

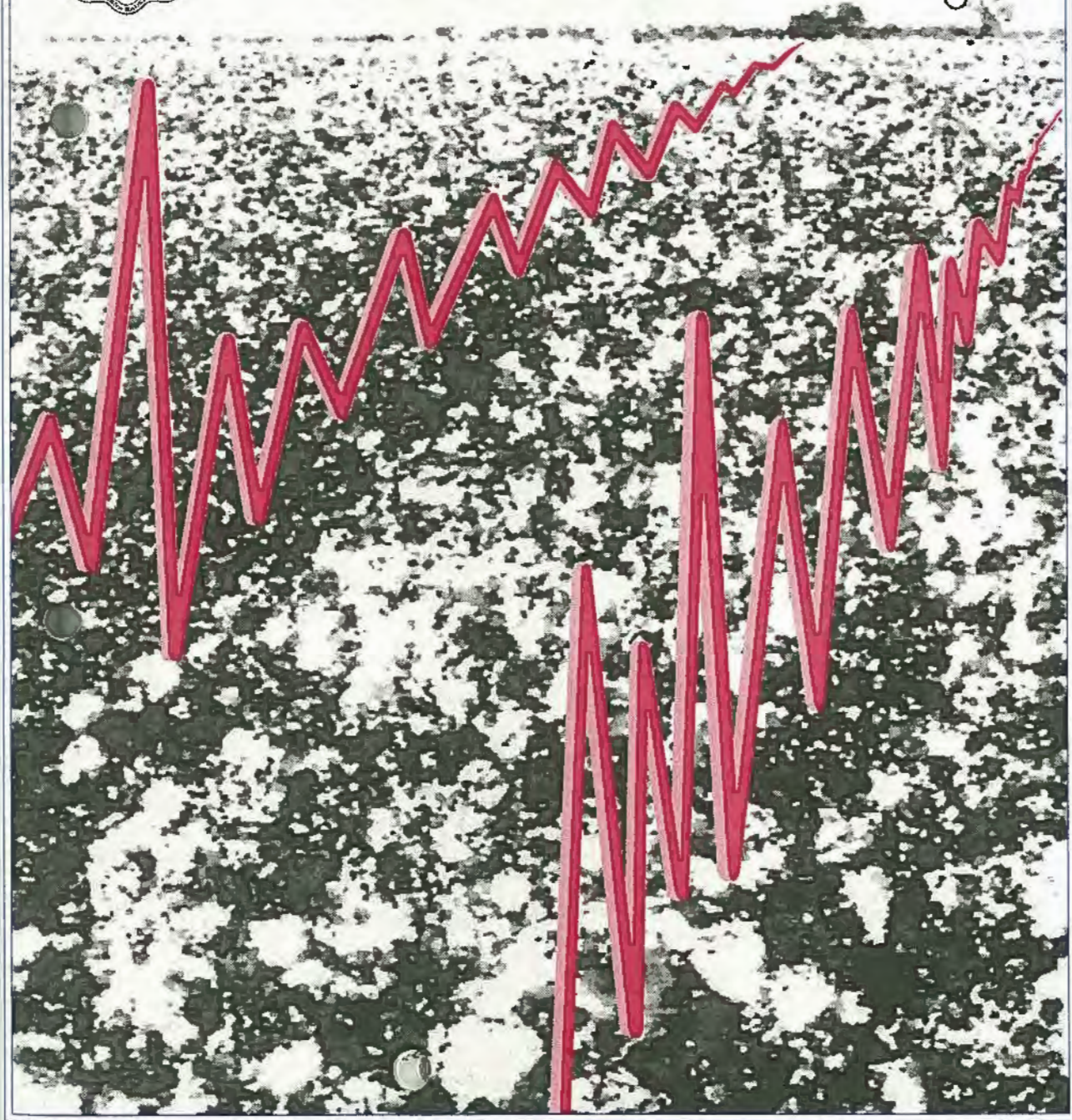
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THE POTENTIAL FOR SITE-SPECIFIC MANAGEMENT OF COTTON FARMING SYSTEMS



A.B. McBRATNEY & B.M. WHELAN



THE POTENTIAL FOR SITE-SPECIFIC MANAGEMENT OF COTTON FARMING SYSTEMS

*A DISCUSSION PAPER FOR
THE AUSTRALIAN COTTON INDUSTRY*

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Co-operative Research Centre for Sustainable Cotton Production



CSIRO - NSW Agriculture - Department of Primary Industries Qld - University of New England
- University of Sydney - Cotton Research and Development Corporation



FOREWORD

This discussion paper has been written as a result of an overseas study grant (US20C) from the Cotton Research and Development Corporation (CRDC). The grant enabled the attendance and presentation of papers at the 2nd International Conference on Site-Specific Management in Agricultural Systems in Minneapolis, Minnesota, March 1994 and the 15th World Congress of Soil Science in Acapulco, Mexico, July 1994. Discussions were also held with scientists in the USA and the Netherlands. This document serves as a report on the international travel. The Co-operative Research Centre for Sustainable Cotton Production is grateful for this support from one of our core partners, the CRDC.

The work described in this document forms part of Program 1 of the Co-operative Research Centre for Sustainable Cotton Production – Protecting the Resource Base and the Environment. It is offered as a discussion paper for the Cotton Industry through Program 4 – Education and Extension.

Site-specific management offers exciting possibilities as you will realise from reading the report. This type of innovative technology is a feature of the Australian Cotton Industry. It is one of the goals of the CRC to ensure that these possibilities are realised.

G.A. Constable
Director

Co-operative Research Centre for Sustainable Cotton Production

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CHAP. XIX.

Of Differences between the Old and the New Husbandry.

IN order to make a Comparison between the Hoing Husbandry, and the Old Way, there are four Things; whereof the Differences ought to be very well considered.

- I. The Expence
II. The Goodness
III. The Certainty
IV. The Condition in which the Land is left after a Crop.
} of a Crop.

Facsimile from Jethro Tull's Horse Hoeing Husbandry of 1733. This influential book, first published in London in 1731, had the full title:

'The New Horse-Houghing Husbandry: or, an Essay on the Principles of Tillage and Vegetation. Wherein is Shewn, a Method of Introducing a Sort of Vineyard-Culture into the Corn-Fields, in Order to Increase their Product, and Diminish the Common Expence, by the Use of Instruments lately Invented.'



INTRODUCTION

The spatial variation in crop yield, and the field-based factors that contribute to it, is developing as a subject of importance to both the farming and wider communities. Increasing attention is being focused on the notion that agriculturally productive land can be managed as a relatively homogeneous unit at the 'within-field' scale. Such an assumption may lead to inappropriate resource application and associated financial, environmental and social costs. The significance of these imposts, such as input waste, yield reduction and soil, water and air contamination has been identified in the Cotton Research and Development Corporation (CRDC) publications compiled by Anthony et al. (1992) and Hearn (1993).

Preliminary research has prompted the proposal of site-specific management as a remedy to many of these environmental and resource-use inefficiency problems (Larsen & Robert 1991). Figure 1 outlines the simple rationale that justifies and supports site-specific management.

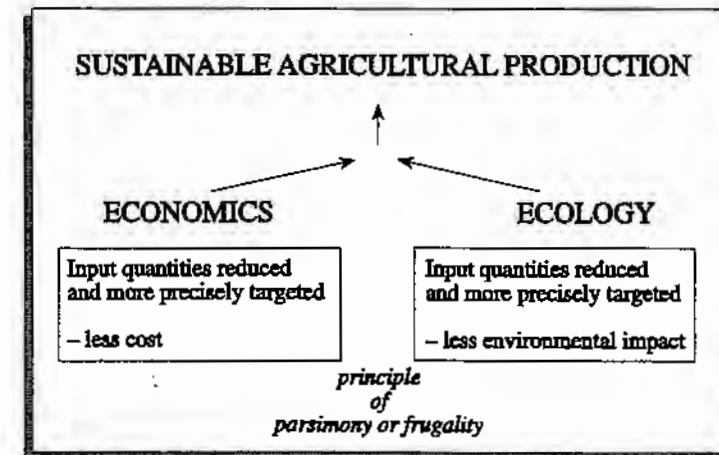


Figure 1. The economic-ecological basis for a site-specific management system.

A site-specific management system is based on matching resource application and agronomic practices with soil attributes and crop requirements as they vary across a site. Collectively, these actions are referred to as the 'differential' treatment of field variation as opposed to the 'uniform' treatment that underlies traditional management systems.

In economic terms, the precise calculation and placement of input resources suggests a more efficient and profitable use of enterprise resources. From an ecological point of view, this precision offers the prospect of reducing the environmental risk associated with



blanket field treatments and provides the ability to work with the natural diversity within each field. By more closely aligning yield goals to the variation in yield potential induced by natural diversity, the sustainability of modern farming systems may be improved.

Achieving the harmony called for in a site-specific management system will require a process to describe, and delineate suitable responses to, variation found in specific components of the cropping system. A union of data acquisition operations, information processing and decision formulation procedures would form the mechanism for this process.

In a cotton cropping system, the field variation in soil type, nutrient levels, moisture content and structural integrity contribute to site fluctuations in the potential fibre yield. Acquiring data on the short-range variation of these influential soil attributes is essential to the operation of a site-specific management system. Measurement technology for this task has developed to the point where 'on-the-go' sensors for the real-time measurement of certain soil attributes have been released or reached final assessment stages. Accurate monitoring of the variability in fibre yield during harvest operations is also a foreseeable achievement. Combining these technologies with vastly improved ground positioning systems allows 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. Small-scale variation in pertinent soil factors can be identified and any fluctuations in productivity potential across a site quantified. The degree of variation in turn influences the differential treatment strategies required to maximise yields and resource application. Yield monitoring at harvest can be used to assess applied treatment effects and refine yield potential goals for the subsequent season. It is envisaged that the entire data acquisition-processing-decision procedure will be undertaken in the field during relevant farming operations, thereby avoiding an increase in the traffic loading.

This document will discuss the small-scale variation in soil attributes and cotton lint yield, highlight the most appropriate agronomic practices for the implementation of site-specific management and examine the methodology necessary to collect and collate detailed data on spatial variability. An economic comparison between uniform and differential treatment shall be made using examples involving the application of nitrogen fertiliser to simulated fields displaying variable initial nitrate (NO_3^-) levels.



THE SPATIAL VARIABILITY OF SOIL ATTRIBUTES & CROP YIELD

THE SPATIAL VARIABILITY OF SOIL

The variation in soil attributes and production potential displayed at a given site, at a given time, are controlled by a number of important processes. The more influential of these are the geological and pedological processes that define the soil type and govern the majority of static soil properties e.g. texture, horizon colour and cation exchange capacity. Additional effects on the variability of soil attributes are supplied by soil management practices and cropping systems. These can greatly manipulate the more dynamic soil properties such as nutrient, water, air and solute regimes.

A true description of small and large scale variation in such soil properties has historically been difficult and costly to obtain. Sampling on a large-scale grid is logistically troublesome and provides data on variability at a very coarse scale. Alternatively, a fine-scale grid sampling scheme may provide more detail on variability but will incur high costs in order to cover a significant area.

Obtaining a more thorough understanding of the extent of soil variability at a site will require methods that allow observations to be made at a diverse range of scales and with greater continuity. Aerial photography is one tool that will help supply data of this kind on spatial variability. Figure 2 demonstrates the extent and continuity of observable variability in soil moisture and texture as detected using aerial photography.



50 metres

Figure 2. Soil variability : red channel of a false colour aerial photographic image (Narrahri, April 1993). Paler zones correspond to lighter textured, lower moisture content soil.

THE SPATIAL VARIABILITY OF COTTON YIELD

Whole farm, and even large paddock lint yields are routinely determined and compared over time. The CSIRO cotton breeding program can be credited with significantly contributing to the well documented increase in bulk lint yield per unit area achieved by the cotton industry since its inception. Importantly, however, the spatial variability of lint yield at the 'within-field' scale has been studied in less detail although its controlling effect on whole paddock yields is easily apparent.

