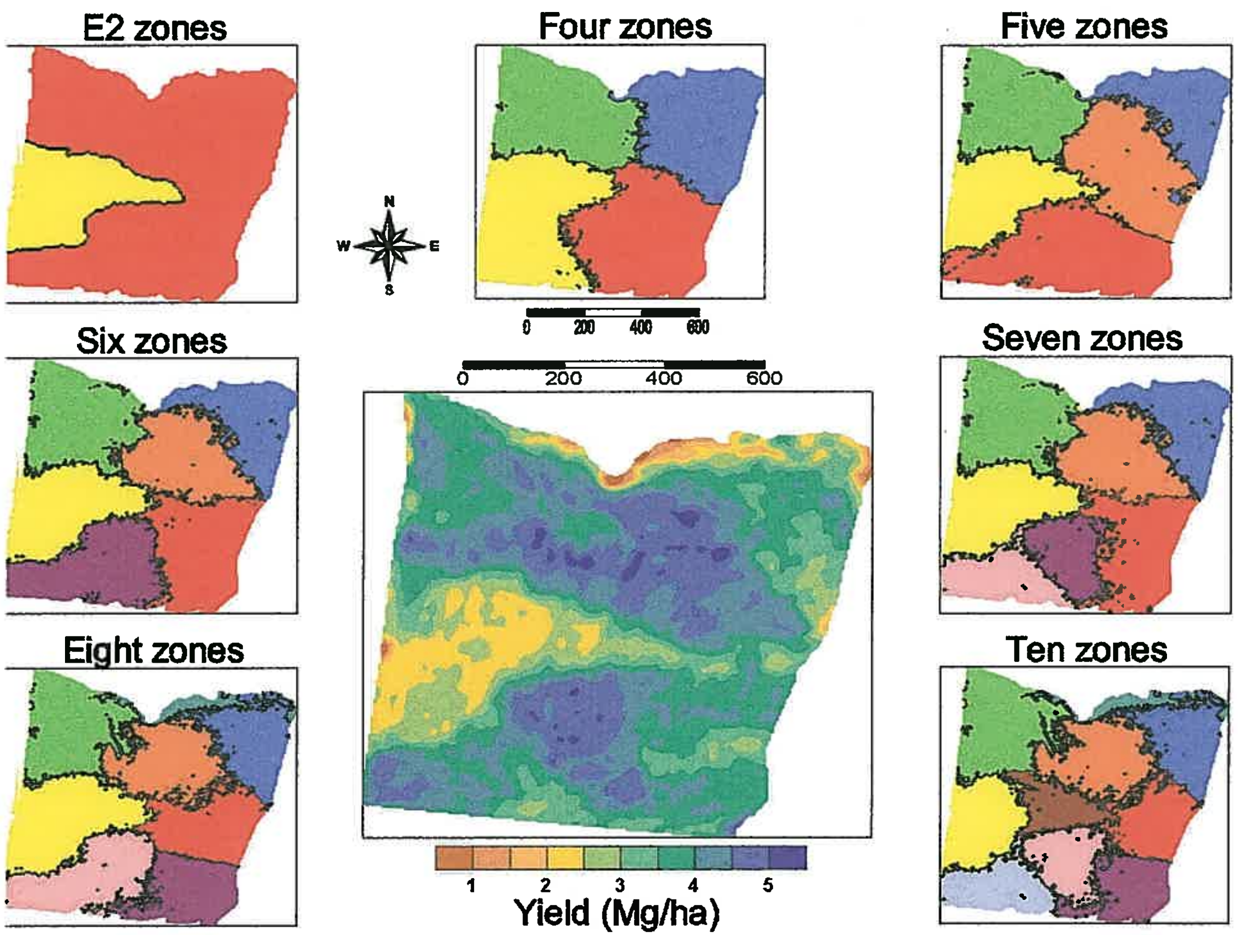

Figure 3. Cluster maps of Yield, Eastings and Northings showing the spatial distribution of potential management zones. 2, 3 and 9 zone models not shown.

