Cotton Catchment Communities CRC

FINAL REPORT

Part 1 - Summary Details

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1. Executive Summary

This CRC Cotton Catchments funded project (1.03.42) identified a number of novel remote sensing applications that have the potential to improve both the economical and environmental sustainability of cotton farming in the future. Such applications included the improved direction of in-season agronomic crop assessments based on varying crop vigour zones, the rapid identification of a range of abiotic and biotic constraints allowing for targeted response, and the development of an image based algorithm for the prediction of total yield and yield variability prior to harvest.

For the Queensland's Darling Downs region, SPOT5 satellite imagery was identified to be the most suitable for commercial adoption due to its low cost (AU$2.70 per km^2), 10m spatial resolution and ability to encompass most of the growing region within one image scene, therefore reducing the amount of image processing required before further analysis. The spectral reflectance maps produced from the SPOT5 imagery were comparable to those produced by higher resolution platforms, and when quantified in relevant agronomic terms including yield, provided accurate representation of actual crop variability.

In regards to the prediction of yield, atmospherically corrected SPOT5 imagery captured later in the growing season i.e. February and March, produced a higher correlation between measured yield samples and corresponding image data values. This correlation was further increased (R^2 = 0.66; n=82) through the derivation of a mid infrared plant cell density (MidIRPCD) index which minimised spectral saturation issues evident in near infrared based indices. The linear algorithm developed from the correlation between sampled crop yield and corresponding MidIRPCD values (Yield = 9.2686 * MidIRPCD - 13.996) proved to be an accurate predictor of total yield and yield variability of 20 validation crops within the Downs' (up to 100%, 24 ha) and Burdekin (up to 93%, 39 ha) growing regions. By using this protocol to derive in-season yield maps, growers have the opportunity to identify the location and extent of underperforming crop regions, enabling decisions regarding remedial action to be made, as well as have a reference layer to compare to commercially produced yield monitors. At a regional level, an accurate in-season estimate of total production can enable growers, Gins and marketers to form improved harvest, storage, processing and on-selling strategies prior to harvest.

This project endeavoured to collaborate with a diverse group of growers and consultants within the Downs region and as such was successful in generating much interest in the remote sensing applications. The trialling of GoogleEarth as a distribution host of derived imagery products was highly successful with most participants already having some experience with the free software. This result indicated the need to establish a standardised system for the Australian cotton industry that has the capacity to host imagery data as well as offer growers, consultants and researchers an interactive framework for storing all relevant crop data that is spatially referenced.

2. Publications

- **A. Robson** (2009). Practical remote sensing applications for various farming systems. Southern Farming Systems of Queensland (SFSQ) field day, Kingsthorpe, Qld. 26th November 2009. (Attachment 4)

- **Dr Andrew Robson**. Satellites sense problem crop areas. Newspaper article. Ed. Roseanne Schefe. 'Rural Weekly'; December 11, 2009. (Attachment 5).

- **Dr Andrew Robson** and Jon Medway (2009). Remote Sensing applications for cotton. The Australian Cottongrower. August- Sept. 2009. Volume 30 (4). (Attachment 6).

- **Robson, A.J.**, Wright, G.W., Bell, M.J., Medway, J., Hatfield, P., and Rao. C.N. Rachaputi (2009). Practical remote sensing applications for the Peanut, Sugar cane and Cotton Farming Systems. Poster presentation and abstract. 13th Annual Symposium of Precision Agriculture in Australasia. Armidale, NSW. 10- 11th September 2009. (Attachment 7).

- **Andrew Robson** and Chris Abbott (2010). Assessing remote sensing as an effective tool for predicting yield variability and total yield within the Australian cotton industry. Poster Presentation. 15th Australian cotton conference. Gold Coast, Qld. 10- 12th August 2010. (Attachment 8)

- **Andrew Robson** and Christopher Abbott (2010). Remote sensing applications for the Australian Cotton industry. 14th Annual Symposium of Precision Agriculture in Australasia. Albury, NSW. 2- 3 September 2010. (Attachment 9)

- **Dr Andrew Robson** and Jon Medway (2009). Improving adoption of Remote Sensing within the Australian cotton industry. 2009 CRC science forum, Narrabri, NSW. 17- 19 August 2009. (Attachment 10).

- A.D. McHugh, B. Boughton, J. Eberhard., L. McKeering,. **A.J. Robson**,. and S.R. Raine (2009). Relationships between plant based measurements and remotely sensed data for irrigation scheduling of cotton. NEC11- Final Project report, NCEA Publication 1001574/8. National Centre for Engineering in Agriculture. University of Southern Queensland. (Attachment 11).

3. Background (from proposal)

The expected improved management outcomes offered by precision farming technologies, particularly for input management is widely recognised, with the current CCCCRC strategic plan having a targeted of adoption of recognised precision farming practices for 50% of the annual cotton area by 2012. Research and surveys within other cropping industries both in Australia and overseas is now identifying common factors as being common barriers to further adoption of spatial management practices that are also likely to be significant within the Australian cotton industry. Primarily these include;

- Lack of understanding of the extent and impact of spatial variability,
- Limited demonstration of the cost benefit of spatial management beyond vehicle guidance,
- Significant support services for assistance with data collection, analysis and interpretation.

International and Australian research has however regularly highlighted the ability to identify variability using a variety of techniques such as soil and crop monitoring, remote sensing and yield mapping. Consequently, applied research that is able to demonstrate the practical application of these technologies and their cost benefit will significantly influence spatial management adoption. Of these technologies, remote sensing has the demonstrated potential for use in crop management applications relating to:

• site specific management of water, growth regulators and nutrients in the cotton industry, therefore potentially allowing for the future implementation of variable rate technology (VRT)

• detection of bacterial, fungal and viral diseases before symptoms are readily visible, and associated potential for site specific and variable rate spray technologies for control programs

• early detection of under-performance in crops at a paddock scale, thus prompting possible intervention by growers and consultants.

• detection of heterogeneity in crop performance due to water stress in faulty/under-performing irrigation systems, thus prompting growers/advisors to remedy problems and significantly improve crop water-use efficiency.

• Early detection of insect infestations and therefore potential for intervention to reduce spread.

To date most commercial application has focused on the use of simple crop vigour indices to detect variability, with most management interventions requiring significant field inspection to interpret the reasons for the variability prior to management intervention. Without appropriate processing infrastructure it has also been difficult to deliver products in a timely manner over large areas.

By enabling the current commercial imagery services to shift from simple vegetation indices to biophysical crop variables such as Leaf Area Index (LAI), Canopy Cover and Fraction of Photosynthetically Active Radiation (FPAR); and use of these products with existing crop simulation models, diagnostic management capabilities will be significantly enhanced. Using the calibrated imagery products will allow specific growth rate products to be derived for enabling site-specific management of growth regulators and more precise water management. Users will also be able to measure and interpret these products directly in the field using rapid assessment methods, and derive inputs for existing agronomic management models.

Over the last 10 years the capacity to derive biophysical crop variables from remote sensing has been well proven within a research environment. However, delivering these products within a commercial environment requires more robust automated processing systems than currently available in Australia. Internationally the most successful commercial application to date has been developed by French company Infoterra (http://www.spotimage.fr/html/_167_194_201_640_.php), and marketed as the FARMSTAR service.

Terrabyte Services (TBS) has been delivering commercial remote sensing services to the cereal, viticulture, rice and cotton industries since 2001. Recently TBS has been focusing product development on the rice industry, which has seen more than 50% of the industry adopt the service within 3 years. The service is based on simple crop vigour indices delivered through automated processing and delivering systems within 24-48 hours of satellite overpass. The service has demonstrated benefits in variable nitrogen management and yield exceeding $100/ha from a $3.60/ha product. Over the last 2 years TBS has been developing LAI and biomass products that will significantly reduce the need for field biomass measurements. TBS also has also been working with French company Infoterra to adapt the highly successful "FARMSTAR" system for Australian conditions and Infoterra have agreed to provided in-kind assistance to this project through access to software and image processing.

The precision agriculture team based at QDPI&F Kingaroy has researched a range of PA technologies which have been shown to have cost effective applications in the Australian peanut industry. In particular, in-season infra-red remote sensing of peanut crop canopies using high resolution aerial and satellite imagery offer peanut advisors and growers the potential to better assess and ultimately manage the 'spatial variability' that typifies their systems. Applications shown to have commercial value include aflatoxin and crop maturity management, where segregation of harvested peanuts into regions of high and low aflatoxin risk, and early and full maturity, have significantly improved gross returns to growers arising from improvement in product quality (see Wright at al, 2005, Robson et al, 2005).

4. Objectives

4.1. Demonstration of the measurement, extent and impact of spatial variability in typical cotton fields.

Measurement: This project investigated a number of spatial technologies including high (0.8m) and mid resolution (10m) satellite imagery, hyperspectral data, electro magnetic (EM) surveys and commercially produced yield maps for their ability to identify spatial variability within cotton crops and across whole farms. This included identifying optimal image capture timing and vegetation indices from imagery, size of representative ground truthing sample and consistency between each data layer.

A vast improvement in the cost and availability of high resolution (sub metre) multispectral imagery (i.e. IKONOS, QuickBird, World View2 etc) has seen adoption increase across many cropping systems, particularly for yield prediction and for the identification of abiotic and biotic constraints. Within the Australian cotton industry, research and adoption of these technologies has been limited and as such a number of applications including the identification of disease (e.g. Fuzarium), soil health (e.g. salinity), management issues (e.g poor germination, irrigation inefficiencies) and yield prediction were investigated. To ensure that this project was not biased toward the higher resolution imagery, 10m (SPOT5) imagery was also assessed. SPOT imagery is more affordable than the higher resolution satellites (AU$2.70 per km^2 compared to US$28.20 per km^2 for IKONOS) and with the inclusion of a mid infrared spectral band allows for additional vegetation indices to be derived and assessed against measured parameters such as yield. Imagery captured at differing growth stages was also assessed to identify the optimal image capture timing for yield prediction.

Hyperspectral sensors measure changes in the spectral properties of separate plant leaf constituents resulting from physiological change and exposure to stress. As such this technology was investigated for its ability to predict the leaf water potential (LWP) of a growing cotton crop to aide in future irrigation management.