In an attempt to quantify the small-scale variation in lint yield observable down and across cotton rows, cotton yields from a CSIRO 1993/4 variety trial conducted at Field 10 Norwood, Moree (Reid pers. comm. 1994) were analysed. The trial consisted of 240 plots, 14m x 3m, laid out in five 6 x 8 plot blocks, giving an overall dimension of approximately 424 x 24m (~1.02 ha). To extract the variation attributable to soil and environmental factors, the variety means were removed from the data to give yields for a 'pseudo' uniformity trial. These remaining yield figures reflect, to a large degree, the yields that would be expected from the uniform planting of a single variety having a mean yield of 1830 kg/ha.

This data is mapped in Figure 3, showing considerable plot-to-plot variation, both along and across the rows. A more detailed examination of this variation is displayed in figures 4 and 5.

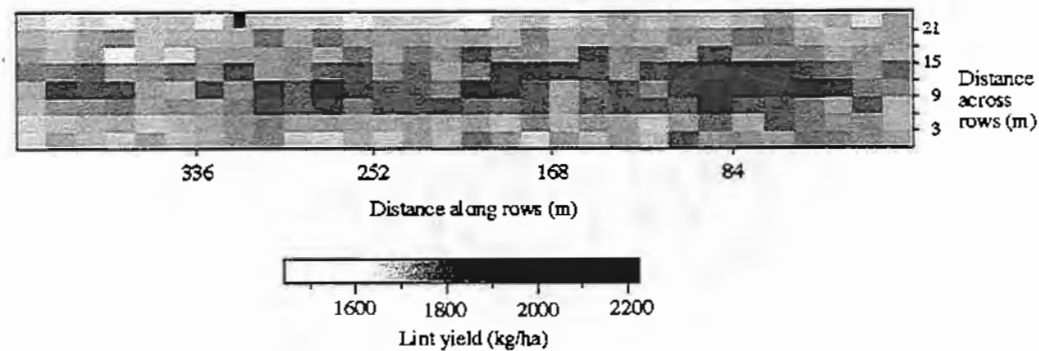


Figure 3. Distribution of cotton lint yields for the 'pseudo' uniformity trial.

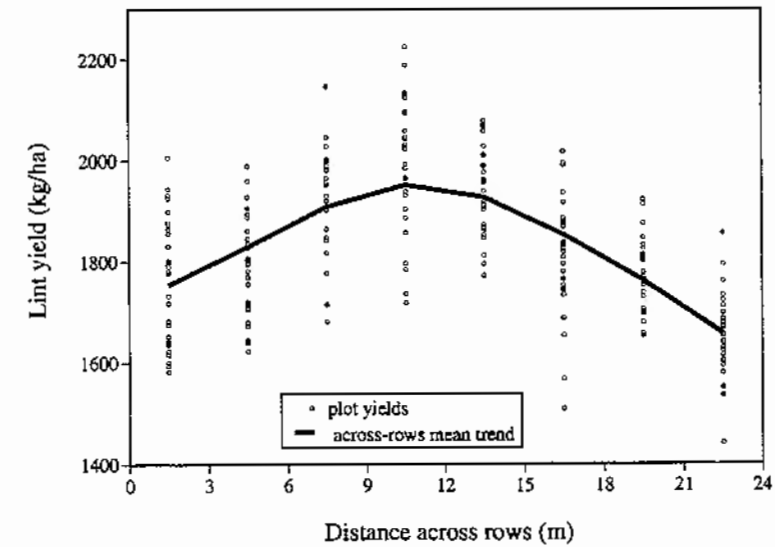


Figure 4. Mean yield trend across the cotton rows.

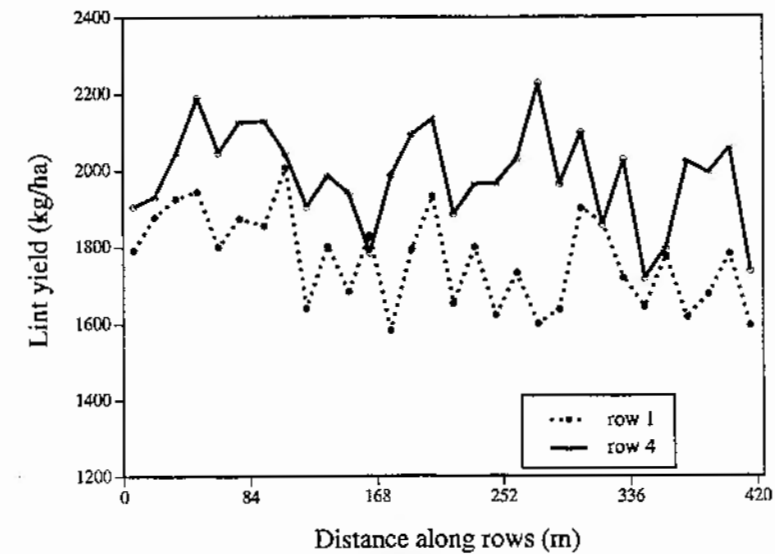


Figure 5. Yield trend along cotton rows 1 & 4.



In Figure 4, the mean yield trend across the field highlights the much larger yields in the middle rows. The yield trend along the rows is characterised by Figure 5. Here the data clearly shows a higher mean yield for row 4 as compared to row 1, but also distinguishes considerable variation along the rows. A variance analysis of this data set, along with that of a 1965 Pima (*Gossypium barbadense* L.) trial in Arizona (Kuehl & Kittock 1969) (also approximately 1 ha in area), proved reasonably similar and suggested a two-part model for the spatial variance in lint yield of the form:

$$v(d) = \begin{cases} 28000 \left(\frac{d}{2r} - \frac{3d^3}{2r^3} \right), & \text{when } d \leq 40\text{m} \\ 28000 & \text{when } d > 40\text{m} \end{cases} \quad (1)$$

where:

- v = yield variance of small plots less than 1m × 1m (kg/ha)²
- d = distance (m)
- r = range, or the distance beyond which the variance does not appear to increase (m)

This is a useful working model, and serves to quantify the degree of spatial variation in yield that may be observed in a typical cotton field. The model is graphically depicted in Figure 6. However, different fields will demonstrate a deviation from this model depending on the specific inherent soil variation and management history etc. Clearly, much more research is needed here.

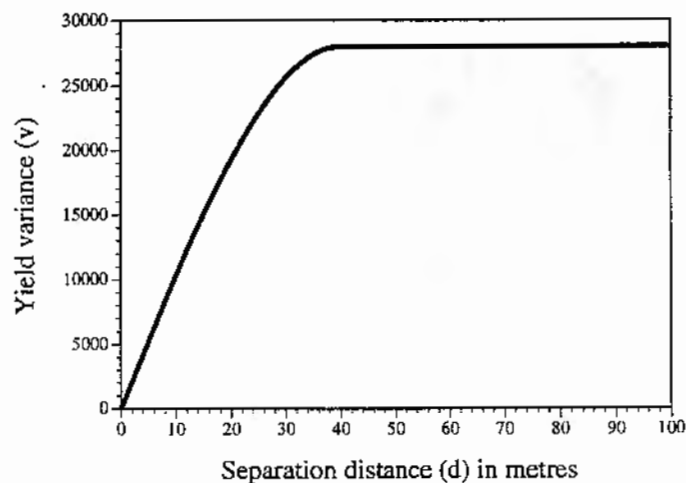


Figure 6. Variogram relating yield variance to separation distance along the rows.



A practical application of this model is shown in Figure 7, where the range of yields expected within 70% and 95% confidence limits is calculated as a function of cotton row length.

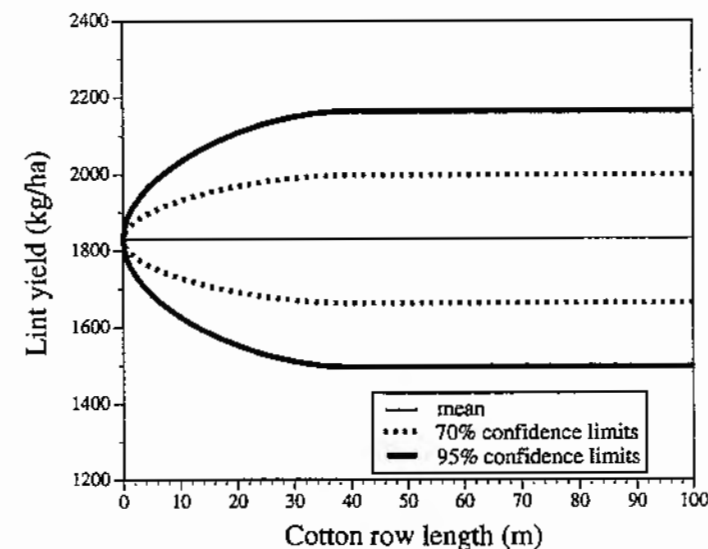


Figure 7. The range of cotton lint yields expected with varying confidence limits for a given row length.

This analysis implies that as the separation distance between locations along a cotton row increases, the expected variation in lint yield also increases, attaining a maximum standard deviation of 167 kg/ha at separation distances greater than 40 metres. Furthermore, the substantial short-range variation in cotton lint yield highlighted by this analysis suggests considerable promise for site-specific management.

THE PROBLEMS ASSOCIATED WITH SPATIAL VARIABILITY IN CROPPING SYSTEM COMPONENTS

There are economic, environmental and social problems faced by managers of traditional cotton cropping enterprises that arise from spatial variation in attributes of the soil-crop system. In general the problems arise from a decision to use 'mean of field' information to guide the amelioration of an area. This may result in zones being under- or over-treated. The most relevant attributes that exhibit spatial variation are:



SOIL NUTRIENTS (ESPECIALLY NITROGEN)

The application of fertilisers to provide sufficient nutrients for optimum crop growth and yield is essential in intensive cropping systems. Synthetic nitrogenous fertilisers are routinely applied in the cotton industry to meet the high nitrogen requirements of modern cotton production.

Testing for soil nitrate (NO_3^-) concentrations is recommended in September (Daniells & Larsen 1991) as a guide in determining the rate of nitrogenous fertiliser to apply pre-sowing. When soil NO_3^- is found to be below desired levels, traditional treatment with 'blanket' fertiliser applications, may produce areas of under and over-fertilisation.

ORGANIC MATTER (OM)

The amount of OM provides an indicator for the inherent soil fertility in most circumstances. Specifically, the quantity of mineralisable nitrogen provided by the OM may influence the requirements for synthetic nitrogenous fertiliser application. The typically slow operation rate of the mineralisation process limits the release of nitrogen, but this source may provide a significant contribution to dry-land cropping or during the drying cycle on irrigated land. The importance of OM in this storage and release of plant available nutrients will increase as the percentage clay content decreases.

The amount of OM present will also effect the degree to which inactivation processes act on soil applied pesticides. This is particularly relevant for non-ionic active ingredients and as the percentage clay content of the soil decreases.

SOIL STRUCTURE

Soil structure can be simply defined as the arrangement of particles in the soil and the distribution of voids between these solid particles. The structure of the soil affects the physical penetration, growth and anchorage of roots along with regulating the air/moisture balance required for plant growth and microbial activity. Soil structure also influences soil drainage/water retention and erosion potential. Poor soil structure subsequently restricts root penetration and growth, retards plant uptake of water and nutrients, and ultimately reduces the crop yield.

SOIL TYPE/TEXTURE

Changes in these attributes may indirectly influence the yield potential of a site by contributing to the variation in nutrient storage and availability, fluid retention and transport, and soil stability to potentially disruptive processes.



PEST INFESTATIONS

The distinctly aggregated colonisation mechanism used by many cotton field pests may result in whole-field applications of pesticides that are overestimated or unwarranted. Conversely, portions of the crop where colonisation is high may be inadequately protected using 'mean of field' applications.

The problems that may be associated with inadequately budgeting for the variability in these attributes are summarised in Table 1.