APPENDIX 2

DEVELOPMENT OF A METHODOLOGY FOR THE VARIABLE-RATE APPLICATION OF FERTILISER IN IRRIGATED COTTON FIELDS

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ABSTRACT

The technology to apply different rates of fertiliser within a single field has existed for some time, however methods for determining fertiliser rates at this scale are still problematic, especially for irrigated cotton in Australia. A majority of the research in variable-rate fertiliser application has focused on either developing 'nutrient budgets' for a crop based on pre-sowing soil nutrient levels and crop nutrient uptake or by identifying similar regions within a field termed 'management zones' from both spatial and temporal data sources. This study has examined the suitability of both these methods for determining site-specific nitrogen fertiliser recommendations for cotton in Australia. Measurement of pre-sowing soil nitrogen levels from directed soil sampling of each field based on yield maps and soil electrical conductivity data enabled a nitrogen fertiliser requirement map to be developed using response curves for yield versus fertiliser generated for the local area. Secondly, multivariate clustering of a number of data layers was used to determine homogeneous zones within the field which then received fertiliser based on the yield potential of each zone. Both methods were implemented simultaneously within a field as well as the traditional fertiliser approach used by the grower as a means of comparison. No benefit in terms of yield was achieved with either variable-rate approach compared to the uniform approach, however the results indicated there is potential for variable-rate fertiliser application when more appropriate fertiliser recommendations for site-specific application exist.

Keywords: **variable-rate fertiliser, management zones, nitrogen management**

INTRODUCTION

An area in which the development of technologies associated with precision agriculture is expected to bring significant benefit is through the variable-rate application of fertilisers. Correct determination of local fertiliser requirement will result in more efficient fertiliser use, which has positive impact both economically and environmentally. The success of a variable-rate fertiliser strategy is dependent on the generation of accurate application maps. How best to achieve this has not yet been established with any degree of certainty. In fact, the results from uniform versus variable-rate fertiliser trials to date have been varied, especially when nitrogen management has been the focus. Broadly classified, these trials have taken either a 'nutrient budget' approach or 'management zone ' approach for the generation of the necessary fertiliser application map.

The 'nutrient budget' approach, also referred to as a 'balance sheet' method, relies on pre-sowing soil testing to replenish essential nutrients to a level which will maximise economic optimum yield (Ferguson et al., 1996; Robert et al., 1996; Herget 1997; Yang et al., 1999; Leclerc et al., 1999; Ferguson et al., 1999). Generally, this assumes an expected uniform yield for the field, adjusted site-specifically by the soil test results. Yang et al., (1999) reported higher average sorghum yield at the 0.10 significance level for variable-rate nitrogen compared to uniform, but this did not offset the fertiliser costs. Both Ferguson et al., (1999) and Herget (1997) used soil organic matter in conjunction with soil nitrate levels to produce application maps but neither showed any yield benefit over the uniform approach. Hergert (1997) did however report a trend towards decreasing soil nitrate residues. Robert et al. (1996) used soil depth in addition to soil mineral nitrogen and also obtained no significant difference in yield for barley and wheat between the classical and variable-rate approach. The suitability of this approach for calculating nitrogen fertiliser requirement has been questioned. Unlike both phosphorus and potassium levels which can be calculated on simple nutrient balances, the complexity of the nitrogen cycle may make this approach inadequate for estimating nitrogen requirement (Ferguson et al., 1996; Engel, 1997).

An alternative approach to developing a nutrient budget, is the identification of a series of homogeneous units within a field according to their yield potential, commonly termed 'management zones.' This involves coalescing a number of spatial data sources such as yield maps, remotely sensed images, aerial photographs and soil maps to form a fertiliser application map with a different rate for each zone (Peters et al., 1999; Welsh et al, 1999; Fleming et al., 1999). These data sources are usually supplemented by coarser soil sampling than the intensive grid approach, thus addressing some of the concern associated with cost. Fleming et al., (1999) used a bare soil colour map and farmer knowledge to determine low, medium and high productivity regions within a field. Subsequent testing indicated these zones correlated satisfactorily with yield maps, soil conductivity maps and nutrient status. Welsh et al., (1999) used three years of normalised yield maps to identify high and low yielding regions within a field finding different yield response curves to nitrogen application between both regions. Similarly, Peters et al., (1999) using soil texture as a basis for distinguishing soil type zones found different response curves to nitrogen between both soil type and the year grown. Analysis showed using the correct response curve for each region would have brought about an economic benefit from applying variable-rate fertiliser.