Electro magnetic (EM) soil surveys have long been considered as a useful tool for defining paddock soil variability, however this project aimed to determine how the spatial trends identified by EM translate to actual above ground crop growth and yield variability via comparisons with other spatial information such as imagery or yield mapping. A poor correlation between any of the suggested spatial layers would bring to question the relevance of such surveys. Lastly the availability of commercially recorded yield maps was assessed in the hope that they could identify historic yield trends, allow for direct correlations to be made against other spatial layers and if accurate provide validation for image based yield predictions.

Extent: Where available, all spatial technologies were assessed at a paddock level to identify synergies between them as well as to actual crop performance. The spatial variability identified by imagery was quantified for each target crop in agronomic terms such as plant vigour, maturity, productivity and soil nutrition via strategic field samples. At a farm level, the spatial layers were investigated to identify across paddock trends including those that relate to soil and landform, allowing for alternate future farm management strategies to be suggested.

Impact: Results obtained for specific crops provided participating growers with an insight into the spatial variability of crop performance and yield. Classified imagery in particular was demonstrated as an effective tool for identifying low performing regions and for enabling GPS guided crop assessments. The further identification of limiting constraints through field sampling allowed decisions regarding the necessity and feasibility of applying remedial action to maximise production to be made.

This project enabled a number of remote sensing platforms and processing techniques to be investigated so that the most efficient and feasible options could be presented to industry collaborators. Additionally the use of imagery and GPS to identify constraints such as Fuzarium, pest, poor irrigation efficiencies, soil nutrition etc encouraged additional researchers to assess these technologies as a tool for improved management. On a regional level remote sensing does offer the potential to predict the total area of cotton production within a given year as well as form an overall yield estimate based on the correlation between field samples and imagery.

4.2. Identification of the currently available range of recognised precision farming technologies and assesses their potential adoption.

This project examined a number of technologies including satellite imagery (SPOT and QuickBird), field based hyperspectral data, EM surveys and commercially derived yield maps for their ability to measure crop variability as well as the extent of adoption within the Downs growing region. The French SPOT satellite was the predominantly used image data source due to its large coverage area per tile (3600km^2), cost and 4 band spectral resolution. The high spatial resolution QuickBird satellite was also examined for its ability to identify sub metre constraints such as those arising from disease and salinity. Additional tools such as commercial yield maps and EM surveys were assessed for their accuracy in explaining actual yield variability as well as their correlation with imagery. Other precision agricultural tools such as variable rate technologies etc. were not assessed within the Downs' growing region due to access to such equipment.

4.3. Assessment of the cost benefit of spatial management practices relating to irrigation and nutrient management.

Classified vegetation index maps derived from satellite imagery were quantified in terms of yield enabling estimates of lost production resulting from underperforming crop regions to be made. This was achieved by calculating the difference between the actual harvested yield average and the hand sampled yield estimates measured within high performing crop regions. By then determining the nature of the limiting constraint through sampling i.e. soil nutrition, poor drainage, irrigation efficiencies etc, the costs benefit of implementing remedial action such as land forming, targeted applications of fertiliser, modified watering regimes etc could be determined.

4.4. Assessing a range of quantitative image processing techniques.

Previous research undertaken over differing agricultural systems has identified many methods of image processing, vegetation indices and image distribution that were considered relevant to cotton data and as such a large degree of these were investigated. To ensure all temporal comparisons of SPOT imagery were not influenced by erroneous errors associated with atmospheric attenuation etc, all images were corrected for top of atmosphere (TOA) and at canopy reflectance before the data was substituted into a number of vegetation indices (listed in the following methods section). As well as the commonly used near infrared (NIR) based indices, a number of modified Mid Infrared (MIR) band versions were investigated in an attempt to minimise reflectance saturation. This technique did resolve the saturation issue and a strong correlation was produced between the mid infrared plant cell density (MidIRPCD) index and measured yield sampled across two growing seasons, multiple varieties, irrigated and dryland environments and different row-spacing. The predictive algorithm derived from the MidIRPCD and yield correlation enabled yield forecasts to be made for 20 additional crops within the Downs' and Burdekin growing regions based on their pixel and average index value.

For the delivery of processed imagery to consultants and growers, GoogleEarth (kmz) files were trialled in conjunction with static word documents and pdf formats, with a great deal of success. In general most collaborators had some exposure to GoogleEarth and therefore found the software easy to use and visually appealing. This method of imagery delivery also removed the need for large image files and therefore presented itself as an ideal platform for future data sharing.

Point source commercially recorded yield data was interpolated into a continuous yield layer using Imagine software, layer stacked onto the satellite imagery of the same crop and sub-setted to ensure pixel alignment. Data was exported as a text file into Excel enabling correlations between the vegetation index values and the measured yield to be identified.

Hyperspectral data analysis was undertaken using the Unscrambler software, where reflectance data was converted to absorbance (Log 1/ Reflectance), spectral regions prone to water absorption (1350- 1420, 1760- 1956 and 2450- 2500 nm) were removed, data was smoothed with a Savitzky- Golay algorithm and then a partial least squares regression (PLS-R) and discriminant analysis (PLS-DA) were applied. Those wavelengths identified to have the highest regression coefficients in explaining leaf water potential (LWP) were identified as wavelengths of interest.

4.5. Development of material for use by the industry to address existing barriers to the adoption of recognised precision farming practices.

The in-season distribution of classified imagery quantified by ground truthing data and grower knowledge provided a very useful agronomic tool for improving management strategies and therefore crop production. The further development of the yield prediction algorithm and derived in-season yield variability map allowed underperforming crop regions to be expressed in terms of actual production and therefore assisted in estimates of lost production to be made.

The Queensland component of this project produced a training manual for the image analysis software ENVI (provided as attachment), so that industry users could undertake their own analysis if required. A precision agriculture manual for cotton (also attached), was compiled however it is still waiting for comment by the NSW component of the project regarding EM technologies etc.

4.6. Extension of the results and outcomes of the project to the wider cotton industry via field days, newsletters and industry forums.

The Queensland component of this project produced a number of presentations and publications that are provided as attachments and include:

- 14th Annual Symposium of Precision Agricultural in Australasia; Albury. NSW. 2010.
- CRC science forum in Narrabri. 2009.
- Southern Farming Systems of Queensland (SFSQ) field day Kingsthorpe, QLD. 2009.
- DEEDI Central Region Management Team meeting. Emerald. 2009.
- 13th Annual Symposium of Precision Agricultural in Australasia; Armidale NSW. 2009.
- 15th Australian cotton conference. Gold Coast, Qld. 2010.
- The Australian Cotton Grower Magazine (Aug- Sept. 2009 Vol 30, No4)
- 'Rural Weekly' article (11 December 2009);
- ABC radio interview 'The Country Hour' (26 November 2009);
- Contribution to 'CRC for Irrigation Futures (NCE11) final project report';
- 2nd PA and opportunities for cotton farming systems- mini symposium. Narrabri, NSW. 2010.
- 'Managing Paddock Variability using Precision Agriculture' GRDC workshop manual presented at 6 Qld locations during July to Aug. 2010.
- Manual for Precision Agricultural applications in the cotton industry (initial draft);
- Manual for the image analysis software ENVI;
- Compilation of multiple in-season reports for collaborating growers, agronomists and industry representatives.

5. Methodology

5.1. Overview of Queensland component collaborators and study regions.

The Queensland component of this project concentrated on a 60km x 60km study region over the Central Darling Downs region (refer to Figure 1) working with a range of research bodies, industry representatives and growers including:

- *Research bodies:*
  - National Centre for Engineering in Agriculture (NCEA)
  - The Commonwealth Scientific and Industrial Research Organisation (CSIRO).
  - Dept. of Environment and Resource Management (DERM).
  - Dept. of Employment, Economic Development and Innovation (DEEDI).

- *Regional cotton extension officers:*
  - Paul Grundy, Janelle Hare, Graham Harris, and Susan Mass (DEEDI);

- *Consultants/agronomists:*
  - Angus Blair (Landmark, Ag N Vet)
  - Andrew Johnson (Dalby Rural Supplies)
  - Gary Chesterfield
  - Brad Tatzenko
  - Trevor Philp (Pacific seeds)
  - Malcolm Salisbury and Mathew Holding (Meteora Pty Ltd)
  - Jamie Innis (Landmark) and
  - Sharon and Ash Commens (DJAS Crop Data)

- *Collaborating Farms and sample events:*

Classified cotton vigour maps were derived by Terrabytes for many farms including: Anchorfield, Armitage*, Arundel, Ashmore, Aura Lea*, Barrabool*, Belmont*, Bemarng, Birrilli, Bonedon, Branchview, Colenso*, Dalmeny, Davies, Gilgai*, Glen Idol, Glenmore, Glover, Hall, Hampstead, Ivanhoe, Janerin, Kar- Lee, Kirkton*, Merlewood, Nothdurft*, Oakpark*, Sommerset*, Swainston*, Tyguna, Warrawee, Weerona*, West Meadows, Westend, Whitten*, Wynola, Yanco* and Zephyr following the 13 March 2008 (*), 29 Dec. 2008 and 23 Feb. 2009 image captures. EM surveys were also provided for Barabool, OakPark and Whitten (2007/2008 season). Historical imagery was sourced by DEEDI for the majority of the 2009/2010 sample farms to investigate temporal trends in production.