	Economically Significant Yield Loss	Excess Fertiliser Cost	Excess Fertilisers in Tailwater or Groundwater	Excess Denitrification Products	Excess Pesticide Cost	Excess Pesticide in Tailwater or Groundwater	Pesticide Residues in Soil
Soil Nutrients (especially N)	✓	✓	✓	✓			
Amount of soil O.M.	✓	✓	✓	✓	✓	✓	✓
Soil Structure	✓	✓	✓	✓		✓	
Soil Type/Texture	✓	✓	✓	✓	✓	✓	✓
Pest Infestations	✓				✓	✓	✓

Table 1. Problems associated with the spatial variation in attributes of a cotton soil-crop system.

For the majority of impacts listed in Table 1, the implications are obvious and require no further elaboration. The significance of excess denitrification products provides an exception. In areas with soil nitrogen levels above crop requirements, there is a greater opportunity for the excess nitrogen to result in increased production of nitrous oxide (N_2O) through the denitrification process. N_2O release contributes to the global greenhouse effect and is instrumental in the breakdown of stratospheric ozone (Hauck 1984).



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

All these problems may be eventually addressed by treating the field variation in these cropping system attributes using a site-specific farming program.

OPTIMISING PRODUCTIVITY WITH SITE-SPECIFIC MANAGEMENT

A HISTORICAL PERSPECTIVE

The premiss underlying site-specific management, namely that soil heterogeneity influences the productive potential of agricultural land, can not be regarded as a new concept. Equally, the knowledge that measuring the degree of heterogeneity and using this as base data with which to manipulate farming operations is long held. Haines and Keen (1925) employed a dynamometer to record the continuous variation in drawbar pull required during parallel transects of a field (refer Figure 8).

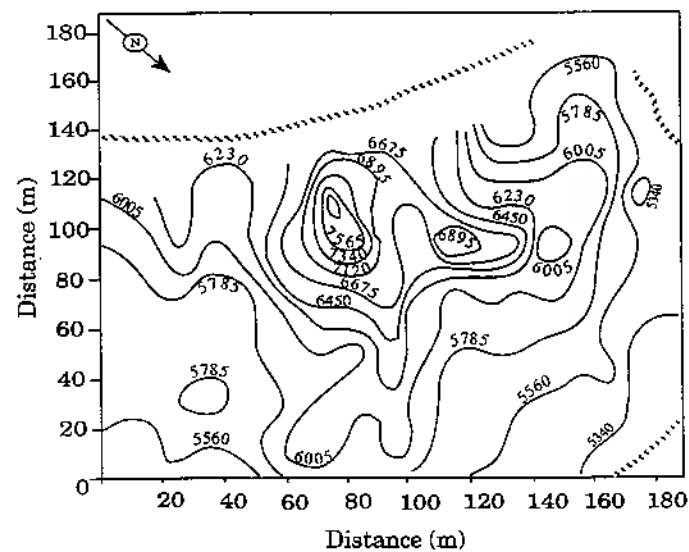


Figure 8. Continuous map of draw-bar pull (newtons) (after Haines & Keen 1925).



The map effectively depicts the resistance of the soil to the plough, a factor influenced by the soil cohesion, plasticity and surface friction which indirectly reflects a wide range of other soil variables such as moisture content, organic matter levels and soil structure. Their conclusions as to the influential effect of this inherent soil heterogeneity on field experiments and plant growth are fundamental to soil-specific management in all crop production enterprises.

Russell (1959) also contemplated the effect of soil variability and speculated (with considerable elegance) on the extent to which mechanical and chemical changes could be imposed on the soil:

"Automation may yet invade the farm, commercial market garden and nursery even though an escapist reaction may keep it out of the private garden. An electronic controller programmed to respond to changing weather and soil conditions as revealed by self recording instruments, and to changing plant conditions recorded by photographic devices operating light cells, may yet by remote control send the proper cultivating implement to the proper spot and direct its operations, select the proper chemical agent for each particular purpose and direct a discharge of the proper amount to the proper place; never itself making a mistake but being eternally watchful to correct those of any human intruder who thinks he knows better."

PROSPECTIVE MANAGEMENT OPTIONS

The technology is now becoming available to tackle the operations suggested from the past. Providing further impetus is the now greater general awareness of the natural boundaries limiting resource requirements, availability and application. It is therefore feasible to attempt to account for, and operate with, spatial variation as the solution to the problems of soil spatial variability outlined previously. Figure 9 encapsulates the design of a system for continuous soil/crop management that is proposed to support these endeavours.

In implementing this type of management, rate-driven operations that influence crop yield can be targeted to achieve a desired yield potential with the minimum input of resources. Such governing operations occur at nearly all phases of the crop growth cycle.

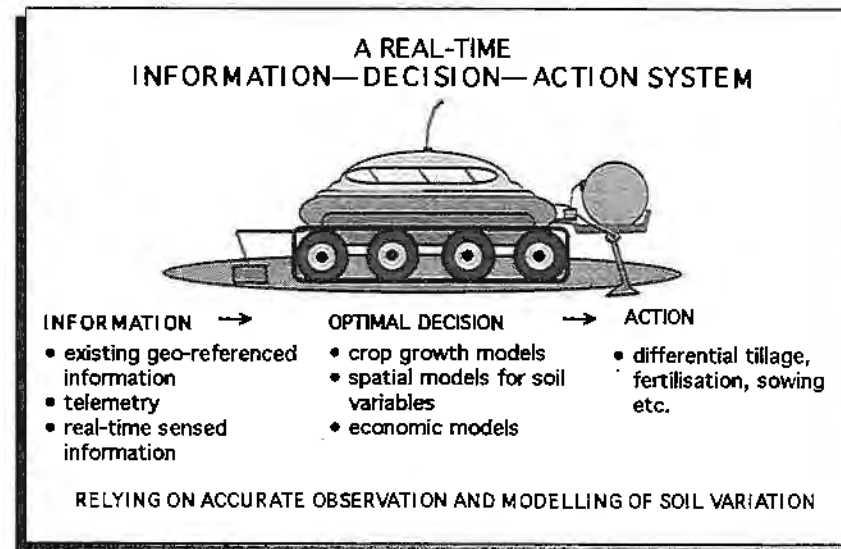


Figure 9. A real-time system linking information acquisition, decision making and action operations.

For the cotton industry the important areas of managerial intervention would include:

Soil Tillage

Generally, the current tillage systems in use attempt to apply a uniform treatment to the soil at a site irrespective of the spatial variation in soil tilth/condition that may occur. Tillage operations modify the soil propensity for plant growth and erosion by imparting compaction/disintegration forces on the soil aggregates while endeavouring to achieve a desired level of soil disturbance and crop residue/ameliorant incorporation.

The depth of operation and the type of implement employed directly influence the surface roughness, porosity and organic matter incorporation. Voorhees *et al.* (1993) noted that the degree of incorporation can be controlled by the type of implement used. They report that incorporation increases as tillage is changed from chiselling to disking to mouldboard ploughing. Soil moisture content and soil texture at the time of operation also govern the effect of an implement (Allmaras *et al.* 1967).

By quantifying both the original and desired soil condition on the same scale, e.g. by mechanical impedance or porosity measurement, the degree of tillage required could be determined. The most suitable tillage implement to achieve this goal could then be chosen based on the moisture content and texture of the soil.



A sensor mounted in front of the implement could monitor the initial soil condition and the resulting condition of the tilled soil gauged by a trailing sensor. A hydraulically controlled tool frame supporting a variety of implements with real-time engaging and depth control could perform the tillage operation. Voorhees *et al.* (1993) suggest including a front disk gang for residue incorporation backed up by a chisel gang for deeper or more vertical disturbance.

Such a system may be useful prior to pre-season bed forming to minimise soil structural damage, control residue incorporation to reduce erosion potential and remediate zones prone to waterlogging or compacting.

Granular Fertiliser Application (both in quantity and in mix)

Following the identification and mapping of yield potential variation over a site, and in association with 'on-the-go' measurement of soil nutrient and OM levels, the required level and mix of synthetic or organic fertiliser may be prescribed and applied to discrete areas. This area promises the greatest advance in efficient control of applied nutrients to the landscape, achieving higher maximum economic yield, and offering solutions to the growing problems of fertiliser waste, runoff and gaseous breakdown.

Variable-rate technology (VRT) systems for the co-ordination of this task are being developed for the grain industry. A recently released mobile unit from the U.S.A., integrating GPS, map reading technology, fertiliser mixing and a precision application apparatus is shown in Figures 10–12.

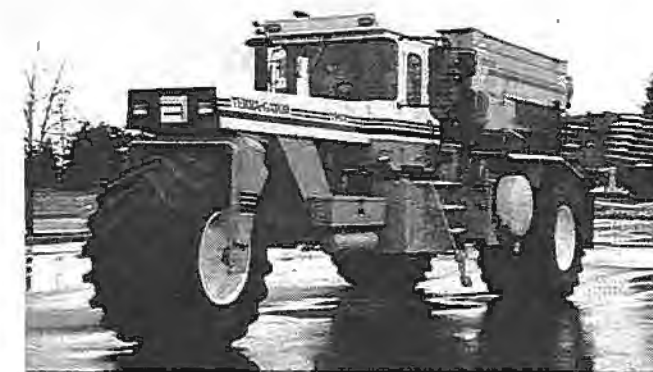


Figure 10. Mobile unit showing fertiliser tanks and flotation tyres

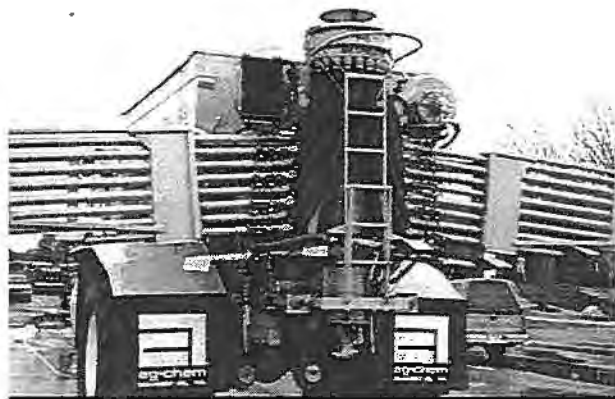


Figure 11. Spreader unit and precision delivery mechanism

The unit, marketed by Ag-Chem[†], uses a predetermined fertiliser requirement map to control the rate of application. The software employed picks up application rates from a screen based field map comprising colour coded polygons that represent zones requiring differential fertilisation.



Figure 12. Full view of vehicle and application boom

Tyler[§] have also released a fertiliser applicator with VRT capability for use in conjunction with an 'on-the-go' OM sensor. The level of soil OM preceding the applicator is sensed

[†] Ag-Chem Equipment Co., Inc. Minnetonka, Minnesota, USA.

[§] Tyler, Benson, Minnesota, USA.



and used, *via* calibration and decision software, to calculate the fertiliser application rate required. The correct amount is subsequently applied as the applicator bar passes over the observation point.

Anhydrous Ammonia Application

Although these units are unsuitable for the application of anhydrous ammonia in a permanent bed cotton cropping system, adaption of the technology through the use of a four wheeled (or tracked) vehicle in combination with controlling mechanisms to suit liquid/gaseous phases of anhydrous ammonia would appear easily achievable.

Robert *et al.* (1991) reported the development and evaluation of a variable rate anhydrous ammonia application system utilising common farm implements. A predetermined application map (based on discrete soil sampling and subsequent yield goal determination) was used to direct the quantity of fertiliser applied. The map is loaded and read through a cab-mounted lap-top computer that is connected to a ground speed monitor, a flow rate indicator and a rate control valve. Gaseous anhydrous ammonia is converted to the liquid phase in an expansion chamber and then applied through the applicator knives at rates between 60kg N/ha – 260kg N/ha.

Such an application system, when combined with a GPS navigation system and a soil colour sensor to monitor soil OM and soil type in real-time, would be suitable for use in a cotton cropping enterprise.

Nitrification Inhibitor

The loss of applied nitrogen through the gaseous products of the denitrification process is a limiting factor in the efficient utilisation of artificial N fertilisers. Freney *et al.* (1992) reported a 57% recovery rate for ¹⁵N labelled fertiliser applied one month prior to sowing and in the absence of nitrification inhibitors. Significant increases in the recovery rate were achieved using the nitrification inhibitors N-Serve (74% recovery) and wax-coated calcium carbide (78% recovery). For a mean field application of 190kg N/ha the inhibitors allow access by the crop to approximately 33 kg/ha – 40 kg/ha more N.