Irrigated cotton in Australia is typically grown on vertisols and relies on the application of nitrogen fertiliser to achieve satisfactory yields. At present, rates are estimated by either a 'Rule of Thumb' approach based on the crop rotation and the previous yield or from a response curve for the local area using a pre-sowing soil nitrate test of bulked samples from within the field. A computer-based decision support program called CottonLOGIC has been developed which provides growers with these nitrogen fertiliser recommendations using the soil nitrate test procedure. Potentially, the benefits from adopting a variable-rate approach to nitrogen application could be substantial due to the necessary reliance on nitrogen fertiliser.

The aim of this research is to test both the 'nutrient budget' and 'management zone' approaches as a basis for variable-rate nitrogen application for cotton against the traditional uniform application approach determined using either the 'Rule of Thumb' or CottonLOGIC method.

MATERIALS AND METHODS

At the conclusion of the 1998/99 growing season, two irrigated fields for which their cotton yield maps displayed substantial variability were selected as the trial sites for the 1999/2000 season. Both fields are typical of the heavy-cracking clay soil (Usterts) on which irrigated cotton is predominately grown on the plains of northwestern New South Wales. Site 1, is a 99 hectare field on a property called 'Oakville' while Site 2 is a 100 hectare region of a 240 hectare field on a property called 'Auscott Midkin'. A trial of this size was thought necessary as Australian cotton fields are typically in this size range.

An electromagnetic (EM) survey using both a Geonics™ EM38 and Geonics™ EM31 was used to estimate the soil apparent electrical conductivity (EC_a) for the root-zone and subsoil respectively. This survey was conducted using a mobile system designed to produce detailed within field maps (Triantafilis and McBratney, 1998). Assuming uniform soil moisture content and negligible soil salinity, the EC_a can be related to soil texture, mineralogy and nutrient status. Additionally, at Site 1 a Landsat 5 satellite image representing yield estimates collected during the 1998/99 growing season based on the normalised difference vegetation index (NDVI) was also available.

Management Zone Determination

Forms of multivariate clustering have been used to establish within field regions displaying similar properties (Lark and Stafford, 1997; Fleming et al., 1999). In this case, the non-hierarchical, hard clustering technique, k-means was used on the yield map, EM maps and the satellite map (Site 1 only) to delineate management zones for each site. It was assumed this would indicate areas of analogous yield potential, based on the intrinsic variability in the soil texture and mineralogy. The number of management zones for each site was determined by selecting the number of zones that gave a mean yield difference of approximately one bale (227kg) per hectare between the zones. This gave:

Site 1: Zone 1: Low Yield (1385 kg ha^{-1}), V.High EM values (197-222 mS m^{-1})
Zone 2: High Yield (1566 kg ha^{-1}), High EM values (197-199 mS m^{-1})

Site 2: Zone1: Med Yield (1203 kg ha^{-1}), Med EM Values (132-167 mS m^{-1})
Zone2: Low Yield (976 kg ha^{-1}), High EM values (143-177 mS m^{-1})
Zone3: High Yield (1362 kg ha^{-1}), Low EM values (115-146 mS m^{-1})

Soil Analysis

Soil sampling used a targeted strategy based on the management zone map for each site. It was decided to take 100 samples, as this is both a minimum for a reliable variogram (Webster and Oliver, 1992) and secondly gives a density of one per hectare, commonly used for variable-rate map making (Griffen, 1999). Instead of a grid sampling approach, sample locations were determined using a centroid sampling scheme similar to that described by Brus et al. (1999). It was hoped this method would allow for better spatial interpolation of the soil properties. Soil was collected six weeks prior to sowing and composited for 0-30cm depth as this is the standard procedure for estimating nitrogen fertiliser requirement from soil nitrate-nitrogen levels in the Australian cotton industry. Soil nitrate, Total N, pH, phosphorus, potassium, sodium, calcium and magnesium were measured.

Experimental Design and Rate Determination

The soil nitrate concentration for each sample location was entered into the CottonLOGIC program (ACCRC staff, 1999), which selects a response curve to estimate fertiliser requirement depending on the region, time of soil sampling and an estimate of soil structure. Using block kriging, a fertiliser application map was generated from the CottonLOGIC estimates (nutrient budget approach). After consultation with the grower at each site, rates were assigned to each management zone based on expected yield potential using a 'higher yield higher fertiliser rate' approach to create an alternate map (Table 1). At Site 1, the historical or 'Rule of Thumb' approach was used as the uniform rate, in this case 180 kg ha^{-1}. For Site 2, the CottonLOGIC approach of taking the average value of all soil samples was used as the uniform rate, 150 kg ha^{-1}. Therefore, three application maps were generated for each site.