Table 1: list of all crops sampled within the Queensland region during the CRC project

Farm name	No. of Paddocks	Stage sampled	Sample Total
Westend	2 (2009/10)	Flowering (23 Dec 2009), yield prediction (22 April 2010)	4
Rhule	2 (2009/10)	Flowering (23 Dec 2009), yield prediction (22 April 2010)	4
Jackson	1 (2009/10)	Flowering (23 Dec 2009), yield prediction (22 April 2010)	2
Fairview	1 (2009/10)	Flowering (23 Dec 2009), yield prediction (22 April 2010)	2
Donnybrae	1 (2009/10)	Flowering (23 Dec 2009)	1
Weerona	2 (2007/08 2008/09)	Flowering (17 Jan 2008) (21 Jan 2009), yield prediction (5 March 2009)	3
Dalmeny	2 (2007/08 2008/09)	Flowering (17 Jan 2008) (21 Jan 2009), yield prediction (5 March 2009)	3
Tyguna	1 (2008/09)	Flowering (21 Jan 2009), yield prediction (5 March 2009)	2
Bemarng	1 (2008/09)	Flowering (21 Jan 2009), yield prediction (5 March 2009)	2
Glen Idol	1 (2008/09)	Flowering (21 Jan 2009), yield prediction (5 March 2009)	2
			25

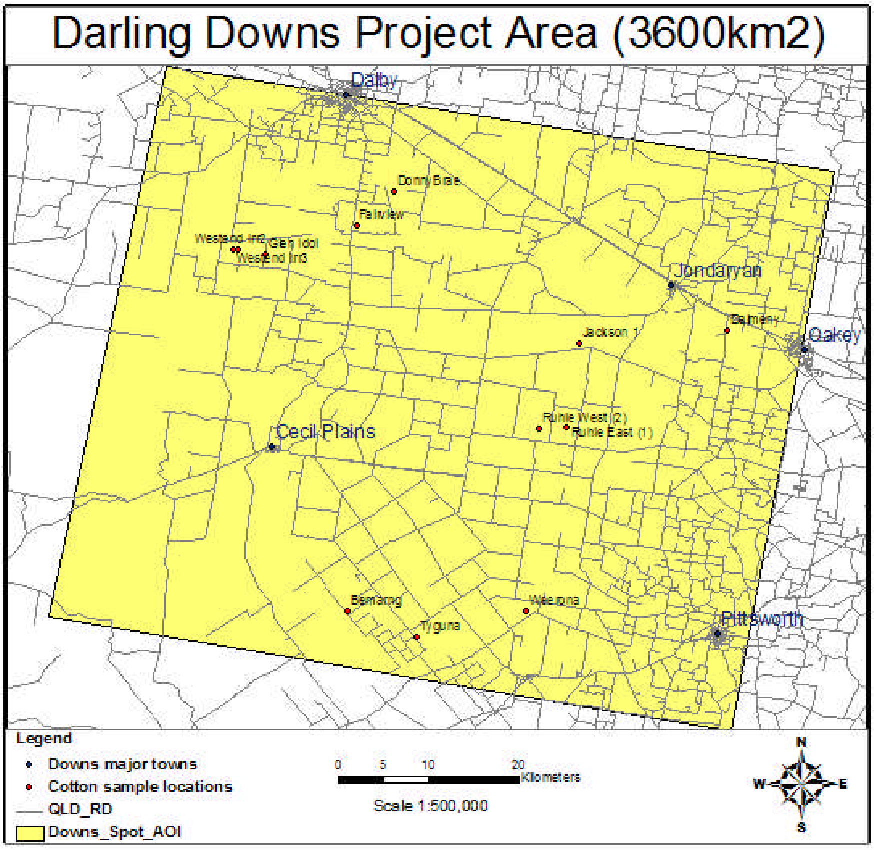


Figure 1. Darling Downs study region and location of field sampling sites.

An additional target area within the newly established Burdekin growing region was also imaged on the 14 May 2010 with SPOT5 imagery (Figure2).

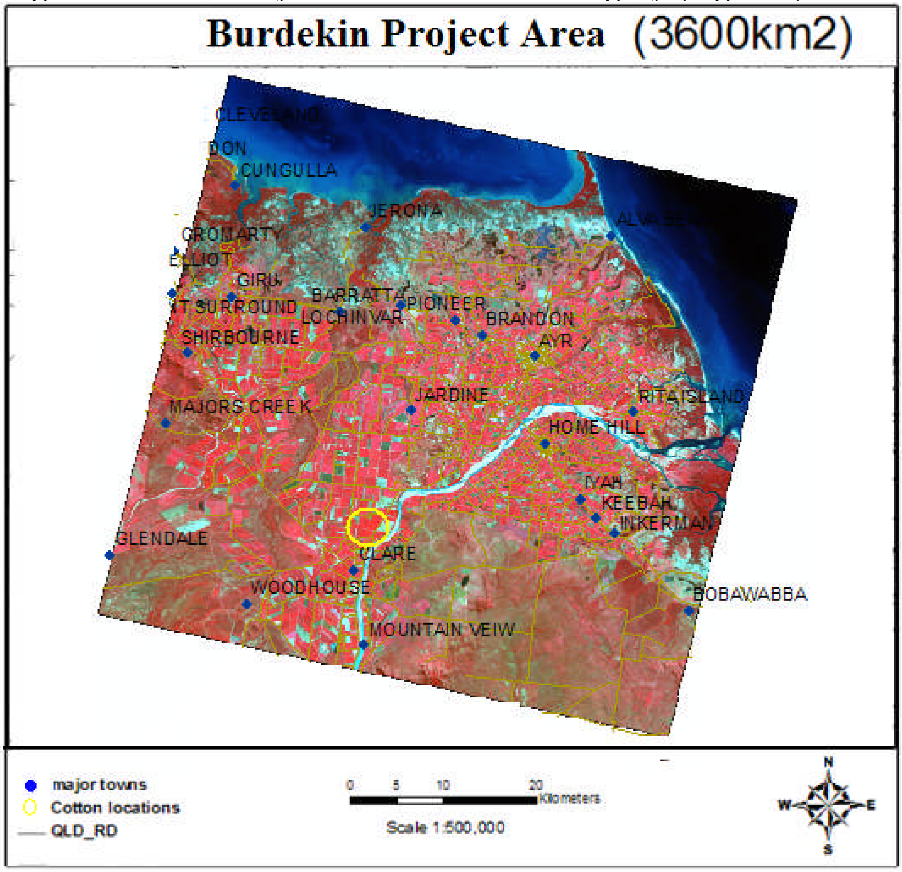


Figure 2. False colour SPOT5 satellite image of Queensland Burdekin region, captured 14 May 2010. Main cotton growing area identified by yellow circle.

5.2. Obtain existing spatial data (i.e. yield maps, EM surveys) including farmer knowledge.

Few growers were identified to have historic yield maps and those that were located were generally in a format that was useable for additional analysis. The Westend farm operated by DJAS Crop data supplied yield maps for a number of 2008/09 irrigated crops that were correlated against imagery captured during the same growing season. Each point source data set was interpolated into a continuous layer using ERDAS Imagine software, geographically aligned using an image to image rectification, set to a 10*10m grid to match the spatial resolution of the SPOT 5 imagery and layer stacked to produce a yield map/ four band satellite composite image. The area of each crop was then sub-setted with the NDVI, Mid NDVI and yield monitor data exported into Excel for further correlation analysis. A similar process was adopted for those EM soil surveys undertaken by Terrabytes Pty Ltd within the first year of the project.

Farmer and consultant knowledge regarding prior land changes, locations of differing soil types, issues with planting, germination, irrigation, salinity, soil disease etc was highly beneficial for explaining variability within crops identified by imagery. The GPS guided ground truthing of these study sites not only supported growers prior knowledge but allowed estimates of area affected, impact on yield and therefore estimate of lost production resulting from differing constraints to be quantified.

5.3. Acquire and analyse multi-spectral spatial data (from satellite and/or airborne sources) to quantify spatial and temporal variability via IR canopy reflectance at whole farm level.

Imagery

The number of image captures over the Downs region was greatly restricted by continued cloud cover and issues with the DEEDI airborne. One high spatial resolution (2.4m and 0.6m panchromatic) QuickBird image was captured over a 100km^2 region on the 9 March 2008, whilst seven SPOT2, SPOT4 and SPOT5 images, each encompassing 3600km^2 were captured over the Darling Downs region during the 2007/08 (30 December 2007, 13 March 2008), 2008/09 (29 December 2008 and 23 February 2009) and 2009/10 (10 December 2009, 10 January 2010 and 19 March 2010) growing seasons. An additional SPOT5 image was captured over the Burdekin region on the 14 May 2010. SPOT 5 and SPOT 4 images have a spatial resolution of 10m and 20m respectively, both contain four spectral bands (wavelengths), including; Green (0.5-0.59μm), Red (0.61-0.68μm), Near-Infrared (0.78-0.89μm) and Mid-Infrared (1.58-1.75μm) with an 8-bit radiometric resolution. All images were converted to irradiance values (W-m^{-2}-sr^{-1}-nm^{-1}) using gains and offsets supplied with imagery metadata using equations defined SPOT Image (2008) and then converted to 'Top of atmosphere' reflectance values (%) (Landsat Science Data Users Handbook, NASA 2009) using ENVI 4.7 software (ITT Visual Information Solutions). All SPOT5 images were atmospherically corrected to represent 'at canopy' reflectance, ensuring anomalies such as those associated with sun elevation, sensor 'look' angle and the Earth-Sun distance were removed using the improved dark-object subtraction technique (Chavez (1988); Song et al 2001).

Data Analysis and yield prediction

All sampled yield measurements, encompassing 11 crops, 2 growing seasons, dryland and irrigated environments (n=82) were correlated against a number of commonly used vegetation indices (Table 2) to identify the highest correlation coefficient. The linear equation produced from this correlation was used to predict the total yield of 14 non-sampled crops on the Downs and 6 within the Burdekin by substituting the average index value for the entire crop into the equation, providing an average yield. This value when multiplied by the area of the crop produced the total yield. Yield variability maps were also produced by applying the equation on an individual pixel basis. The accuracy of the predictions were validated against the actual total harvest of the crop as measured by delivery gin weight.

Table 2: Vegetation indices assessed for their correlation to cotton yield

Normalised Difference Vegetation Index (NDVI)	$R_{NIR} – R_{Red}$ / $R_{NIR} + R_{Red}$
GreenNDVI	$R_{NIR} - R_{Green}$ / $R_{NIR} + R_{Green}$
MidIRNDVI	$R_{MIR} – R_{Red}$ / $R_{MIR} – R_{Red}$
Plant Cell Density (PCD)	R_{NIR} / R_{Red}
MidIRPCD	R_{MIR} / R_{Red}
NDVIPCD	NDVI / R_{Red}
MidIRNDVIPCD	MidIRNDVI / R_{Red}
Transformed chlorophyll absorption reflectance index (TCARI)	$-3*(R_{Red} – R_{Green}) – 0.2*(R_{Red} – R_{Green}) *(R_{Red} / R_{NIR} + Red))$

Where:
Green = wavelengths 0.5-0.59μm
Red = wavelengths 0.61 – 0.68μm
NIR = "Near-Infrared" wavelengths 0.78 – 0.89μm
MIR = "Mid-Infrared" wavelengths 1.58 – 1.75μm

5.4. Implement a coordinated plant and soil sampling strategy (with the aide of the consultants and growers) to diagnose underlying causes of spatial variability by in-field testing, observation and on-farm research and identify opportunities to improve productivity of under performing regions of the crop.