Freney *et al.* (1992) also indicated that a greater increase in the recovery rate (92%) could be achieved using 2-ethynylpyridine, however the cost for commercial field use appeared prohibitive. For the use of this inhibitor, along with the others discussed, identifying the spatial variation in denitrification potential at a site may allow differential application and reduce the cost of treatment. A combination of real-time moisture monitoring with textural or OM measurement could provide the required data on zones in a field more susceptible to waterlogging.

The variable rate application technology developed for fertiliser application would require only minor adaptations to control a differential treatment with nitrification inhibitor.



Gypsum / Lime Application

The dispersion of clay and the decline in soil structure associated with sodic and highly sodic soil may be alleviated through the application of calcium in the form of gypsum (CaSO_4) or lime (CaCO_3). Sodic soil is identified as containing sodium concentrations that contribute >6% to the total cation exchange capacity. The addition of calcium acts to flocculate dispersed clay by increasing the total content of soluble salts in the soil solution and helps maintain aggregation by replacing sodium ions on the clay surfaces.

Ion-selective electrodes are currently in use for the laboratory analysis of sodium ions in soil solution samples. These instruments could be adapted for 'on-the-go' monitoring of sodium concentrations in the soil and this data compared with a field average concentration required to exceed the 6% threshold. Sodic areas may then be graded in severity and mapped.

A differential application regime could then be calculated and applied according to the varying sodicity mapped within a field. This would offer the potential for savings in chemical costs, physical and financial application costs and improved synchronisation of soil-crop requirements.

Seeding Rates

Matching the rate of sowing to a predetermined yield potential also 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. If no improvement in the yield potential is to be undertaken, then sowing higher rates in areas where production potential is lowest and lower rates on better country, would both optimise seed inputs and co-ordinate with a calculated differential fertiliser regime.

Crop Variety

Cotton varieties as identified in the Cotton Seed Distributors Variety Handbook could be used to advantage in fields where significant soil textural change or variation in the degree of compaction is identified. For example, by planting a variety such as Siokra L22 in compacted areas and Siokra 1-4 on lighter textured, non-compacted zones, the quantity of lint yielded may be optimised.

At present, such a combination of cotton varieties within a field may raise concern over the non-synchronisation of maturity dates and the associated defoliation and harvest problems. Also, a mixed variety cotton bale may be considered of lower quality due to inconsistencies in fibre dimensions and other attributes. As restrictions are imposed on other aspects of cotton management these concerns may reduce in importance.



Herbicide Application

As the cotton industry moves towards a more permanent bed system that encompasses crop rotation and a reduction in soil tillage operations, the spread of weed propagules is likely to be reduced. This may result in more stationary individual weed populations and a more clustered overall weed pattern in a field. Greater clustering implies an increase in weed-free areas. This more irregular pattern presents the opportunity for differential treatment as opposed to blanket field applications of herbicide.

For example, the spreading pattern of nutgrass (*Cyperus rotundus*) is predominantly controlled by the growth of tuber bearing rhizomes, viable seed production being almost non-existent (Charles 1992). This propagation method is suited to control by the identification and differential treatment of primary areas of infestation. Blanket treatment using tillage or herbicides is both expensive and deleterious to the environment.

Two approaches to identification and treatment can be considered. Firstly, areas in a field that display a level of infestation that required treatment during a growing season could be precisely mapped. The map may then be used to direct the site-specific application of a contact herbicide prior to the next season planting. Stafford and Miller (1993) have reported the development of such a system for winter cereal cropping, in which they propose applying a greatly reduced herbicide rate over the entire field and raising concentrations at previously identified weed locations.

The second approach involves the employment of a real-time weed recognition system. Detectspray[®], originally developed in Australia to commercial prototype by Felton *et al.* (1991), uses reflectance discrimination to identify and treat only green weeds in a fallow or stubble covered field. This system has an obvious use replacing fallow weed control by tillage.

Brown *et al.* (1994) utilised aerial still-video camera images captured using four discrete spectral windows to discriminate between seven weed species in a corn field. The spectral regions were chosen to allow separation of the different plant species based on their individual spectral signatures.

A combination or modification of these two systems could provide a method to detect weeds in a cotton crop that remains green all season.

Insecticide Application

In principle, site-specific crop management could be applied to the control of insect pests in cotton crops. Aerial photographic and ground-truthing techniques may be applied to detect crop stress or damage inflicted by initial insect infestations. Mapping these areas

[†] Detectspray International Pty Ltd, Albury, NSW, Australia.



within a field may be useful in identifying zones suitable for initial treatment to prevent further spread or for directing the differential application of insecticide over the entire field. In this second case, the whole field may receive a minimum application rate with higher rates being applied to the outbreak zones.

The appropriateness of site-specific management of insect pests would, however, be limited to the more sedentary pests and lifecycle stages, because insect population dynamics are often greatly influenced by environmental factors on a larger scale than those considered here (Crossley *et al.* 1984).

Application of Irrigation Water

This may not be feasible in a flood irrigation system at present, however, the investigation of superior methods of control now appears warranted on the basis of financial, social and environmental considerations. Drip irrigation management poses particular problems with cultivation and flow control but could offer future solutions to the gaseous and percolatory loss of chemicals from the field.

Field textural variation may already be contributing to variation in infiltration so research in the immediate future may focus on textural monitoring and more frequent but smaller water applications to ensure more control of soil water movement.

COLLECTING DATA ON SPATIAL VARIABILITY

A critical requirement for collecting data on the spatial variation in any land-based attribute is an ability to accurately resolve ground positions in the field. All data must be georeferenced to facilitate the production of a representative field map and for the purpose of correlating the information on various attributes obtained from a field. The technology is now available to determine the position of a stationary/moving vehicle with much increased accuracy.

REAL-TIME POSITIONING SYSTEMS

Two types of system have been developed, Global Positioning Systems (GPS) based on information received from a number of geo-stationary satellites, and a local triangulation system which operates using information from a land-based beacon system.

GPS receivers have been developed by a number of companies that utilise navigation satellites owned by the government of the United States of America (NAVSTAR).



Another constellation of satellites is controlled by a consortium headed by the Russian Government (GLONASS), using a similar operations system. In Australia, the US satellite network appears more accessible so its operation will form the basis of the following general discussion.

The American satellites are currently controlled by the U.S. Army who regulate the quality of the signal available to civilian users. This 'selective availability' reduces the accuracy of GPS especially in the 'stand-alone' mode of operation whereby a ground position is calculated using a single receiver that tracks and obtains data from the satellites. The reported accuracy of this system varies from ± 30 metres up to ± 100 metres.

The errors introduced by selective availability can be reduced with the introduction of a second receiver installed at a fixed, surveyed position. The position data collected by the fixed receiver can be used to calculate a correction factor that may be applied to the data gathered by the mobile receiver. Using a GPS in this operational configuration is known as differential GPS (DGPS). This correction may be applied to the mobile receiver's data following an entire mapping operation (post-processing) or as individual positions are calculated by the mobile receiver (real-time).

Figure 13 depicts the basic set-up of a real-time DGPS. The mobile machinery (A) and the fixed position base unit (B) interrogate the navigation satellites (C). (B) continually compares its surveyed position with that calculated using the data from the satellites (C). A correction (differential) is computed to truth the incoming data and the differential is relayed by radio frequency to the mobile unit (A). The mobile unit is thus able to more

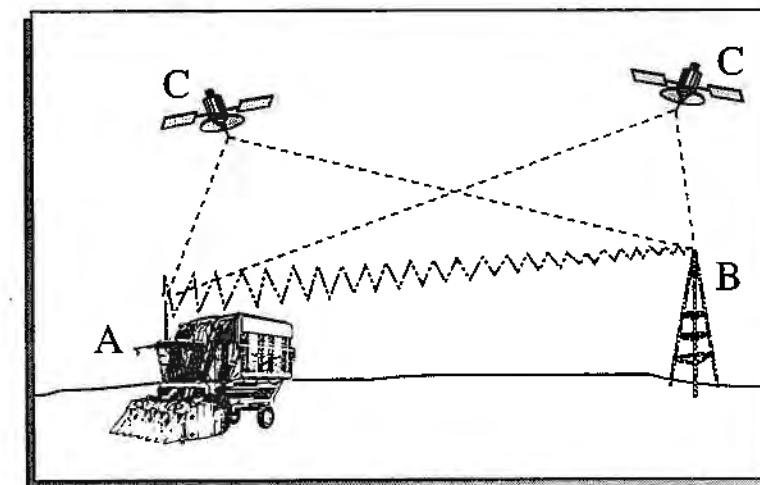


Figure 13. Operational configuration of a real-time Differential GPS (DGPS)



accurately calculate its position from the satellite data (C) and the differential supplied by the base station (B).

Real-time DGPS allows instantaneous position reckoning and the associated ability to store position information with other observations while they are being observed. This is not possible with post-processing of the differential. If the differential signal is broadcast on a FM frequency side-band, the range of the GPS system becomes quite extensive. The capability to accommodate multiple users, and therefore shared costs, also becomes a possibility. Correction signal coverage is available for the major cotton growing regions through Auslig[†] who lease a proprietary programmed receiver to the user.

The differential calculated using one fixed receiver reduces/removes the GPS system errors produced by the selective availability of the signal, the internal position and time monitoring errors associated with the satellites and the time monitoring errors associated with the receivers. Accuracy can be improved to within ± 1 metre, however the precision depends upon the proximity of units A and B such that the accuracy degrades to approximately ± 3 metres at a separation distance of 150 kilometres.

To further increase the accuracy of the system requires reduction/removal of the errors attributed to variation in the transmission of signals through the atmosphere. These increase in magnitude as separation distance induces differing satellite 'lines of sight' in units A and B. A solution has been designed (Figure 14) that incorporates a wide network of fixed position receivers (D) that communicate with the GPS satellites (E) and calculate an individual correction which is then passed to a master station (F). The master station

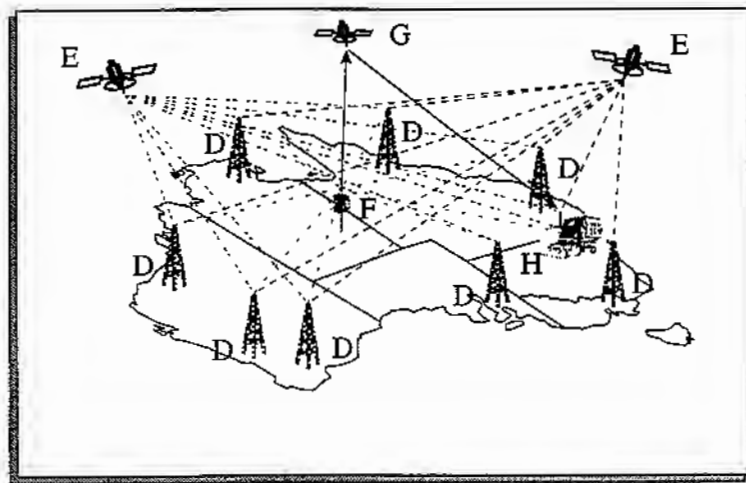


Figure 14. Operational configuration of a Wide-Area Differential GPS (WADGPS).

[†] Auslig, Canberra, ACT, Australia.



computes a vector correction from all the individual stations and relays this to a general communications satellite (G) that increases the broadcast range to remote users (H). This correction dramatically reduces the 'line of sight' error as well as further decreasing the GPS system errors previously mentioned. This operational configuration is known as Wide Area Differential GPS (WADGPS) and can provide sub-metre accuracy that only slowly degrades to approximately ± 2.5 metres at 3500 km. Internal receiver noise contributes significantly to the remaining error and should be reduced as electronic technology continues to advance.