A 36 metre wide by 50 metre long grid was then placed over each of the maps (approximately 560 plots), as the fertiliser spreader was 12 metres in width, thus ensuring each plot would contain three passes. Each plot was assigned a treatment letter determined randomly for the first three plots. This was 'A' for uniform, 'B' for nutrient budget and 'C' for management zone map (Figure 1). From this, an application map for each site was created by selecting the average fertiliser requirement value for each plot from the map corresponding to the treatment letter (Figure 2).

Table 1. **Nominated Fertiliser Rates for Each Zone**

	Site 1 - Oakville	Site 2 - Auscott
Zone 1	140 kg ha^{-1}	150 kg ha^{-1}
Zone 2	170 kg ha^{-1}	170kg ha^{-1}
Zone 3	-	130 kg ha^{-1}

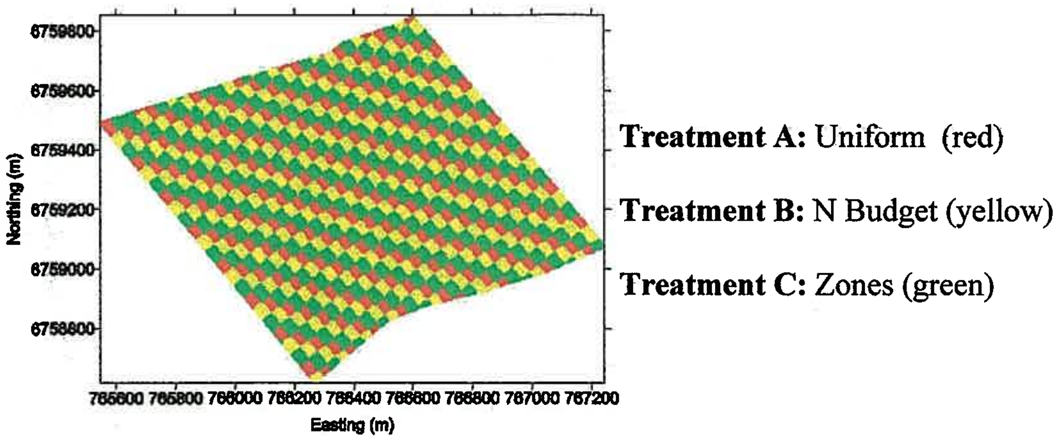

Figure 1. Experimental design used to generate nitrogen fertiliser map

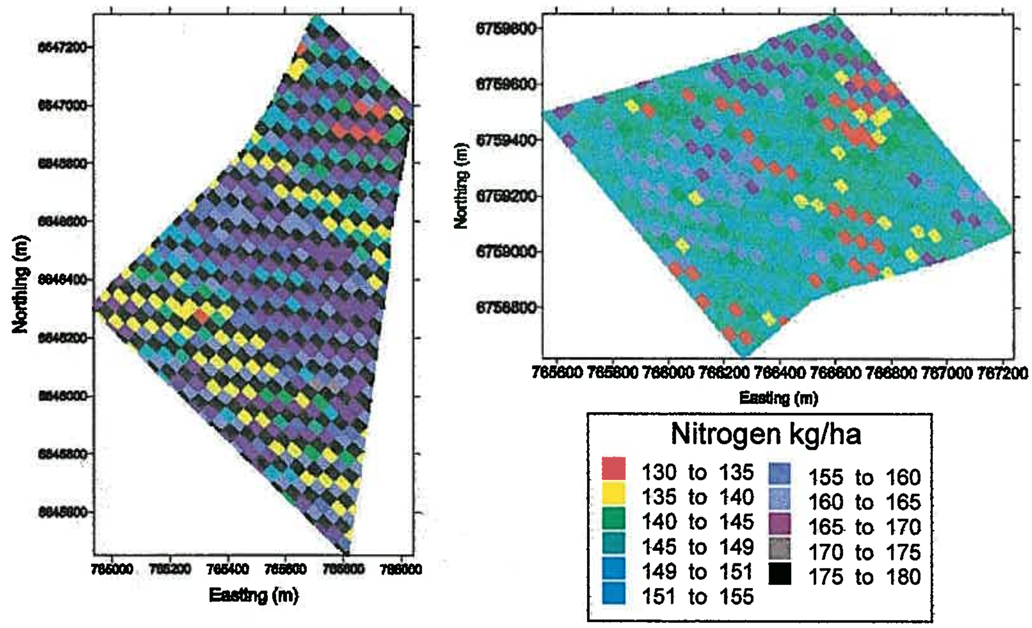

Figure 2. Nitrogen fertiliser application maps for Site 1(left) and Site 2

Fertiliser Application

At both sites, fertiliser was applied as anhydrous ammonia gas, injected into the sides of the raised bed with dump knives. At Site 1, this was done as a split application of 100 kg ha^{-1} three weeks prior to sowing (August) and a variable-rate side-dress in December, while at Site 2 all fertiliser was applied pre-sowing. The fertiliser was applied using a Vision System® controller hooked into a DICKY-John® Land Manager located on the fertiliser spreader. This system is essentially an equalizer (heat exchanger) which converts the anhydrous ammonia gas into a liquid form that can then be metered out according to the application map from the Vision™ controller.

Crop Monitoring