Each paddock of interest was sub-setted from each respective SPOT or QuickBird scene, converted into a Normalised Difference Vegetation Index (NDVI) and then classified into five vigour classes using the natural break method. Three replicate locations representing the high, medium and low vigour classes were targeted for strategic crop sampling. Due to the 5 metre accuracy of the non- differential GPS, sampling points were selected from homogenous class regions that were no less than 25 pixels for SPOT 5 and 200 pixels for QuickBird imagery.

Field samples collected towards the middle of growing season (late December, January) (14 sampled crops over two seasons- Table 1) were undertaken to represent actual agronomic assessments of plant height, plant width, plants per square metre and number of nodes above white flowers (NAWF). This enabled spatial variability within these agronomic measures to be identified. A second sampling event towards harvest was also undertaken to identify yield variability calculated by:

Cotton yield (bales /ha) = Plants/ m * boll count* boll factor
(Where boll factor represents the value denoted by Cotton Seed Distributors (2010)).

The actual size of the representative sample was also considered as it had to be both efficiently obtainable as well as be representative of the regions it was being sampled from. As such two sampling techniques were assessed during the first year of the project where the average measured results of 16 by 1 metre row samples (8*8 metre grid) was compared to only the single metre measurement obtained within the centre of the grid. The result identified the 1 metre sample to be generally within the standard deviation range of the averaged 16 samples for all parameters measured and so to further improve this accuracy, 2*1 metre lengths of parallel cotton row was established as the base line for all future ground truthing samples.

Soil cores (10cm diameter) were also extracted from a number of the sample farms to correspond with each above ground sample point at depths of 0-15cm and 15-30cm, with a comprehensive soil nutrition and chloride test undertaken on each sample.

5.5. Develop and evaluate cost-effective management responses to maximise productivity at paddock and farm scale.

To evaluate the cost efficacy of applying remedial action to improve overall crop production an estimate of lost production resulting from less than optimal regions was calculated. This was achieved by subtracting the total crop yield defined by delivered commercial weight from the total calculated yield if optimum production was achieved (i.e. mean of the three high NDVI replicates * crop area). By then determining the nature of the limiting constraint i.e. soil nutrition, poor drainage, irrigation efficiencies etc, the costs benefit of implementing remedial action such as land forming, targeted applications of fertiliser, modified watering regimes etc could be determined.

5.6. Measure the $ value of the PA data and management changes.

Apart from the cost analysis mentioned previously a lack of access to variable rate technologies and project time constraints prevented the actual cost benefits of these remedial actions to be calculated. If given the opportunity it would be highly advantageous to re-image the sites to identify if suggested remedial action undertaken on low performing crop regions resulted in improved productivity.

5.7. Synthesise and integrate learning and communicate them to the wider grower and advisor communities.

Within the Downs region all data interpretation and field activities were undertaken with guidance from growers and agronomists to ensure that industry relevance was maintained and collaborators were provided with some exposure to spatial technologies and processing techniques. The additional inclusion of the Burdekin region was to further promote the technology to a wider Queensland cotton growing community as well as to evaluate the accuracy of the yield prediction algorithm derived over the Downs under an alternate growing environment. In regards to the project as a whole, the integration of results between the NSW and Queensland components of this project did not eventuate, as no recorded field data was supplied by the NSW component for the duration of the project. At no stage of the project where the Queensland component fully informed of research activities being undertaken within NSW, with constant requests to review data collected, ignored. The NSW project leader Jon Medway could not be contacted for extended periods throughout the project due to personal issues and overseas commitments. As a result of this lack of communication project results could not be collated, relations with industry collaborators were strained as promised EM surveys were not undertaken, and all presented data was formed primarily on Queensland based data.

5.8. Jointly undertaken activities include;

- *Overall project planning*- Achieved to some extent during the first year of the project but very little follow up provided by the NSW component for the remainder of the project.
- *Specific research activity design*- Input from the NSW component for the first project year only.
- *Combined annual and final reporting* - Qld reports submitted to Terrabyte before the CRC due data however reciprocated NSW reports were never received by the Qld component.
- *Site selection (together with Regional Cotton Extension officers and consultants)* - Achieved for Queensland component.
- *Conference papers* - compiled with only Queensland data.
- *Data analysis planning* – Input from the NSW component for the first project year only.
- *Promotion/communication plan* - Input from the NSW component for the first project year only.
- *Joint field day/conference activities* – Next to no support provided by the NSW component.

5.9. Others (DEEDI) DPI&F responsibilities;

- *Qld field site activities* - 25 sampling occasions across 15 crops.
- *Qld data processing (field and Remote Sensing)* – Achieved with results presented in the following section and attached documents.
- *Airborne data acquisition, system development and data processing* – Not achieved due to ongoing issues with the system.
- *Attending Qld field days (industry and project)* – presentation of Qld project results at the 2009 Southern Farming Systems of Qld (SFSQ) field day Kingsthorpe 2009; Supplied remote sensing section (including cotton imagery) to GRDC 'Managing Paddock Variability Using Precision Agriculture' workshops presented at 6 Qld locations during 2010. Presented cotton results to growers and agronomists' at DEEDI Central Region Management Team meeting. Emerald. 2009.
- *Review/comment on NSW data analysis/reporting* – Qld component never received any NSW field data or written reports for the duration of the project.

6. Results

All Queensland field and imagery results are provided as attachments for each growing season (submitted as annual reports), with a summary of major findings and additional data detailed below.

6.1. Demonstration of the measurement, extent and impact of spatial variability in typical cotton fields.

Measurement: As stated previously this project investigated a number of technologies including high (0.8m) and mid resolution (10m) satellite imagery, hyperspectral radiometer, EM surveys and commercially produced yield maps for their ability to identify spatial variability within a number of cotton crops. High resolution imagery provided clear representations of sub metre constraints including those related to disease (Fuzarium), soil health (salinity) and management (poor germination, irrigation inefficiencies); However, due to its higher cost (US$28.20 per km^2) this imagery was deemed to be only commercially viable for specific applications within small agronomic regions rather than for coverage of the entire Downs region. The availability of only a near infrared band (NIR) also made this imagery susceptible to infrared reflectance 'saturation'. The 10m SPOT 5 imagery was identified to be more optimal both in monetary terms (AU$2.70 per km^2) with scenes covering the entire Down growing region, and for the spectral resolution with the addition of a mid infrared band. This imagery was also effective for identifying a wide range of growth constraints as well as accurately predicting yield. Images captured closer to commercial harvest date were identified to produce higher correlations than those images captured between December and February.

The hyperspectral data was identified as a useful tool for identifying specific wavelengths that correlated with leaf water potential (LWP) with the wavelengths 540nm, 685nm, 758nm and 810nm identified to higher regression coefficients when explaining the predictive model following a partial least squares regression analysis (PLS_R). The identification of these specific wavelengths would have commercial benefit if a low cost sensor could be developed that was specific to LWP, however the use of currently available hyperspectral airborne system is costly and therefore better suited to small research based applications rather than large commercial applications.

Electromagnetic (EM) soil surveys identified variability across a number of cotton blocks however those trends were generally unrelated to variability in above ground plant vigour, measured by satellite and commercial yield maps. Poor regression coefficients were identified for two crops ($R^2 = 0.28$ and $R^2 = 0.14$) between plant cell density (PCD) and EM38 values and ($R^2 = 0.14$ and $R^2 = 0.10$) between plant cell density (PCD) and EM31 values (refer to attached 2007/08 annual report). This may indicate that growth constraints were primarily driven by factors that were unrelated to soil conductivity such as soil nutrition, management, pest or disease and may question the usefulness of EM surveys for defining yield variability within cotton grown on Downs' soils.

Availability of commercially recorded yield maps was limited with only three data sets obtained from the 2008/09 season from the Westend farm. Regression coefficients of $R^2 = 0.48$ and $R^2 = 0.47$ where identified between NDVI and MidNDVI index values obtained from SPOT 5 imagery captured on the 23 February 2009 and final commercial yield maps (refer to attached 2008/09 annual report). This indicated that imagery can provide a useful surrogate to commercial yield maps if modified mathematically. Also vigour trends identified within the imagery can provide a useful reference for ensuring yield trends produced by the commercial picker are yield related and not the result of human or machine error.

Identification of representative field sample area:
The comparison of averaged field samples collected over a 8 metre grid (brown dots) against that of one linear metre (white dot) (Figure 3) did identify an optimum sample size both in terms of a representative sample to the zone it was collected from and in regards to time and labour efficiency to collect it.

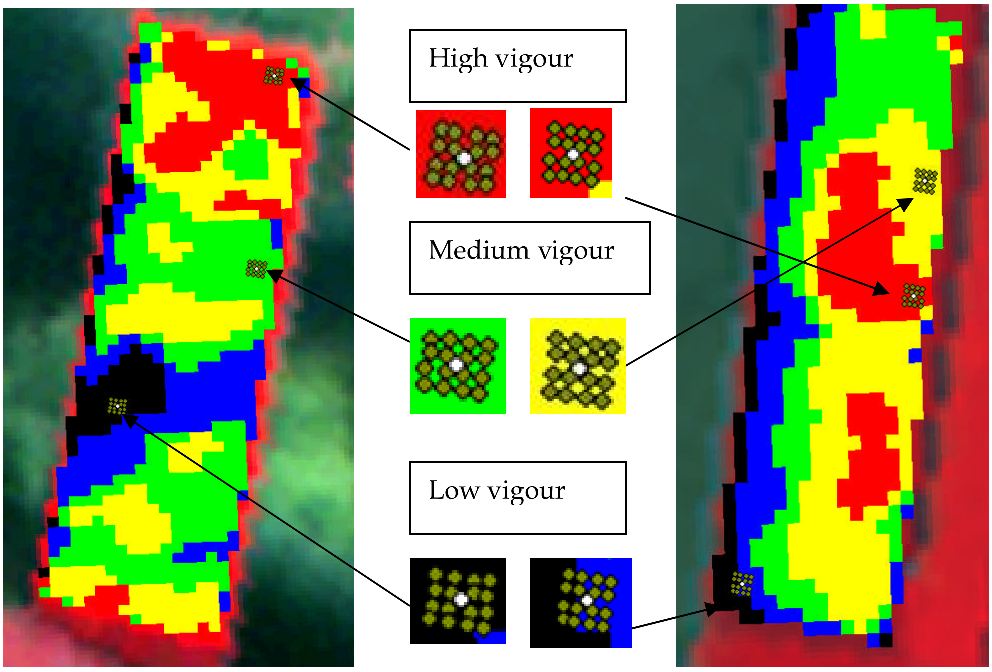


Figure 3. Classified NDVI images of two irrigated cotton crops with both the 8*8 grid (green dots) and central (white dot) in field replicate sample displayed.