Local triangulation systems rely on calculating a position relative to a configuration of ground based beacons. One such system, Accutrak[†], currently offers individual Canadian and U.S. farms a radio-frequency, time-multiplexing positioning network. As depicted in Figure 15, the mobile unit (I) is in radio contact with previously surveyed fixed beacons (J) that allow radial distance real-time positions to be calculated and converted to x,y data at a rate of 10 times per second. Beacons may be permanently fixed in position or moved to allow coverage of new areas, however the position must always be initially surveyed. The low power system currently available has an operating radius of 15-25 kilometres. A high power system (~44 MHz) is being developed to cover 30-50 kilometres. The availability of this band for civilian use in Australia must be investigated.

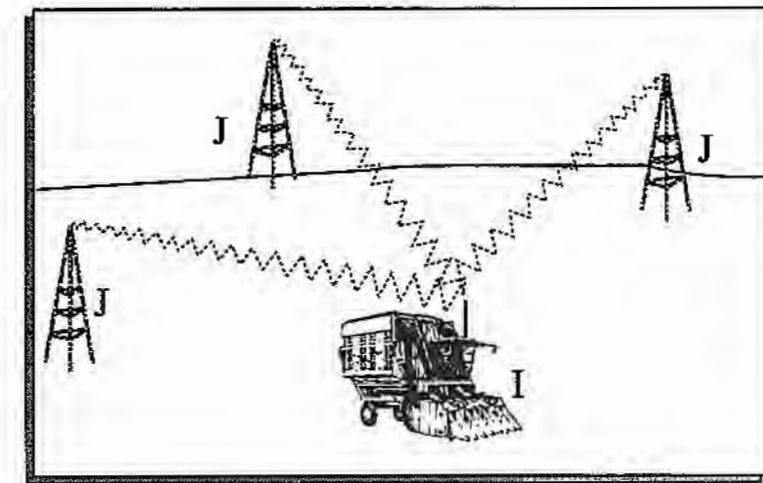


Figure 15. Operational configuration of the Accutrak[®] System.

[†] Accutrak Systems Ltd., Regina, Saskatchewan, Canada.



ATTRIBUTE OBSERVATION STRATEGIES

Data Already Available

Some data on soil/crop variability may already be available. Shire soil maps are compiled from coarse-scale survey information but may be useful as an initial indication of the soil variation to be expected on a farm level. Soil sampling and testing that may have been carried out in previous years would also provide useful data on temporal variation and soil response to treatment strategies. Lint yield and concomitant chemical application regimes from past harvests, on a farm or field basis, will also provide valuable information.

Discrete Sampling

This refers to the sampling of variables within a field using either a grid-based or statistically based random sampling strategy. In the cotton industry, the technique is mainly applied in observation of soil attributes but could be applied to pest levels (such as *Heliothis armigera* pupae levels in the soil).

Sampling by grid is at present a laborious procedure if large areas are to be tested. For the production of accurate soil maps, the appropriate grid size must be determined. At present this is dependent upon the variable/s of concern and the trade-off between accuracy and cost. To increase the speed and efficiency of such sampling (and eventually reduce the per-sample cost) a small wide-tyred utility vehicle such as a 4 wheel motorbike, equipped with positioning technology and an industrial grade personal computer could be employed. Such a unit could be used to collect soil samples for *ex situ* chemical analysis or perform *in situ* measurements of attributes such as moisture content by TDR, structural interpretations using air permeability (Fish & Koppi 1995) and salinity by electromagnetic induction (EM). The position of the sample site would be logged simultaneously using the on-board positioning technology.

Continuous Sampling

This refers to the practice of measuring variables 'on-the-go'. Collecting data on the variable/s during a pass over the field produces a more fluent data set and removes the need for grid sampling and post-sampling analysis. There are no sample transport/storage concerns, no laboratory variation to contend with and no delay in accessing the results. Ultimately, the results are available in real-time so that farming operations dependent on sampling outcomes may be accomplished in the same pass of the field.

Development of technology in the areas of soil sampling and yield measurement is progressing rapidly. The more important and advanced areas of sensor research include:



Nitrogen

For soil nitrate sampling, ion selective probes have been produced and involved in a limited release (Borgelt 1993). Continuing work is focusing on the use of 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. Encouraging responses to nitrate ions are being observed (Borgelt 1993).

The development of electrochemical nitrate measurements using a nitrate selective electrode in an electrochemical cell to monitor nitrate levels in an extraction obtained from an 'on-the-go' sample is progressing. Adsett and Zoerb (1991) designed and tested a mechanised monitoring station that operated at a forward speed of 3 km/hr and sampled every 30 seconds. The major limitation, at this stage, is the time to obtain the nitrate extraction. Commercial release may be expected in 1995.

Organic Matter

An innovative soil organic matter (OM) measurement device has been recently released. Amounts of OM may directly influence the levels of herbicide and fertiliser that should be applied to a field, with the magnitude of this influence mediated by the percent clay content of the soil. By monitoring the variation in OM during the application operation, the required level of chemical can be applied. The idea, marketed by Tyler[§], uses single wavelength (660 nm) red light to measure the colour of the soil. Red light emitters and a sensor (Figure 16) are mounted on the base of a tine (Figure 17) that is attached by an articulating mechanism to the front of the application vehicle (Figure 18). The scanning light system requires calibration for each new landscape and moisture content level.

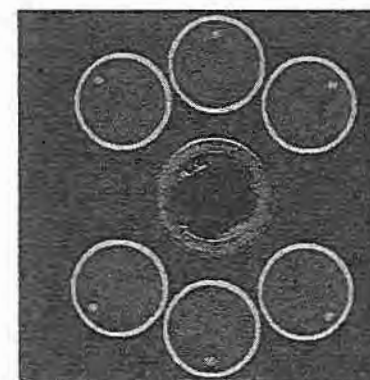


Figure 16. Red light O.M. sensors



Figure 17. Tine mounting for sensor

[§] Tyler, Benson, Minnesota, USA.



Figure 18. Mounting system for the tines

The OM quantity reading obtained from the sensing array is passed to an on-board computer that calibrates chemical application rates with this information. These rates are then used to control the output of the chemical applicator as it passes the measurement point. The variable-rate application technology (VRT) that has been developed for this process has been discussed in an earlier section.

A more complex system utilising near infrared (NIR) light of multiple wavelengths is in the process of commercialisation. This will be a landscape and moisture independent sensor, and although more costly and less robust, will provide a more versatile measurement tool. For the Grey Cracking Clays and Black Earths of the north-west cotton fields, the single wavelength instrument may be limited by the characteristic dark colour that is a function of both the organic matter and ferro-magnesian mineral contents. The multiple wavelength device may prove more suitable OM detector when modified for attachment to an angled tine for use in permanent bed systems.

Other soil attributes

For the measurement of soil salinity, EM instrumentation has been mobilised by researchers in Canada and the U.S.A. The Canadian operation involves mounting an EM38 on a sled constructed of PVC piping and towed by a four wheel motorbike (Henkes & Dietz 1994). This offers a continuous assessment of salinity levels in the crop root zone, and could be adapted for pre-sowing use in permanent bed cropping. A more expensive, and more robust, tractor mounted EM38 forms the basis of the American salinity assessment program (Rhoades 1992) that would be suitable for use in cotton cropping without modification.



The soil reflectance sensor, previously discussed as a means of determining organic matter content, may also prove useful in recognising gradual changes in soil type and texture that would be valuable in the accurate classification of field variation in crop yield potential. This technique appears particularly promising for use in areas where cracking clay soil intergrades with lighter textured red soil.

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. The requirements and development of a number of contact and non-contacting sensing techniques, including electrical resistance, microwave attenuation, capacitance probes, nuclear magnetic resonance (NMR), near-infrared reflectance, microwave reflectance and ground-penetrating radar (GPR) are examined by Whalley & Stafford (1992). The contact sensing techniques, with the inclusion of the Time Domain Reflectometry (TDR) measurement technique, appear most suitable for incorporation in a cultivation tine. GPR appears to offer the greatest depth of penetration of the non-contacting sensors.

Information on the variation in soil compaction may be obtained via the moisture calibrated correlation with soil strength. Alihamisyah and Humphries (1991) tested and recommended a shank-mounted, horizontally operating penetrometer with a 30° prismatic tip leading-edge to measure the mechanical impedance of the soil 'on-the-go'. This technique could be employed in conjunction with a moisture probe to quantify soil strength.

Yield Monitoring

The continuous measurement of crop yield has received much attention in the grain industry and sensors for grain yield and moisture content are being routinely fitted to headers in the U.S.A. The cotton industry has not fully embraced the concept of yield mapping, however a sensor suitable for use in a cotton picker could be developed.

Once the cotton has cleared the trash extractor unit, a sensor to measure the density of fibre passing a given point in the pneumatic conveyor could be employed (Figure 19). Alternatively, the mass of lint leaving the conveyors over a certain time period could be determined using a load-cell based instrument. An instrument designed on either method would need to overcome the relevant operational complications arising from ambient light and dust levels, contaminants within the lint flow increasing the perceived density and mass and machine vibration reducing measurement precision.

A technique utilising the properties of light transmission and absorption appears to offer an effective option. A prototype sensor based on this principle has been developed (Wilkerson *et al.* 1994). It combines a plane of light propagated orthogonally to the cotton flow and a light receptive array that responds to the light attenuation caused by the passage of cotton.

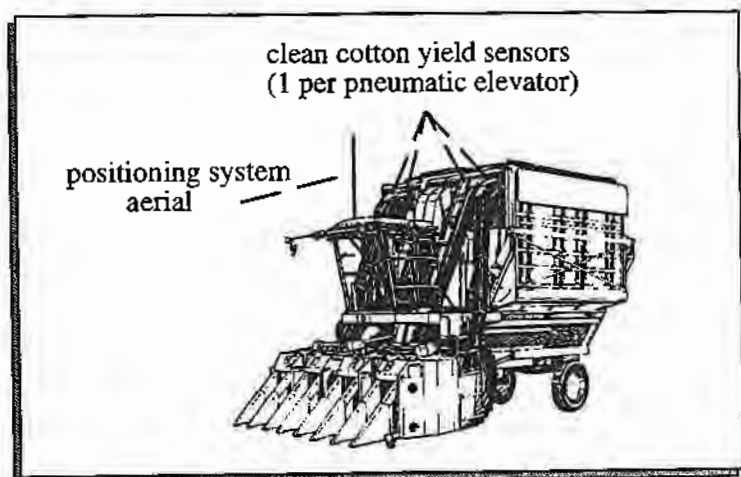


Figure 19. Proposed location for a lint yield monitoring system on a cotton picker

The output of the sensor correlates with the volumetric flow rate of cotton in the pneumatic conveyor. Installation of such a sensor, shown diagrammatically in Figure 20, in each pneumatic conveyor would provide extremely valuable data on the variation in productivity at small scales over the farm.

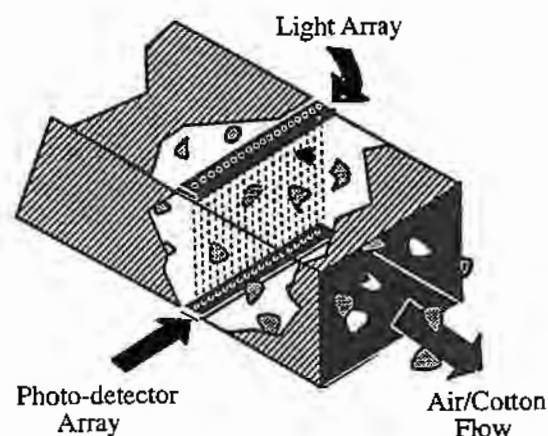


Figure 20. Proposed lint yield monitoring system for a cotton picker (after Wilkerson *et al.* 1994)

Remote Sensing

Aerial remote sensing is a technique for collecting data on the spatial variation of both soil and crop parameters. Sensing prior to sowing a fallow field may provide data on soil moisture and texture variability (refer Figure 2) and during the cropping phase vegetative growth can be monitored for variation resulting from nutrient deficiencies, water stress or pest infestation. This form of data is highly suitable for quantifying more coarse-scale variation but as the resolution of the technology increases, and ground-truthing is improved, this may become a more useful tool for assessing small-scale variation.