During both early-December and mid-February each site was photographed using a multi-spectral imaging system mounted in a light aircraft. This acquired images in the blue, green, red and near-infra red bands, which allowed the NDVI to be calculated at a resolution of 5 metres to provide a measure of growth throughout the season. In addition, leaf tissue samples were taken at selected fertiliser rates contemporaneously and analysed for total leaf nitrogen using the LECO-CHN analyser (McGeehan and Naylor, 1988). At harvest, both fields were yield monitored and the data interpolated onto the fertiliser grid points. Traditional analysis methods were used to compare the different treatments and fertiliser response, both on a whole field scale and management zone scale.

RESULTS AND DISCUSSION

Generally, fertility status of the soil other than nitrogen is usually medium to high in the cotton growing areas of Australia. It is expected that the variation in yield between the management zones at each site is a function of the soil water-holding capacity and nitrogen levels. Comparison of the nutrient status between the zones for each site suggests that these are the major factors (Table 2). Although phosphorus content is low at both sites, and in the case of Site 2, significantly higher in Zone 3, readings vary depending on cultivations and time of year the samples are taken. Very little response to phosphorus fertiliser applications has been reported for cotton in Australia. Site 1 is classed as sodic, with the higher exchangeable sodium in Zone 1 an explanation for the expected lower yield as this is usually associated with poor soil structure.

Table2. Average nutrient levels for each management zone

	pH $CaCl_2$	**P** mg/kg	**K** cmol(+) /kg	**Mg** cmol(+) /kg	**Ca** cmol(+) /kg	**Na** cmol(+) /kg	**CEC** cmol(+) /kg	**Tot N** Dag/kg
Site1								
Zone 1	8.28	5.2	1.27	14.41	33.28	**6.41**	**55.41**	0.06
Zone 2	8.19	5.5	1.30	14.57	33.20	4.70	53.83	0.06
Site 2								
Zone 1	7.74	5.3	1.13	9.36	24.37	0.70	35.61	0.06
Zone 2	7.79	5.2	1.16	**10.11**	24.37	**0.83**	36.53	0.06
Zone 3	7.74	**8.1**	**1.32**	8.87	23.35	0.66	**34.24**	0.06