Table 3: Comparison of measured agronomic variables averaged from the 8*8m grid to those measured within a central 1 metre row (ticks indicate those centre values within the standard deviation of the averaged 8*8 grid sample).

	High				Medium				Low			
	16 point ave	St.Dev.	centre	within st.dev	16 point ave	St.Dev.	centre	within st.dev	16 point ave	St.Dev.	centre	within st.dev
PLANTS (per metre)	7	1.1	6	√	6	1.5	6	√	3	0.9	2	2.1
HEIGHT (cm)	85	6.2	90	√	65	6.6	75	71.6	72	8.4	60	63.6
WIDTH (cm)	72	7.1	80	79.1	53	7.0	65	60	59	8.1	60	√
NODES (per plant)	19	1.4	18	√	15	1.6	16	√	18	1.9	19	√
NAWF	6	0.8	6	√	6	1.2	6	√	7	1.5	6	√

	High				Medium				Low			
	16 point ave	St.Dev.	centre	within st.dev	16 point ave	St.Dev.	centre	within st.dev	16 point ave	St.Dev.	centre	within st.dev
PLANTS (per metre)	12	1.5	14	13.5	12	2.1	9	9.9	11	2.4	9	√
HEIGHT (cm)	89	5.7	90	√	87	5.1	90	√	79	11.1	80	√
WIDTH (cm)	67	5.4	70	√	67	7.7	70	√	65	10.8	65	√
NODES (per plant)	18	1.4	18	√	18	2.2	19	√	17	1.4	18	√
NAWF	6	0.9	7	6.9	6	0.8	7	6.8	6	1.1	6	√

From Table 3 it can be seen that those agronomic measures obtained from the centre metre area are generally within the standard deviation of the averaged 8*8 m grid sample. To further ensure that samples were representative of the homogenous area in which they were collected from, the sample area was increased to 2 parallel metre of cotton plants.

Extent: All technologies were able to identify differing degrees of spatial variability within all cotton fields tested, which was quantified through strategically located field sampling in terms of agronomic variables such as plant vigour, maturity, productivity and soil nutrition. At a paddock level a large degree of spatial variability of plant height (up to 39cm), width (up to 40cm), as well as yield (up to 8.9 b/ha) was identified with large differences in chloride, exchangeable sodium percentage (ESP), suspected water holding capacity and inefficient drainage identified to be driving variability within some crops (figures provided in attached annual reports). At a farm level, satellite imagery was able to identify vigour trends that extended across blocks that were predominantly the result of soil variability i.e. prior drainage lines, paddock histories etc. whilst on a regional level the imagery could be used to identify all cotton crops particularly during the high growth period mid season, although this analysis was beyond the scope of the current project.

Impact: The results obtained for specific crops not only provided participating growers with a insight into the spatial variability of crop performance in agronomic terms but also yield, that when equated in monetary terms emphasised the cost of lost production resulting from under performing regions. This information coupled with the nature of the limiting constraint enabled growers to make informed decisions on the necessity and feasibility of applying remedial action in an attempt to maximise overall crop production. Agronomists and consultants involved in the project identified the benefits of using remote sensing as an agronomic tool, with the classified imagery in particular used effectively to guide in field assessments within low performing regions. The identification of a number of other limiting factors such as Fuzarium, poor irrigation efficiencies, soil nutrition etc also encouraged additional researchers to assess these technologies as a tool for improved management including the attempted capture of imagery over the mealy bug damage in Emerald. This however was prevented due to continued cloud cover.

6.2 Identification of the currently available range of recognised precision farming technologies and assesses their potential adoption.

This project successfully examined a range of technologies including remote sensing, EM surveys and yield maps for their ability to measure within crop variability. Of the technologies assessed SPOT5 satellite (10m spatial resolution) imagery presented itself as the most likely tool for broad scale adoption due to its accuracy in depicting crop variability including poor performing crop regions via the mid infrared band; its ability to be correlated with yield allowing for yield maps and total yield estimates to be derived; its low cost for large area coverage, and the ease in which the information can be interpreted and ground truthed by both growers and agronomists. The major limitation in its adoption is the lack of an industry group to purchase, host and on-sell the information to end users through an efficient data distribution source such as the internet. The development of such a network in the future would ensure this technology would be available to the entire cotton industry including research, at an affordable price, and provide an effective tool to support nearly all levels of cotton production. Additional tools such as commercial yield maps may accurately depict yield variability however data to assess this technology was difficult to obtain. EM surveys were identified to be less effective on Downs soils with variability measured in soil conductivity having little correlation with above ground production; this may have been different for the NSW growing regions.

6.3. Assessment of the cost benefit of spatial management practices relating to irrigation and nutrient management.

The quantification of classified vegetation index maps in terms of yield enabled lost production resulting from underperforming crop regions to be estimated. By calculating the difference between average harvested crop yield against measured yield within high performing regions estimations of potential losses included $116,950 (72ha), $60,754 (77ha), $60,061 (31ha), $33,119 (28ha) and $14,247 (26ha). By then determining the nature of the limiting constraint i.e. soil nutrition, poor drainage, irrigation efficiencies etc, the costs benefit of implementing remedial action such as land forming, targeted applications of fertiliser, modified watering regimes etc could be determined. As the true impact of applying remedial action to underperforming regions may take years to quantify the actual costs of these remedial actions were not calculated within this project.

6.4. Assessing a range of quantitative image processing techniques.

The following is a summarised version of image processing techniques investigated throughout this project as well as the results generated, with the full details provided in the attached annual reports and publications.

As mentioned in the methods section all SPOT5 imagery was corrected for top of atmosphere (TOA) and at canopy reflectance before a number of vegetation indices (Table 2) were investigated. This ensured that any atmospheric or sensor related 'noise' issues were removed, a necessity when undertaking the temporal analysis for identifying the optimal image capture timing for predicting yield. The Near Infrared (NIR) band was prone to reflectance saturation which greatly reduced correlations with measured yield and as such the Mid Infrared (MIR) band was substituted into a number of vegetation indices including the mid-infrared plant cell density (MidIRPCD). Figure 4 displays the relationships between measured yield (bales per hectare) collected across two growing seasons, multiple varieties, irrigated and dryland environments and different row-spacing (n=82) and the Normalised Difference Vegetation Index and the Mid-Infrared Plant Cell Density Index. MidIRPCD produced a higher regression coefficient with yield ($R^2 = 0.66$) than NDVI ($R^2 = 0.53$) a result largely driven by the saturation of the near-infra band at the NDVI values of 0.64 (2009 image) and 0.7 (2010 image). Saturation of the NIR band occurs as its sensitivity at higher chlorophyll content or Leaf Area Index plateaus, resulting in no increase in recorded values as chlorophyll or Leaf Area Index increase (Gitelson *et al* 2002). In this study the NIR band recorded its highest possible and therefore saturated radiometric digital value (DN=255) in the 23 February 2009 and 19 March 2010 images. All other indices using the NIR band were also influenced by the saturation effect, creating the same distinct 'columns' in the data.

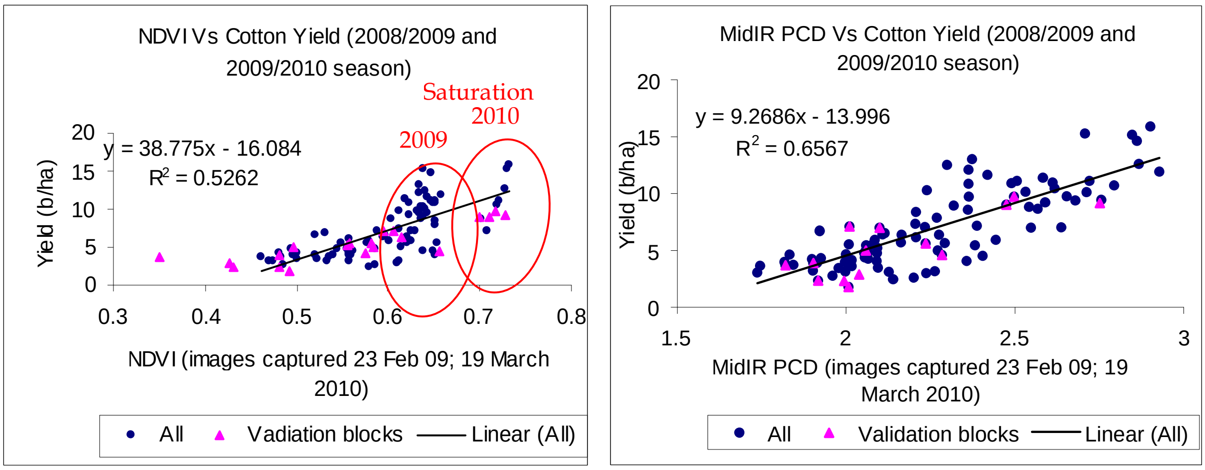


Figure 4: NDVI and MidIRPCD vs Cotton Yield (bales/hectare) for the 2008/2009 and 2009/2010 growing seasons. NDVI and MidIRPCD are calculated from the final image captured in each season.

A time-series analysis (Table 4) showed that all indices derived from the early season capture (12 December 2009) produced poor correlations against final yield ($R^2<0.1$), with a marked improvement with mid season imagery (10 January 2010) ($0.36<R^2>0.62$). The saturation effects within the NIR band indices become apparent with little correlation improvement in the late season capture (19 March 2010). Of the tested indices, the PCD and the MidIRPCD displayed the highest R^2 values (0.63 and 0.62 respectively) from the image captured on 19 March 2010. The MidIRPCD index was chosen as a more appropriate index than the PCD for additional evaluation as it did not experience saturation like the NIR based PCD (Figure 5).