INTEGRATING DATA ON SPATIAL VARIABILITY

Once the data on spatial variability has been collected it is necessary to establish whether the observed variability is significant enough to warrant 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.

At present it would appear that the only method of arriving at such a decision is to apply a purely economic test to the results of a yield simulation model. As previously discussed, the environmental/social costs are difficult to substantiate. However, the possible introduction of stricter chemical-use legislation and associated penalties will introduce a greater tangibility to these societal costs and eventually facilitate their inclusion in objective decision making. The immediate challenge is to ascertain the agronomic suitability of crop yield potential (as employed with the economic models herein) or whole crop growth models as determinants of the required treatment levels.

In either case, the large quantity of data obtained and the diversity in continuity, sampling scale and time frame poses integration, handling and storage problems. Firstly, data from sources already available, along with that obtained from discrete sampling, must be combined with real-time information to predict a value for each soil property at a given location. The previously obtained site knowledge may be derived from digitised soil maps, digital elevation models (Odeh *et al.* 1995), seasonal aerial infra-red scans of the site and point sample data.

New input data, which will provide estimates of short-range variation, would be sourced from the calibrated real-time sensing devices in use at the time of the field operation e.g. tine-mounted nitrogen or organic matter sensors and electromagnetic induction. As an example, a model for this integration process may be based on a generalised spatial model of the form:



$$s(x) = a(x) + z(x) + e(x) \quad (1)$$

where:

- $s(x)$ = soil property (s) at location (x)
- $a(x)$ = previously obtained data for predicting soil property
- $z(x)$ = new real-time input data
- $e(x)$ = residual variation (to be minimised)

The exact models employed may be generalised linear models (McCullagh & Nelder 1989), non-linear generalised additive models (Hastie & Tibshirina 1990), tree-based models or neural network models (Demuth & Beale 1993). The suitability of each form requires assessment for use in a cotton farming system.

In operation, the chosen model will form the basis of a computer program designed for application on-board a mechanised farm implement. A file containing any previously obtained geo-referenced site knowledge would be installed in the cabin computer prior to entering the field. This data file will be accessed, interpolated in real-time, and combined with new real-time input data (using the chosen model) to predict a value for the soil variable at each observation point on the site plan.

To aid the integration process, data based on hard-set classification methods, such as soil class/type extracted from soil maps, would be best converted to a more continuous form that would allow smoother combination with data obtained from 'on-the-go' instrumentation. A method of achieving such a vital operation has been suggested by McBratney & Whelan (1995) but requires further development.

With the data in a more continuous (and therefore more accurate) form, the task of collating both the GPS and field variation data will require a Decision Support System (DSS). This allows the data to be organised into a form that can be readily assimilated into models that predict the necessary action to be taken. A convenient form of DSS is a Geographical Information System (GIS). Many GIS packages are commercially available and would be suitable for use in a cotton production DSS.

The provision of the necessary calibration equations and the optimal combination of prior knowledge and new real-time input data offers an opportunity to greatly improve the information retrieved from cotton field soil surveys and further the development of the cotton industry as a leading innovator in Australian agriculture.



BENEFITS OF INCLUDING SPATIAL VARIABILITY WITHIN A MANAGEMENT SCHEME AND THE PITFALLS OF MISCALCULATING THE VARIABILITY

The economic benefits to be gained from the inclusion of information on spatial variation are more easily substantiated than the environmental or social gains. This arises because these later gains include broad societal improvements such as reduced contamination of the landscape and foodstuffs, along with a potential for improved sustainability through increased collaboration with natural diversity.

ECONOMIC EXAMPLES FOR FERTILISER APPLICATION

Any analysis of the economic benefits ideally requires some knowledge of the nature and degree of soil variation exhibited at a site as this will influence the form of differential treatment undertaken. For the example of differential fertiliser treatment, a site may possess (or be believed to possess) a uniform yield potential but irregular initial soil concentrations of the nutrient in question. The differential application of fertiliser to bring the whole site concentration to a single, required baseline level may be a sufficient treatment (areas already above this baseline would be untreated).

Should the yield potential at a site, as well as the initial soil nutrient concentrations, be deemed to fluctuate over the field, a range of required baseline levels would need to be calculated to co-ordinate the optimum fertiliser application regime.

The possibility of financial benefits from these two different approaches will be examined separately.

Uniform Yield Potential Across a Site

The uniform yield potential of a field may arise from the actual or perceived homogeneity of critical soil attributes governing the yield of a cotton crop. Such homogeneity is assumed in the majority of management systems where soil sample test results are averaged to provide a single estimate of the whole field status. Uniform yield may also be a goal of production.

A simple one-dimensional model has been employed to examine the effect of site-specific management under this scenario. The predictions are based on minimum tillage management of cotton grown on a Grey Cracking Clay; N fertiliser @ \$1.07 per kg of applied N (supplied pre-sowing as anhydrous ammonia and including associated increases in the cost of irrigation, insecticide and defoliant); cotton lint @ \$1.80.



The model tests the difference in financial return obtainable when comparing fertiliser programs based on differential versus mean-of-field treatment. A theoretical 1000 ha site is examined using varied levels of knowledge of the initial soil NO_3^- content. The initial NO_3^- distributions were generated using a first-order autoregressive function of the form:

$$Ns_i = \beta 10^{s_i} \quad (2)$$

where:

- Ns_i = soil NO_3^- level (kg ha^{-1})
- β = median regulating coefficient
- s_i = $\alpha s_{i-1} + k \eta$
- α = autoregressive parameter
- k = coefficient
- η = random sample from a normal distribution ($N(0,1)$)

Six log-normally distributed populations comprising 1000 initial soil NO_3^- values were constructed, three based on each of two mean initial soil NO_3^- levels (11.6 & 45.3 kg/ha). These values were chosen from the minimum tillage treatments of a fertiliser management study by Constable *et al.* (1992). Three different knowledge scenarios for the data on initial soil NO_3^- were compared for each distribution: exact information at each sampling point, an inexact model of the information at each point, and the mean value of the site.

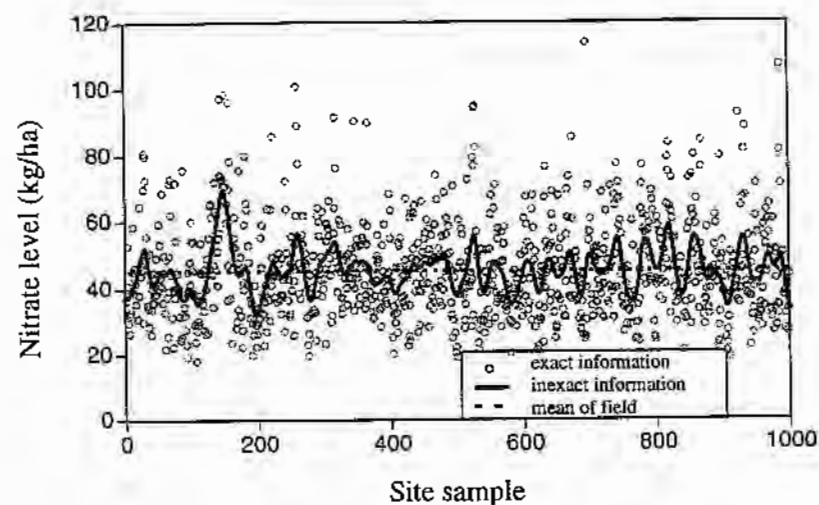


Figure 21. Calculated NO_3^- distribution and associated knowledge levels



Exact information describes the ultimate goal of site-specific soil management. The inexact information, derived from fitting a smoothing spline to the distribution data, is taken to represent the general level of information available when only partial sampling is undertaken or when inadequate data is used in soil fertility models. The mean value of the site is the common method of constructing fertiliser application regimes. An example of these information levels for one initial soil NO_3^- distribution is presented as Figure 21.

Two yield response functions (3 & 4) were utilised. Both are rearrangements of functions from the minimum tillage treatments reported in Constable *et al.* (1992). Function 3 was employed for distributions with a mean NO_3^- value of 16.77 kg/ha while function 4 was engaged for distributions with a mean NO_3^- value of 45.24 kg/ha .

$$y = e^{-(6.7714035 - 0.0055853N + 0.00001367N^2)} \quad (3)$$

$$y = e^{-(7.53871 - 0.004117N + 0.000011N^2)} \quad (4)$$

where:

- y = yield cotton lint (kg ha^{-1})
- N = N application rate ($\text{kg available N ha}^{-1}$)

In the cotton industry, nitrogen application to fields with soil test nitrate (NO_3^-) levels below 25 mg/kg (97.5 kg/ha ; 0-30cm depth; $\rho = 1.3$) is recommended (Daniells & Larsen 1991). Given a uniform yield response function, a desired N level for maximising financial return was obtained using marginal cost analysis on Equations 3 (190 kg applied N/ha) and 4 (177 kg applied N/ha). The applied N required for each scenario (other than mean-of-field treatments) was calculated by identifying the deviation from the mean initial NO_3^- at each point and adjusting the mean N application rate according to the scale suggested by Daniells & Larsen (1991). Summing the individual values and dividing by 1000 provides a mean N application rate per hectare that facilitates financial comparisons.

It is implicitly assumed in this example that the levels of soil N are uniformly available and that the crop response to soil N is uniform across the 1000 ha site.

When other than exact initial N fertility information was used, the calculated applied N quantities were compared with those obtained using exact information and the differences used to quantify points that were under- or over-fertilised. Under-fertilised sites received



a yield penalty based on the relevant response curve, and over-fertilised sites incurred excess fertiliser costs and a yield adjustment according to the effect of increased fertility on the relevant response curve.

Table 2 displays the results of applying the model to 3 'fields' with equal mean initial soil NO_3^- levels of 16.77 kg/ha but differing variances which produces dissimilar soil NO_3^- distributions. By maintaining a constant mean NO_3^- level and modifying the variance of the distribution, the influence of within-site variability on the fertiliser application program may be examined.

Fertilising using exact information produced an increase in returns over using inexact information that ranged from \$2/ha for the narrower NO_3^- distribution to \$14/ha for the wider NO_3^- distribution. The savings afforded by employing inexact information compared to the 'mean-of-field' value ranged from \$1/ha to \$4/ha. The maximum savings, derived from the comparison of fertiliser application based on exact information with that using the 'mean-of-field' value, ranged from \$3/ha to \$18/ha.

Knowledge level	Initial NO_3^- Variation								
	small (CV=15.7%)			medium (CV=32.0%)			large (CV=55.6%)		
	Exact	Inexact	Mean	Exact	Inexact	Mean	Exact	Inexact	Mean
Applied N (kg/ha)	190	190	190	190	190	190	190	190	190
Yield (kg/ha)	1539.4	1539.0	1538.9	1539.4	1537.9	1537.4	1539.4	1534.8	1533.2
N waste (kg/ha)	—	1.6	1.9	—	3.3	3.8	—	5.4	6.4
Return (\$/ha)	2567	2565	2564	2567	2561	2560	2567	2553	2549
Loss (\$/ha)	—	2	3	—	6	7	—	14	18

Table 2. Simple economic analysis of information-based fertiliser programs. 16.77kg/ha mean initial NO_3^- distribution with three differing variances.



Knowledge level	Initial NO_3^- Variation								
	small (CV=15.7%)			medium (CV=32.0%)			large (CV=55.6%)		
	Exact	Inexact	Mean	Exact	Inexact	Mean	Exact	Inexact	Mean
Applied N (kg/ha)	177.0	177.0	177.0	176.7	177.0	177.0	175.7	177.0	177.0
Yield (kg/ha)	2759.5	2754.8	2754.3	2759.5	2742.3	2736.4	2759.5	2706.0	2689.9
N waste (kg/ha)	—	4.4	5.2	—	9.0	10.6	—	15.9	18.4
Return (\$/ha)	4778	4766	4763	4778	4737	4725	4779	4666	4634
Loss (\$/ha)	—	12	15	—	41	53	—	113	145

Table 3. Simple economic analysis of information-based fertiliser programs. 45.24kg/ha mean initial NO_3^- distribution with three differing variances.