Bold indicates significant difference at the 95% confidence level

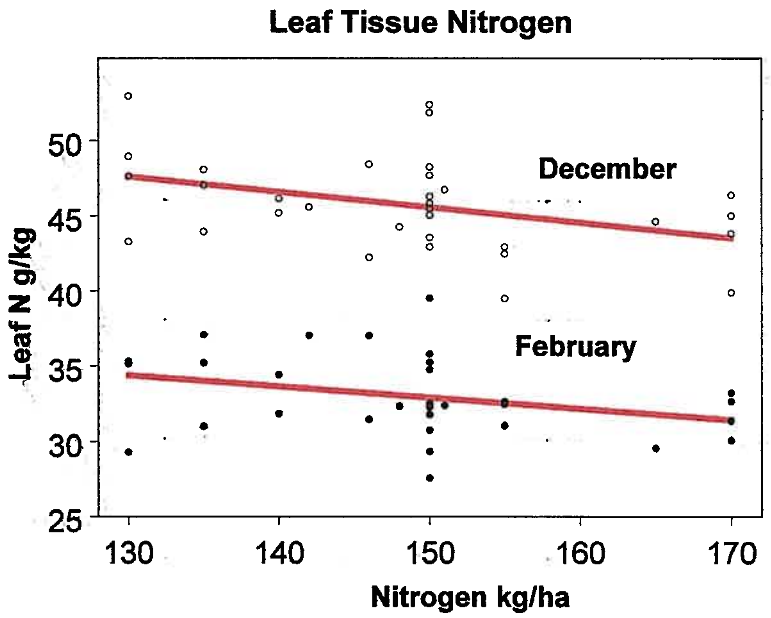

Figure 3. Leaf tissue nitrogen contents for Site 2

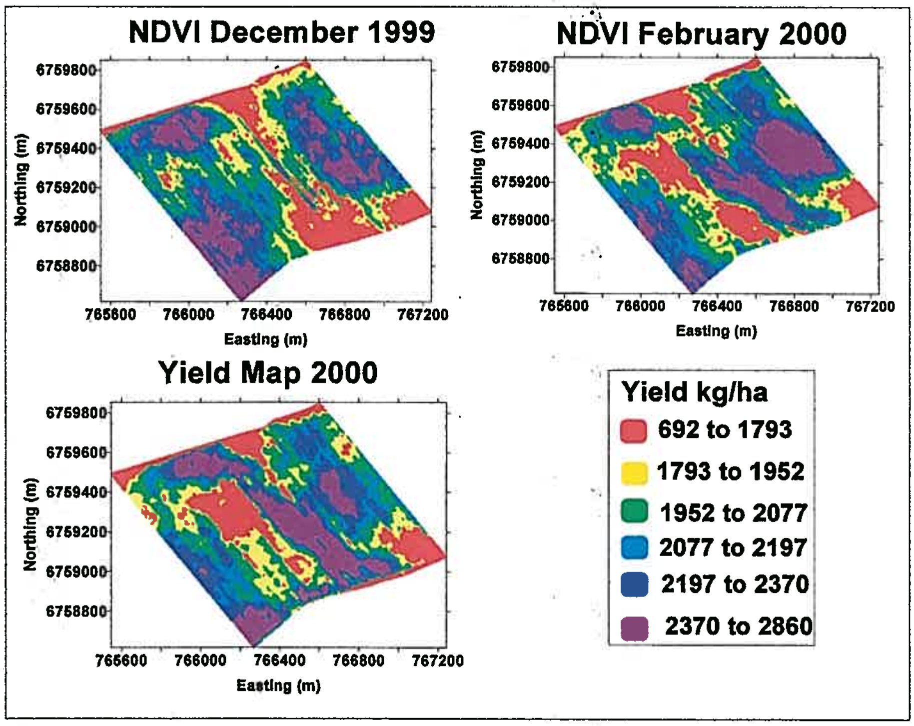

Figure 4. NDVI yield estimates and yield map for Site 2 (6 equal quantiles)

Crop Growth Monitoring

In this paper only the results of the within-season monitoring are presented for Site 2. The leaf tissue sampling and NDVI were obtained 60 days and then

120 days after planting. Leaf N is considered sufficient when between 30 – 45 g kg^{-1}, and generally correlates very well with cotton yield (Gerik et al., 1994). After 60 days, all fertiliser rates had sufficient nitrogen uptake although interestingly at the lower fertiliser rates the plants were taking up more nitrogen (Figure 3). A concern with the high values (>45 g kg^{-1}) obtained was the possibly of excessive vegetative growth which could have detrimental affects during boll filling. Similarly, after 120 days leaf N was sufficiently high to suggest at no rate in the trial was nitrogen a yield-limiting factor. The NDVI images (Figure 4), an estimation of the yield based on the plant vegetative growth, produced similar spatial patterns when compared to the yield map (for Dec r = 0.40; for Feb r = 0.68). This suggests that the early season growth and corresponding N uptake by the leaves were a very good indicator of how the crop was progressing. Unfortunately at the time of the side-dress at Site 1, the crop was not sufficiently advanced enough to allow a similar comparison that may have shown the affects of the later variable-rate application on the yield patterns. The stability in the yield patterns over the season at Site 2 however, does imply there may be some potential for a reactive approach to determining fertiliser rates. If fertiliser is deemed the problem, an additional variable-rate side-dress could be applied to the lower yield areas as indicated by the NDVI.