Table 4: Coefficient of Determination (R^2) for vegetation indices matched to final yield for each of the images captured in the 2009/2010 growing season.

Vegetation Index	Coefficient of Determination (R^2)		
	12-Dec-09	10-Jan-10	19-Mar-10
NDVI	0.07	0.54	0.55
MidIRNDVI	0.08	0.47	0.57
PCD	0.05	0.62	0.63
MidIRPCD	**0.07**	**0.52**	**0.62**
GNDVI	0.08	0.57	0.52
NDVIPCD	0.04	0.36	0.50
MidIRNDVIPCD	0.08	0.43	0.51
TCARI	0.07	0.43	0.44

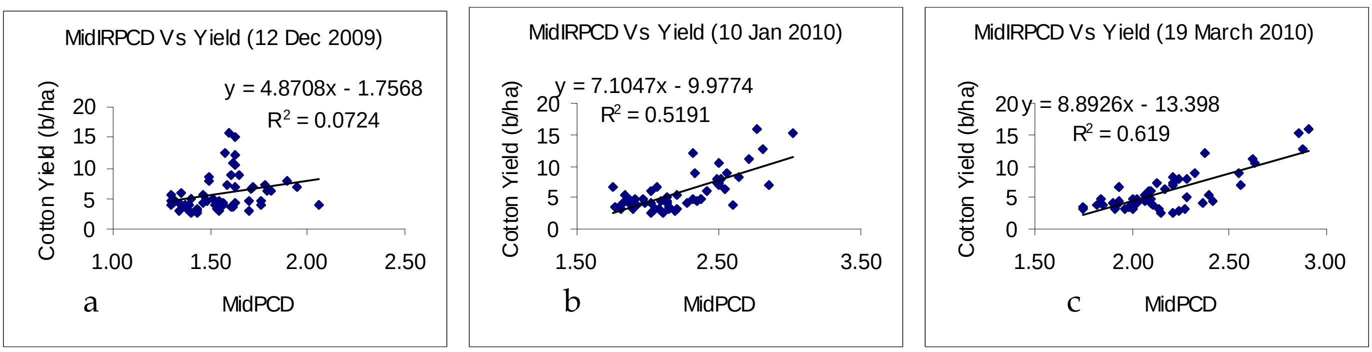


Figure 5: MidIRPCD derived from images across three dates in the 2009/2010 growing season correlated to yield. As the season progresses R^2 values improve.

Using the algorithm developed between yield and vegetation index (refer to attached 2008/09 and 2009/10 annual reports), classified yield maps were generated for each sampled crop (an example provided in Figure 6. In the example provided below (Figure 6) the predicted yield of 344.6 bales at an average of 4.88 b/ha was comparable to actual harvest at 306 bales at 4.3 b/ha.

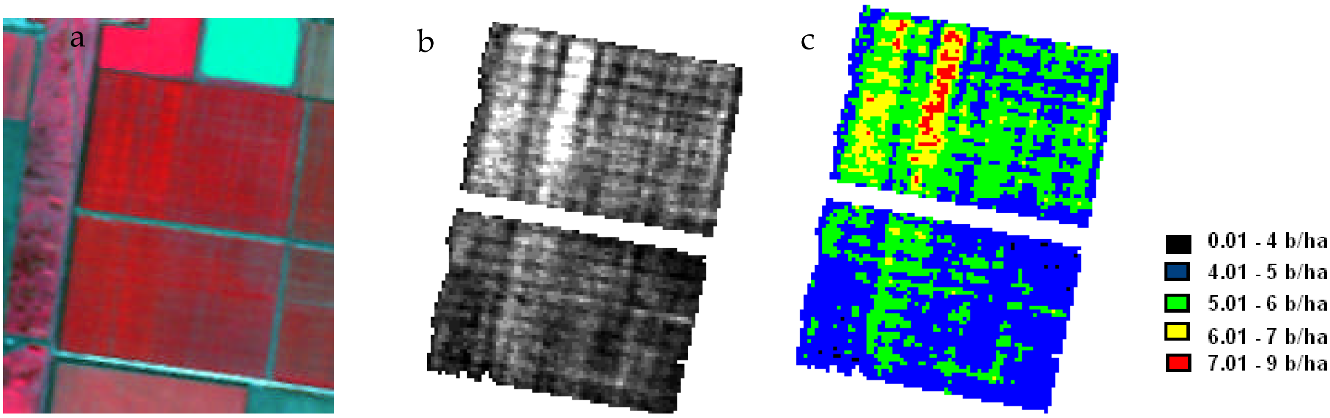


Figure 6: a) SPOT5 false colour image (NIR, Red, and Green) of irrigated cotton crop, b) derived MidIRPCD image c) Classified yield map derived from the MidIRPCD algorithm.

Predictions of average and total yield of an additional 14 non-sampled crops within the Downs region (Table 5) were also made using the algorithm developed from the 2009/10 data (Figure 4). Predictions ranged from 33% under to 99% over prediction of the actual harvested yield. The dry land crops that exhibited very poor predictive accuracy where exposed to extreme early to mid season water stress that influenced both the spectral reflectance of the canopies and final cotton yield. To improve the predictive accuracy of algorithm more observations are required that encompass different growing locations, cultivars and seasonal variation. Alternatively two separate algorithms specific to irrigated and dry land crops be developed especially with the predictive range of irrigated crops ranging between 26% under to 27% over.

Table 5: Yield predictions, actual yield and prediction accuracy of 20 non- sampled and sampled crops.

Growing Environment	Cultivar	Actual Average Yield b/ha	Actual total Yield Bales	Pred. Average Yield b/ha	Pred. Total Yield Bales	Prediction Accuracy (%)
Dryland	Sicot 71BRF	7.1	201	4.7	134	under 33
Irrigated	70BRF	11.8	342	8.70	252	under 26
Dryland	Sicot 71BRF	7.0	147	5.6	117	under 20
Irrigated	71BRF	3.7	74	3.0	59	under 20
Dryland	Sicot 80RRF	5.5	197	4.7	168	under 15
Irrigated	Sicot 70BL	10.23	316	9.96	290	under 8
Irrigated	71BRF	9.7	671	9.3	639	under 5
Irrigated	71BRF	3.9	279	3.7	269	under 4
Irrigated	Sicot 70BL	3.1	88	3.1	87	under 1
Dryland	Sicot 71BRF	9.0	309	9.1	311	100
Dryland	Sicot 71BRF	5.0	120	5.2	125	over 4
Dryland	Sicot 71BRF	5.2	135	5.5	143	over 6
Dryland	Sicot 71BRF	6.4	236	7.2	266	over 13
Dryland	Sicot 71BRF	5.6	75	6.8	91	over 22
Irrigated	71BRF	4.3	306	5.2	378	over 23
Irrigated	Sicot 70BL	9.2	282	11.6	358	over 27
Dryland	71BRF	4.6	220	7.3	349	over 59
Dryland	Sicot 71BRF	2.3	82	3.9	136	over 65
Dryland	Siokra V-18 BRF	2.9	108	5.0	189	over 85
Dryland	Siokra V-18 BRF	2.3	103	4.6	206	over 99

In an attempt to assess the robustness of the Downs' derived algorithm, yield predictions were also provided for 6 Burdekin crops, producing accuracies ranging from 93% (Pred. 7b/ha / Act. 7.5 b/ha) to 68% (Pred. 5.8 b/ha / Act. 8.5 b/ha), with the remaining 79% (cotton 4), 84% (cotton 1 and 6) 85% (Cotton 9) (Figure 7). This result is highly encouraging considering the crops were grown under different environmental and climatic conditions. With the further inclusion of data from other growing regions it is highly probable that a generic yield prediction algorithm could be established for the entire Australian cotton growing region enabling regional forecasts of total production to be made prior to harvest.

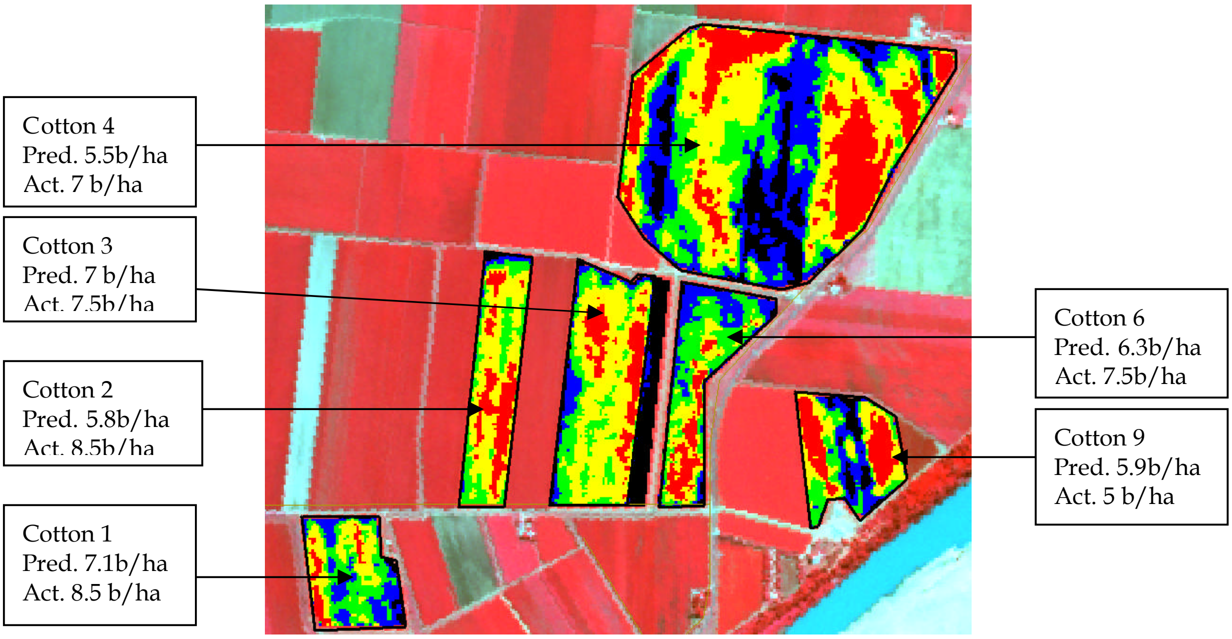


Figure 7. Classified NDVI images of Burdekin cotton crops derived from SPOT5 satellite image captured 14 May 2010.