Table 3 displays the results of applying the model to 3 'fields' with equal mean initial soil NO_3^- levels of 45.24 kg/ha but, as above, differing variances producing dissimilar soil NO_3^- distributions. Applying a fertiliser application program using exact information produced an increase in returns over the use of inexact information that ranged from \$12/ha for the narrower NO_3^- distribution to \$113/ha for the wider NO_3^- distribution. The financial benefit of including inexact information compared to the 'mean-of-field' value ranged from \$3/ha to \$32/ha. The maximum benefit, obtained from the comparison of fertiliser application based on exact information with that using the 'mean-of-field' value, ranged from \$15/ha to \$145/ha.

The results suggest that in a field with very low initial NO_3^- fertility or a small initial NO_3^- variance, the site mean may be an economical estimate for constructing N fertiliser programs. As the initial NO_3^- fertility, or the inherent NO_3^- variability increases, the improvement in returns offered by attention to detail in a N fertiliser application regime become more significant.

This simple economic model provides a basic insight into the economic effects of a site-specific management program in a field where the yield potential is perceived to be uniform. The validity of such an assumption is debatable however it is continually accepted in constructing traditional fertiliser application programs. The inclusion of a more



complex scenario (and arguably more realistic) is warranted in an effort to more thoroughly examine the consequences of site-specific management.

Diverse Yield Potential Across a Site

The inherent diversity in soil will usually extend beyond the initial levels of soil nutrients. In many instances spatial variation in the soil may arise from substantial compositional changes that affect the total yield potential of the soil regardless of management intervention. Such soil variability underlies the natural variation in vegetative growth and yield observed in most native ecosystems. Incorporating this natural variation in a crop management scheme would require a knowledge of the variation in yield response across a site. This model attempts to examine the economic consequences of varying yield potential on a nitrogenous fertiliser regime. Environmental implications can also be inferred.

For this more complex management scheme, the yield potential at 30625 individual points on a two-dimensional field were manipulated by assuming each to be a mix of two soil types (designated A & B) that possess differing yield response functions. Yield response functions for Soil A (Figure 22) and B (Figure 23) were generated using quadratic approximations of those available in Constable *et al.* (1992).

The form of the yield response function is dependent on the initial soil NO_3^- concentration up to an initial concentration of 97.5 kg/ha, the limit where N fertiliser application is assumed to be non-beneficial (Daniells & Larsen 1991).

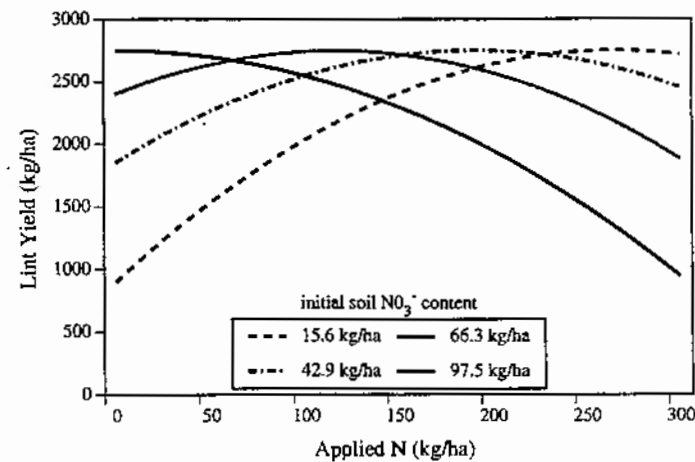


Figure 22. Soil A yield response functions

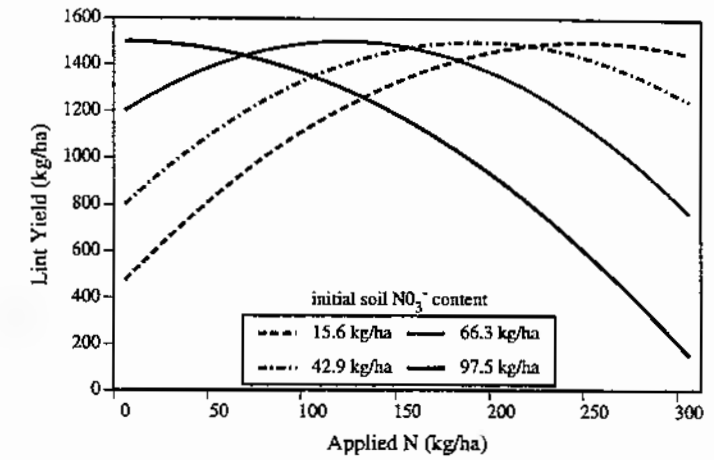


Figure 23. Soil B yield response functions

Combining the functions for a particular soil produces a two-dimensional yield response surface function that encompasses the range of initial NO_3^- and applied N parameters that were used in its construction i.e. initial NO_3^- : 0 to 97.5 kg/ha ; applied N : 0 to 300 kg/ha. These are shown for soil A as Figure 24 and soil B as Figure 25.

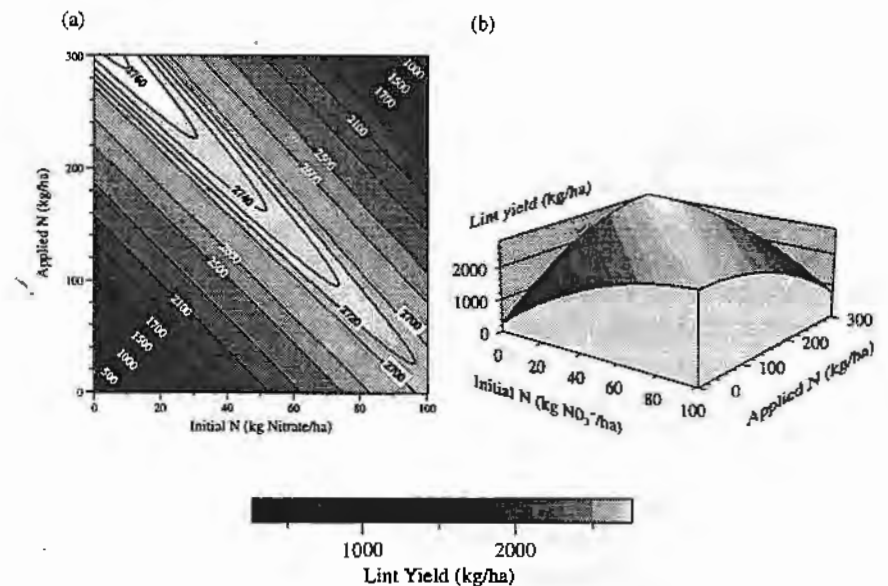


Figure 24. Soil A: yield response surface as a function of initial N and applied N. Shown in contour plan (a) and perspective(b)

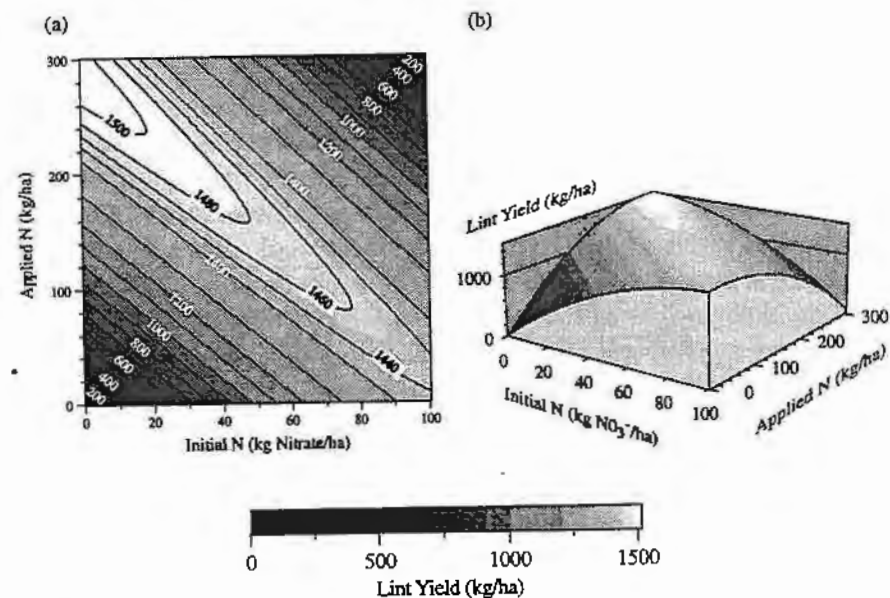


Figure 25. Soil B: yield response surface as a function of initial N and applied N. Shown in contour plan (a) and perspective (b).

A random field describing the degree of membership in soil A at each point was generated (Figure 26). Membership at each point in soil B is the complement of the membership at each point in soil A i.e., the membership in A and B at each point must sum to 1.

Initial NO_3^- levels at each point were obtained from a log-normal distribution with a mean of 45.24 kg/ha (based on a mean field level reported by Constable *et al.* 1992) and a standard deviation of 23 kg/ha. The assumption that this standard deviation represents the variation in a 'real' field is supported by co-efficient of variation (CV) figures obtained from field sampling by the authors (CV = 50%) and data reported by Rochester *et al.* (1991) (CV range of 14% to 98%).

A map of the initial NO_3^- levels is shown as Figure 27. A correlation of 0.3 between initial NO_3^- and membership in soil A is included based on the assumption that soil with greater yield potential would possess more organic matter and therefore retain higher reserves of mineralisable N and thus NO_3^- .

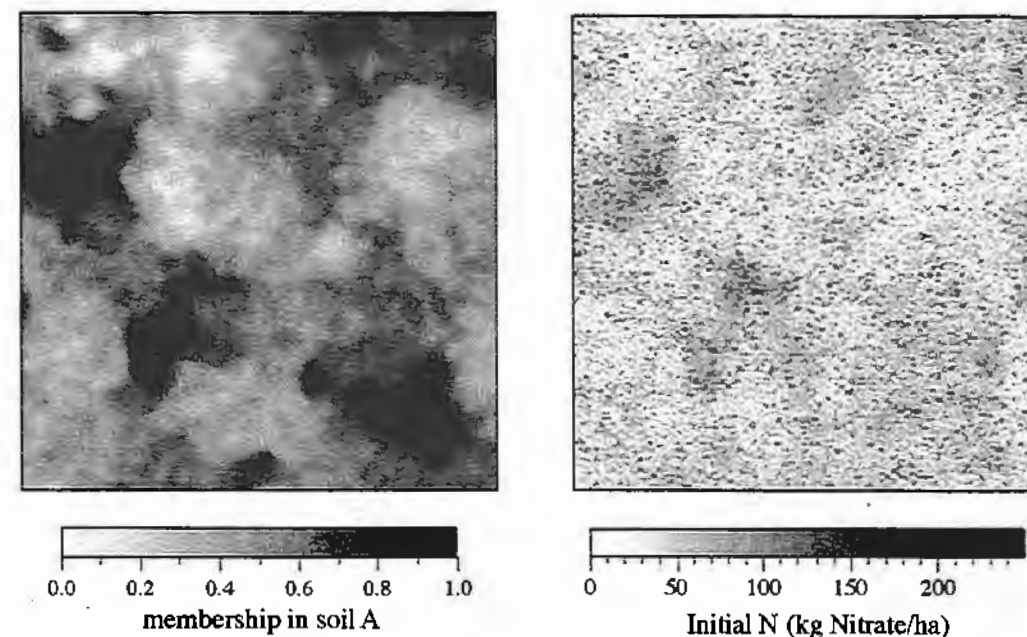


Figure 26. Map of membership in soil A. Figure 27. Map of initial soil nitrate.

Using this information, an individual yield response function for applied N can be constructed for each point on the site. This function can be used to determine the yield at each point for a given amount of applied N or, conversely, determine the amount of applied N required to achieve a yield goal. Here, the yield goal is defined by the economic optimum point on each respective yield response function. This is the point where the financial return for applying 1 unit of N fertiliser equals the per-unit cost of the fertiliser. As in the previous financial example, it is the point where marginal revenue (MR) equals marginal cost (MC).