Comparison of Treatments

Comparison of each treatment on a whole field basis for both sites showed no advantage would have been gained from implementing either variable-rate strategy over the uniform strategy in terms of a yield increase (Tables 3 & 4). Making a similar comparison within each management zone for both sites produced comparable results. At both sites the zone expected to yield the least in fact yielded the highest. The crop at Site 1 experienced problems throughout the growing season in terms of weeds and insect pressure which may explain the reversed yield patterns in those two zones. At Site 2, it was assumed that the higher yielding areas from the 1998/99 season would not do as well as it had been a very wet year that had favoured the coarser textured soil type. This proved not to be the case with yield monitoring on neighbouring fields confirming better yields were being achieved from the coarser textured soil across the farm for the 1999/00 season. However while yield did not differ between the treatments, there was an increase in fertiliser efficiency in terms of yield production. In all zones of both fields, fertiliser efficiency was greatest at the lower rates. This was because at no rate was fertiliser limiting to yield which suggests that the current fertiliser recommendations may be either inadequate or unsuited to making site-specific fertiliser recommendations. Similar results were reported by Dampney et al. (1997) from their trials with winter wheat in which there was no crop production benefit but an apparent environmental benefit from the application of variable-rate N.

Encouragingly the delineation of management zones on estimated yield potential at Site 2 was highly successful. The big differences in yield indicate that once more suitable fertiliser recommendations exist and more years of data is collected to confirm temporal stability, then these zones could then be managed differently. More data would also help to confirm or adjust the management zones for Site 1.

Table 3. Comparison of treatments for Site 1

	ZONE 1	ZONE 2	All Field
	1493 [A]	1452	1471
Yield	1486 [B]	1451	1466
(kg ha^{-1})	1491 [C]	1458	1473
Average	180 [A]	180	180
Fertiliser	159 [B]	156	157
(kg ha^{-1})	144 [C]	167	157
	8.3 [A]	8.1	8.2
Yield	9.3 [B]	9.3	9.3
(kg kgN^{-1})	10.4 [C]	8.7	9.4

A – Historical Uniform
B – CottonLOGIC Variable-Rate
C – Management Zone Variable-Rate

Table 4. Comparison of treatments for Site 2

	ZONE 1	ZONE 2	ZONE 3	All Field
	2077*	1807	2394	2072
Yield	2076	1810	2404	2072
(kg ha^{-1})	2071	1797	2406	2068
Average	150	150	150	150
Fertiliser	149	147	148	148
(kg ha^{-1})	149	166	134	150
	13.9	12	16	13.8
Lint Yield	13.9	12.3	16.2	14
(kg kgN^{-1})	13.9	10.8	18	13.8