Identifying soil constraints:

Strategic soil samples collected within the high and low classified imagery zones identified soil constraints that limited production within a number of cotton crops. Some examples include Exchangeable Sodium Percentage (ESP) at 15-30cm within poor vigour areas of an irrigated crop where sodium was ten times the level of potassium resulting in reduced availaby of potassium from cation competition. Nitrogen levels were also found to be much higher in these poorer areas, 6mg/kg in high vigour areas and 20.67mg/kg in low vigour areas, indicating poor uptake by the crop. An additional site demonstrated salinity to be an issue with chloride at 15-30cm in low vigour areas (249.7 mg/kg) measured at over twice the concentration of that within the higher vigour areas (97.3mg/kg) (additional soil results included in the attached annual reports). These examples demonstrate imagery of canopy reflectance as an effective non- direct measure of soil variability. With this information growers can apply targeted remedial action, therefore optimising productivity whilst minimising inputs.

Delivery of spatial data:
The rapid distribution of imagery and derived spatial layers to consultants and growers is of vital importance if remote sensing is to be adopted as an agronomic tool by the Australian Cotton industry. A number of methods were investigated through this project including shape files (ESRI Arc products), geotiffs, pictures embedded in Microsoft Word documents, Pdf files, text data files and as GoogleEarth (kmz) files. Each project collaborator had a preferred media however the internet delivery of large image files within a Google framework was identified to be the most visually appealing, easily navigated and cost effective with the standard Google Earth software free to download. The future development of an internet based framework that enables the delivery of spatial products as well as the recording and storage of spatially referenced data would be of great benefit to the cotton industry.

7. Outcomes (as stated in the proposal)

Expected Science outcomes:

7.1. Identification of extent and impact of variability will assist with refinement of research priorities for further R&D activities.

This project identified a number of spatial technologies including processed satellite imagery, EM surveys and commercially produced yield maps as effective tools for identifying spatial variability within individual cotton crops and across whole farms. Satellite imagery was identified as the most accessible, economically feasible and accurate method for identifying actual in season crop vigour and final yield variability. Such maps were highly effective in identifying poorly performing crop regions and thus presented themselves as an integral tool to future R&D activities such as directing agronomic crop assessments, coordinating variable rate technologies, improve irrigation efficiencies and for identifying a wide range of abiotic and biotic constraints. The continued development of this technology including the industry wide capturing, hosting and delivery of imagery will revolutionise all facets of the industry including scientific research and reporting of results.

7.2. Quantification of spatial variability in abiotic and biotic stresses relevant to the cotton industry, and development of management applications relevant to the cotton industry.

Vigour maps generated from satellite imagery clearly identified under performing crop regions that were the result of a range of constraints including disease (Fuzarium), soil related issues (salinity, exchangeable sodium percentage), poor irrigation practices and prior land use (examples attached in annual reports). By identifying the location of an under performing crop region, the area affected and the nature of the limiting factor, growers can form decisions regarding the application of remedial action. In the case of Fuzarium, the ability to identify localised 'hot spots' (Figure 8a) when they first appear can enable the appropriate management strategies to implemented to prevent further spread. Similarly for salinity (Figure 8b), by identifying the extent of the crop effected, in this case 32%, management decisions such as an alternate irrigation regime from the lateral irrigator can be implemented i.e. longer watering events to flush the high chloride levels away from the root zone.

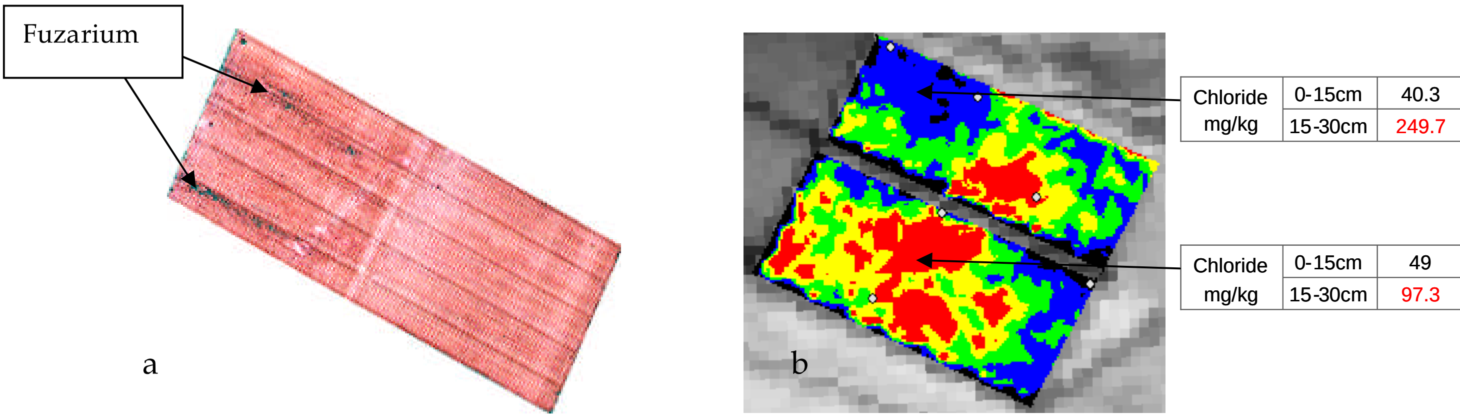


Figure 8. a. False colour QuickBird image identifying plant stress resulting from the soil borne pathogen Fuzarium. b. Classified NDVI Quickbird image identifying a large region of low crop vigour (blue) from high soil chloride levels at depth (15- 30cm).

7.3. Algorithms for a range of biophysical parameter estimation from a range of sensor platforms.

An accurate yield prediction algorithm was developed between measured yield samples and the MidIRPCD vegetation index derived from atmospherically corrected SPOT imagery.

$$\text{Yield} = 9.2686 * \text{MidIRPCD} - 13.996$$

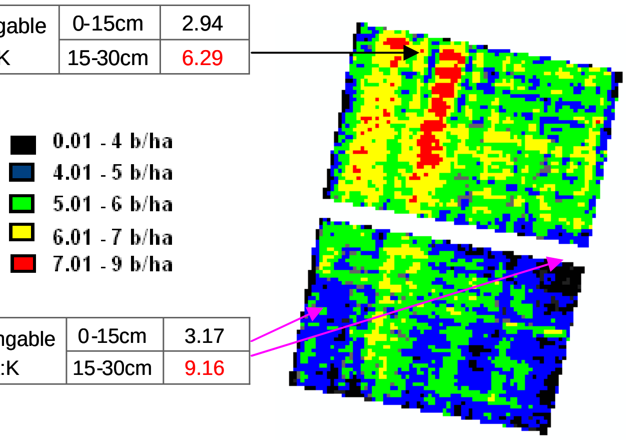
This algorithm was accurate in converting imagery data to yield maps as well as for predicting the average and total yields of a number of un-sampled crops, particularly irrigated crops or those not exposed to in season stress events. The equation does require further development to ensure its prediction accuracy when applied to additional growing locations, environments and cultivars. It was however relatively accurate in predicting the yield of a number of irrigated crops grown in the Queensland's Burdekin region.

Although growers and agronomists were interested in identifying the spatial variability of relevant agronomic measures such as plant height, width, plants per metre, and NAWF across cotton crops, they showed little interest in the development of algorithms to predict these. The classified vegetation index maps accompanied by a general description of the spatial variability in those agronomic measures provided sufficient information (refer to grower reports supplied in attached annual reports).

7.4. Methods for quantifying the major driving variables likely to affect yield/quality and input costs, their spatial distribution, and sensitivity on predicted management outcomes provided by a DSS.

As mentioned, the classified vigour maps derived from satellite imagery were the most effective in identifying the location and area of under performing crop regions. By quantifying these low productivity regions in monetary terms, growers could form informed decisions regarding the economical benefit of applying remedial action. The following example (Figure 9) identifies how an economic estimate of lost production can be calculated for an irrigated cotton crop where highly sodic and low potassium soils are limiting production (blue/black areas). By calculating the maximum production of the 72 ha crop if optimum yield was achieved (7.86 b/ha) and subtracting the actual harvested crop average (4.25 b/ha), an estimated yield deficit from less than optimum production (i.e. 3.6 b/ha) can be determined. In this case a production loss of $116,950 (72ha) can be calculated (260 bales at $450 per bale) from less than optimum production.

Exchangable Na:K	0-15cm	2.94
	15-30cm	6.29



Exchangable Na:K	0-15cm	3.17
	15-30cm	9.16

Estimate of Lost Production	
Total crop area	= 72 ha
Highest yielding Areas	= 7.86 b/ha
Average Predicted Yield	= 4.25 b/ha
Difference (Yield)	= 3.61 b/ha
Difference (Total Bales)	= 260 bales
Difference in Dollars	**= $116950**

Figure 9. Classified yield map of a 72ha irrigated cotton crop with regions of poor crop growth resulting from the soil constraint (Exch. Na:K) represented as blue/ black. Also provided is an estimate of lost production from those regions displaying less than optimum production.

With this information a grower may attempt to remediate the sodic soils by applying gypsum at a rate of 3 t/ha over the low performing areas (pink lined polygons in Figure 10) encompassing 23.3ha or 34.2%. With the cost of this application equated at $6990 (at $100/t) the potential financial benefit of trialling this remedial action is definitely supported.

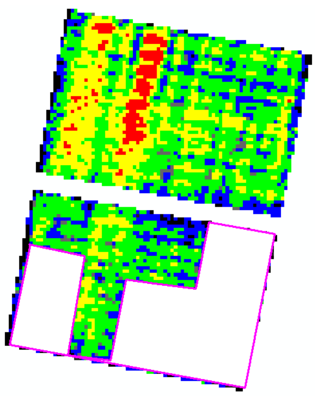


Figure 10. Classified yield map (72ha) with the area of proposed remedial action (23.3 ha) highlighted

Although this example relates to a soil constraint, this application does have similar relevance to other remedial action whether it is herbicide, fungicide, nutrition, additional irrigation etc.

Expected industry/ applied outcomes:

7.5. Understanding of the impact of spatial variability within typical cotton crops and the opportunities this presents for improved management.