In this study, conventional fertiliser management (where the adoption of a fixed quantity application regime is based on mean-of-field initial NO_3^- levels) is compared with a differential treatment system supported by the determination of the economic optimum quantity of fertiliser for every identified point on the site.

For the mean-of field case, the mean initial NO_3^- level of 45.3 kg/ha is assumed to represent the value at each point, and each point is characterised by the soil A yield response curve for this value of initial NO_3^- . Such a scenario results in the calculation of a single fertiliser application level for the entire site.

In the differential treatment scenario, individual initial NO_3^- levels are known for each



point and each point is characterised by its membership to both soil A and B. Equations 5 and 6 show the generalised functions describing yield response to initial NO_3^- and applied N for soil A and soil B respectively.

$$Y_A(N_i, N_{app}) = c_A + d_A \cdot N_i + e_A \cdot N_{app} + f_A \cdot N_i^2 + g_A \cdot N_{app}^2 + h_A \cdot N_i \cdot N_{app} \quad (5)$$

where:

$Y_A(N_i, N_{app})$ = Soil A yield response as a function of Initial NO_3^- (N_i) and Applied N (N_{app})

$c_A, d_A, e_A, f_A, g_A, h_A$ = Soil A yield response function co-efficients

$$Y_B(N_i, N_{app}) = c_B + d_B \cdot N_i + e_B \cdot N_{app} + f_B \cdot N_i^2 + g_B \cdot N_{app}^2 + h_B \cdot N_i \cdot N_{app} \quad (6)$$

where:

$Y_B(N_i, N_{app})$ = Soil B yield response as a function of Initial NO_3^- (N_i) and Applied N (N_{app})

$c_B, d_B, e_B, f_B, g_B, h_B$ = Soil B yield response function co-efficients

Values for the co-efficients as used in this study are given in table 4.

Co-efficient	c_B	d_B	e_B	f_B	g_B	h_B
Value	16.10	26.71	10.44	-0.125	-0.018	-0.096
Co-efficient	c_A	d_A	e_A	f_A	g_A	h_A
Value	261.62	47.04	15.59	-0.225	-0.024	-0.148

Table 4. Co-efficient values for soil yield response functions.



The yield response function applicable to each point is then constructed using a linear mixing procedure. Equation 7 is the generalised form of this function, where the membership values weight the response function co-efficients for soil A and B.

$$Y(N_i, N_{app}, m_A) = (c_B + (c_A - c_B) \cdot m_A) + (d_B + (d_A - d_B) \cdot m_A) \cdot N_i + (e_B + (e_A - e_B) \cdot m_A) \cdot N_{app} + (f_B + (f_A - f_B) \cdot m_A) \cdot N_i^2 + (g_B + (g_A - g_B) \cdot m_A) \cdot N_{app}^2 + (h_B + (h_A - h_B) \cdot m_A) \cdot N_i \cdot N_{app} \quad (7)$$

where:

$Y(N_i, N_{app}, m_A)$ = Soil yield response as a function of Initial NO_3^- (N_i), Applied N (N_{app}) and Membership in soil A (m_A)

From this model the economic optimum N application can be calculated for each individual point. For example, a point in the study site with an initial NO_3^- level of 39.53 kg/ha and a membership in Soil A of 0.593, has a yield response function that falls between the functions characterising the yield response for soil at this initial NO_3^- level and with full membership of 1 in soil A or B (refer Figure 28).

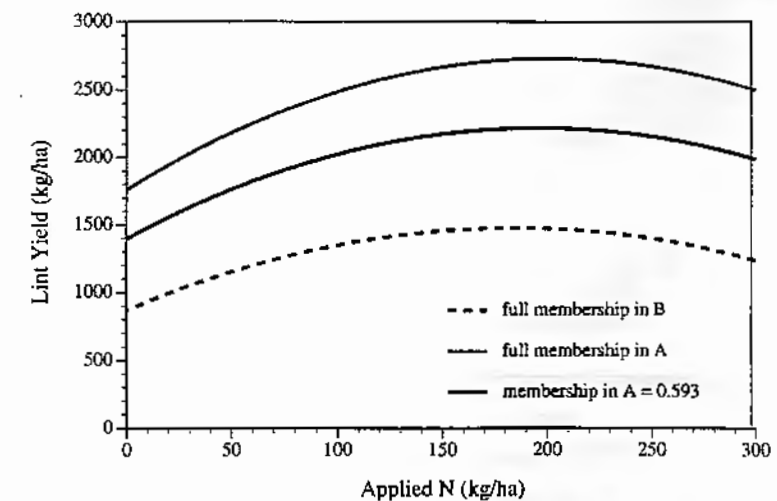


Figure 28. Yield response functions for a point with an initial NO_3^- level of 39.53 kg/ha and soil memberships of 0.593 and 1 in soil A; 1 in soil B.



The final yield achieved in both these scenarios is calculated from the yield response functions determined using the actual membership in both soil A and B at each point. This mimics the effect of natural soil variation encountered even if a mean initial soil NO_3^- test as been used to determine a uniform N fertiliser application. Table 5 details the financial differences in running the two management systems on this simulated site.

Type of Application	Differential	Uniform
Yield (kg/ha)	2202	2114
N application (kg/ha)	165	171
Gross Profit (\$/ha)	3787	3622
Difference (\$/ha)	+165	—

Table 5. Financial comparison between differential and uniform N application.

The differences in yield obtained are displayed in Figures 29 and 30.

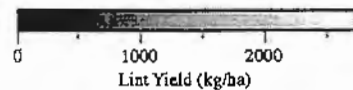
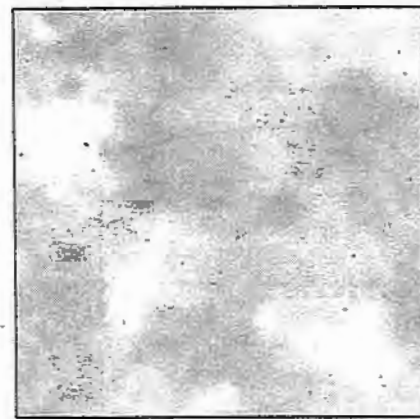


Figure 29. Map of lint yield following the use of differential fertiliser management.

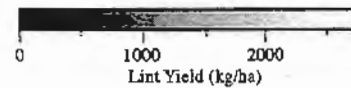
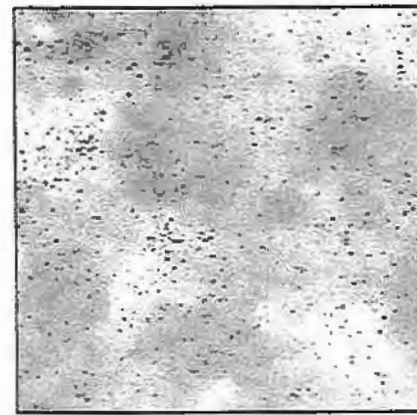


Figure 30. Map of lint yield following the use of uniform fertiliser management.



In Figure 29, the small number of discrete dark spots, indicating lower yield, occur where the initial NO_3^- level was above the 97.5 kg/ha mark assumed to be limiting. Considerably more 'noise' is evident in the yield pattern following uniform treatment (Figure 30) indicating many zones of over- and under-fertilisation at the site. It is important to acknowledge that these figures are the result of field simulations. They are only a guide to the degree of financial benefit, in terms of increased yield and targeted fertiliser use, that may be obtained from differential fertiliser treatment. The cost of additional equipment and operating expenses has not been taken into account, however, neither have the environmental benefits and risk reductions.

An insight into the impact of such a management system on environmental risk reduction can be gleaned from Figure 31. Here the points on the site that have been over-fertilised by the uniform treatment, as compared with the optimum determined using differential treatment, are displayed. The map reveals many instances where between 50 kg/ha and 175 kg/ha of unnecessary N fertiliser has been applied. These indicate areas of potentially excessive denitrification emissions, nitrate leaching and general resource waste. In the future, it is not unlikely that such environmental effects will be penalised financially.

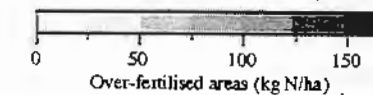
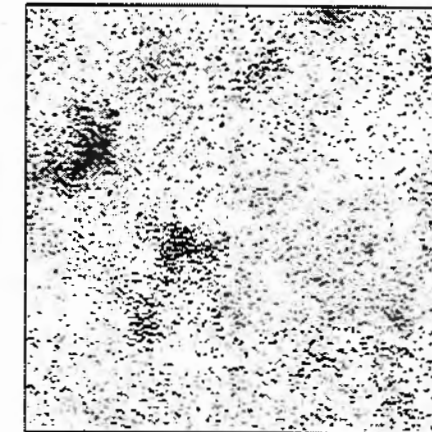


Figure 31. Zones of over-fertilisation at the simulated site

Intuitively, as the financial difference increases between the unit cost of a field operation (e.g. fertiliser application) and the unit value of cotton lint, the per-unit savings afforded by differential treatment will decrease. Current cotton lint prices of A\$2.50-\$3.00/kg and a relative stabilisation in the cost of N fertiliser and its relevant on-costs may reduce the savings proposed in Table 5. It is, however, difficult to conceive a situation where accurate knowledge of the variability in an influential soil attribute would not produce financial and



financial and environmental benefits.

The equipment cost is difficult to assess at this early stage in the development of a site-specific management scheme. Much research remains to be instigated and performed. Rudimentary experimentation in the U.S. Grain and Root Crop Industries has shown additional mean field management costs of between A\$20/ha (Wollenhaupt & Buchholz 1993) and A\$35/ha (Hammond 1993) to maintain a differential fertiliser application program for the nutrients N, P and K. These figures are useful as a basic guide for the Australian cotton industry.

RECOMMENDATIONS

This document has been prepared as a discussion paper and as such attempts to present information and ideas that may find future application in the cotton industry. The authors view the concept of site-specific management as an example of a precision agriculture philosophy. Its ultimate objective is the construction of a fully unified, real-time data acquisition-integration-decision process that, when appropriate, provides differential treatment to suit the variation in influential cropping system components. Economic optimisation of resource use and the minimisation of environmental impact is mandatory.

In the short term, it is recommended that consideration be given to preliminary investigation of the 3 main aspects of the proposed real-time model. They are:

- (1) *Data acquisition* – commence development, or adaption, of continuous yield and soil monitoring devices. The light-attenuation yield sensor appears viable and could have a wide application in the industry. Nitrate, organic matter and soil strength sensors are under development. Ideally, work on such instruments, designed for local conditions, should be instigated here, but co-operation with the prototype manufacturers abroad may hasten their adaption to the Australian cotton growing environment. In addition, a real-time soil moisture sensor needs to be developed to suit local soil conditions.
- (2) *Data integration* – experimentation is required to ascertain the most suitable model for the efficient collation of variability data already available with that obtained from real-time sensors. An agronomic study to define the importance of yield response surfaces or whole crop growth models in estimating crop yield potential at a site also necessary. This may be achieved in collaboration with the OZCOT/CERCOT simulation model.



- (3) *Management options* – development or adaption of machinery and controlling software for differential treatment is essential. Differential application of nitrogen fertiliser would appear to offer the greatest benefit to the industry in the future, given the probability of more restrictive environmental legislation. Co-operation with the commercial enterprises that are releasing technology for this purpose overseas would allow hybrid technology to be produced for the cotton industry. Engineering projects that consider the adaption of tillage and seeding implements to respond to real-time commands would also seem prudent.

As previously highlighted, the site-specific management concept hinges critically on the ability to accurately position machinery and sample sites in the field. Evaluation of external positioning aids must be undertaken. The cost of the different systems is decreasing as technology improves and usage increases. Local triangulation and WADGPS offer high precision but local triangulation may prove more operationally and financially cumbersome than WADGPS. Locally operated DGPS is a cheaper, though less accurate, alternative.

The long-term recommendations would urge the industry to consider developing the integrated system as a realistic and scientific method of reducing the misappropriation of inputs and attenuating the environmental impact of cotton farming to a level where wider societal expectations are met.



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