* CottonLOGIC Uniform

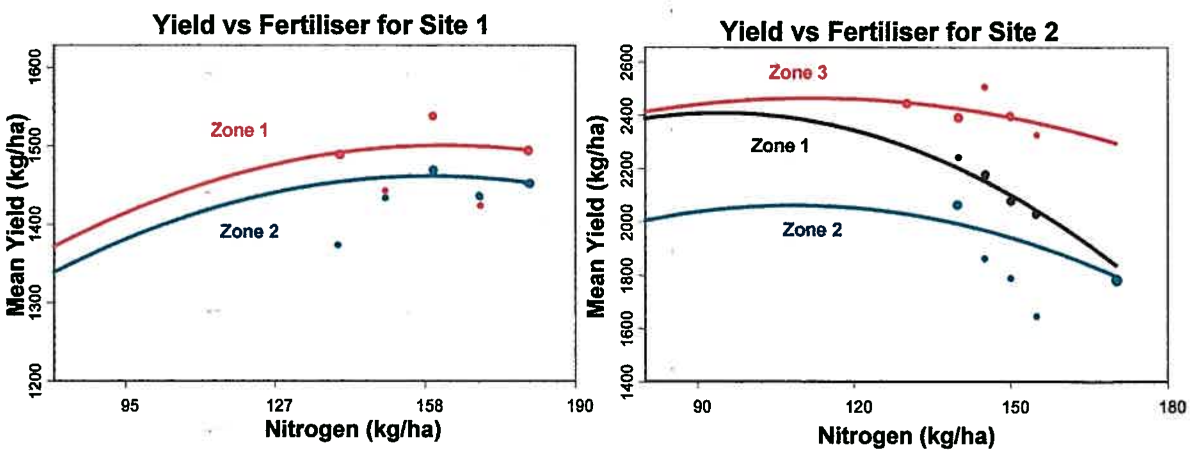

Figure 5. Response curves for Site 1 and Site 2. (dot size proportional to number of observations divided by standard deviation)

Table 5. Optimal Fertiliser Rates for each Zone

	Quadratic Parameters	N rate for Max Yield	Max. Yield	Economic Optimum N Rate	Economic Optimum Yield[a]	Variable Rate Saving [b]
Site1						
Zone 1	$1000+6.17N-0.019N^2$	162	1501	154	1500	+ $2
Zone 2	$969+6.18N-0.0194N^2$	160	1462	151	1461	$0
Site 2						
Zone 1	$1517+18.9N-0.10N^2$	94.5	2410	93	2409	+ $60
Zone 2	$1239+15.2N-0.07N^2$	109	2064	106	2063	$0
Zone 3	$1839+11.2N-0.05N^2$	112	2466	109	2466	$0

a- Anhydrous ammonia @ $AUD0.67 kg^{-1} and lint yield @ $AUD2.11 kg^{-1}
b- Calculated on a per hectare basis by using the optimal rate for each zone compared to a uniform rate N=150kg ha^{-1} at Site 1 and N=110kg ha^{-1} at Site 2

Crop Response

It was assumed that at both sites the fertiliser rates in the trial were at or just past the optimum yield level in terms of a traditional quadratic response from yield versus fertiliser application. In order to fit a quadratic response function for each zone nil fertiliser strips on adjacent fields at the same crop rotation stage were used to estimate the yield for zero N application. An area, which needs addressing when implementing this form of on-farm experimentation in a commercial environment, is the amount of low fertiliser rates that should be incorporated into the experimental design to allow the adequate generation of response functions. For both sites a weighted quadratic function was fitted based on the number of observations at each rate and the variance (Figure 5).

Table 5 shows the optimum economic yield and maximum yield that could be achieved for each zone. At Site 1, there was very little difference between the optimum fertiliser rates for both zones which if set at 150 kg ha^{-1} would result in no economic benefit from implementing a variable-rate approach. As this site experienced problems throughout the growing season further investigation may still reveal benefits from a zone-based approach. Secondly, more years of data would allow the management zones to be determined more accurately. Site 2, at which the initial delineation of the management zones was successful, indicates there would be an economic benefit from varying the fertiliser rate. Applying 93 kg ha^{-1} of N to Zone 1 and 110 kg ha^{-1}of N to Zones 2 and 3 compared to a uniform application of 110 kg ha^{-1} to the entire field would bring about a $AUD 60 per hectare benefit for the Zone 1 region, covering approximately half the field.

CONCLUSIONS

Neither variable-rate strategy for applying nitrogen increased yield over the traditional uniform approach. This was most likely caused by the inadequacy of the current fertiliser recommendations for predicting site-specific requirement. At both sites current fertiliser rates appeared to be too high. However, the management zone approach was successful at delineating regions of the field according to their yield potential. If methods for determining fertiliser recommendations can be developed relevant to a site-specific approach, then the perceived benefits from variable-rate fertiliser application should become a reality. On farm experimentation will probably be vital in determining fertiliser recommendations for management zones distinct to a farm.

Additionally the use of remote sensing may offer a way of taking a reactive approach to applying fertiliser.

ACKNOWLEDGEMENTS

The authors wish to thank the Australian Cotton Research and Development Corporation for providing funding for the research, the staff at Auscott Midkin and Oakville for their cooperation and the in-kind support from Incitec Fertilisers, Andrew Smart of IAMA Pty Ltd, John Triantafilis, Andrew Huckel, Ian Rochester and The Farrer Centre at Charles Sturt University for collecting the aerial imagery.

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