Refer to outcomes 2 and 3 above.

7.6. Higher yield and quality of cotton, and lower input costs through identification and amelioration of low performing zones in cotton fields, using PA technologies that have a proven cost-benefit.

Refer to outcome 3 above. Unfortunately due to a lack of access to variable rate applicators and available project time, a full evaluation of the cost benefit of applying targeted input applications based on the methodology mentioned previously was not able to be achieved. This would however be a highly beneficial task for increasing the adoption of PA technologies if opportunity for future funding arises.

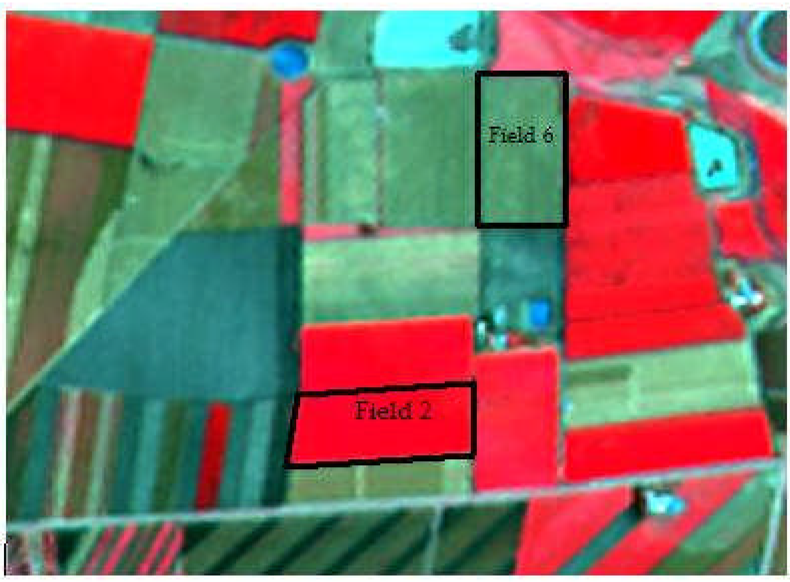
7.7. Identification of the most cost effective combinations of imagery type and frequency for in-season management decisions that are also commercially viable

As stated previously this project investigated both high (0.8m) and mid resolution (10m) satellite imagery. High resolution imagery provided clear representations of sub metre constraints, however, due to its higher cost (US$28.20 per km^2) was deemed to be only commercially viable for specific applications within small agronomic regions rather than for coverage of the entire cropping region. The availability of only a near infrared band (NIR) also made this imagery susceptible to infrared reflectance 'saturation'. The 10m SPOT 5 imagery was identified to be more optimal both in monetary terms (AU$2.70 per km^2) with scenes covering the entire Down growing region, and for spectral resolution with the addition of a mid infrared band. This imagery was also effective for identifying a wide range of growth constraints as well as accurately predicting yield. Images captured closer to commercial harvest date were identified to produce higher correlations than those images captured between December and February.

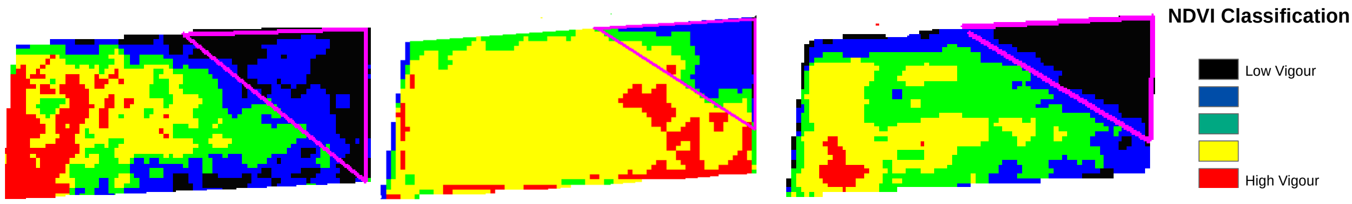
7.8. Methods for optimising in-season and between season variable zone management within a commercial environment. Quantifying sensitivity of management decisions and economic/environmental implications. Eg based on growth rate variability (change in LAI) identified in imagery how can water, nutrients and growth regulation be spatially optimised across a field to maximise yield, and what will the gross margins of 3 different scenarios be over 4 management zones?

The methods adopted for in-season zone management based on economic benefit are addressed in the previous section. In regards to environmental stewardship the methodologies presented for the improved identification and then management of underperforming crop regions support the implementation of variable rate technologies. Such technologies aim to direct the specific application of crop inputs at exact locations and rates where they are required and therefore reduce the risk of potentially harmful farm run off or excessive chemical use. Although no actual measure of environmental changes resulting from improved management strategies were undertaken within this project, it can be suggested that the strategic application of crop inputs is more environmentally responsible then blanket applications.

The stability of crop vigour zones across seasons and cropping rotations was also considered important as this can define inherent spatial trends of a paddock which then can be used by growers to direct improved management strategies prior to a growing season. As such the temporal assessment of a number of cotton blocks within the Downs region was undertaken (Figure 11). The following example identifies trends within two Downs blocks in a sorghum/ cotton rotation across three growing seasons (2007/08, 2008/09 and 2009/2010) with imagery acquired on the 30 December 2007, 13 March 2008, 29 December 2008, 23 February 2009 and 10 January 2010. Classified indexed imagery of both blocks could not be obtained from all imagery due to crop rotation effects such as the senescence of sorghum crops (Field 6 Figure 11a) and cloud cover.



a. False Colour Image captured 23 February 2009. Two cotton blocks of interest highlighted.



b. 13 March 2008 23 February 2009 10 January 2010

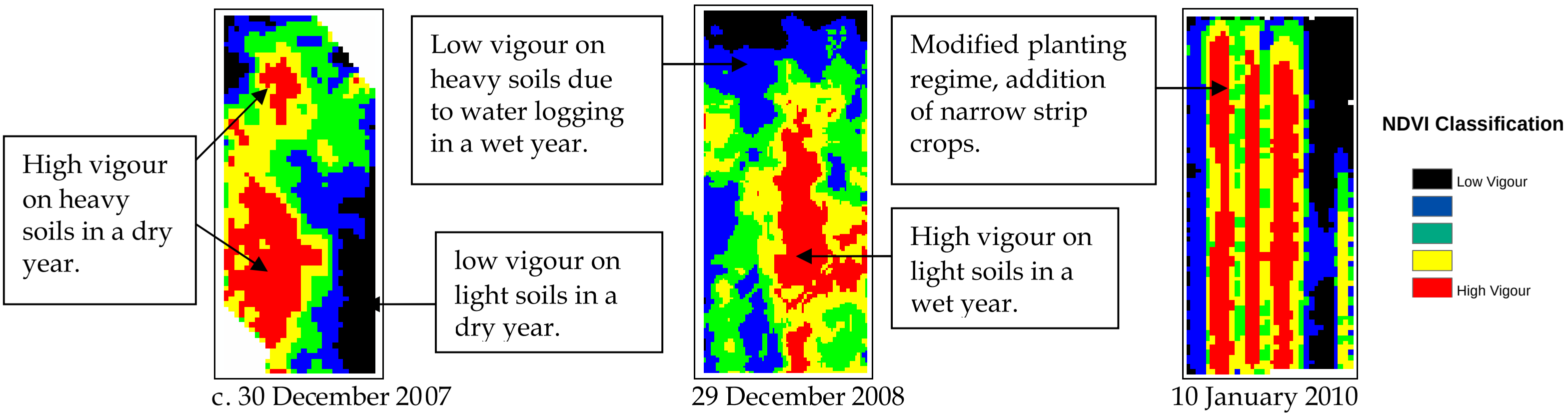


Figure 11: False colour (a) and classified NDVI images (Field 2 (b), Field 6 (c)) identifying seasonal trends in the spatial variability of two Downs cotton blocks.

Field 2 (Figure 11b) exhibited a consistent spatial trend across the three growing seasons, with the north eastern side (pink triangle) exhibiting consistently less vigour, identified to be a result of reduced soil water holding capacity. By understanding the seasonal reoccurrence of this trend the grower can decide whether the cropping of this region is unviable, or apply remedial action such as clay or organic matter to improve water holding capacity and therefore yield. The second example (Figure 11c) identifies a block with no consistent spatial trend, a result of the interaction between soil type and climatic variability i.e. heavy rainfall and water logging in heavier soils during the 2008/09 season, and changed management before the 2009/2010 season. As such the development of a generic management strategy based on previous crop history is impossible; indicating the need for seasonal imagery to identify regions of reduced production, enable coordinated agronomy and direct remedial action.

8. Conclusion

Research within the Queensland, Darling Downs cotton growing region identified a number of novel and useful remote sensing applications relevant to Australian cotton industry and included targeted agronomy based on varying crop vigour zones, the rapid identification of a range of abiotic and biotic constraints and the prediction of yield variability prior to harvest. All these applications have the potential to improve current management strategies to support both economically and environmentally sustainable farming in the future.

The SPOT5 satellite (10m spatial resolution) was identified to be a cost effective source of imagery data at AU$2.70 per km^2, providing scenes that encompassed the entire Downs growing region and produced crop vigour maps with spatial trends comparable to the higher resolution platforms. Such vigour maps were highly accurate in defining actual crop variability and therefore provided an effective tool for guiding relevant in-season agronomic crop assessments including plant height, width, nodes above white flower (NAWF), plants per metre, incidences of disease, irrigation inefficiencies and soil health.

For yield prediction, imagery captured later in the growing season i.e. February and March, produced a higher correlation between measured yield samples and corresponding image data values. The further development of the mid infrared plant cell density (MidIRPCD) index minimised spectral saturation issues evident in commonly used near infrared based indices. The linear algorithm developed from the correlation between sampled crop yield and vegetation index values was accurate for predicting the total yield and yield variability of a number of un-sampled validation crops both within the Downs and Burdekin growing regions. The derived maps were not only useful for identifying yield variability and therefore supported decisions regarding the application of remedial action, but also provided an effective reference for ensuring the accuracy of commercial yield monitor data. The ability to accurately predict yield at both a farm and regional level can enable production estimates to be made prior to harvest, allowing for improved strategies regarding the harvest, storage, processing and on-selling of cotton to be formed.

This project endeavoured to collaborate with a diverse group of growers and consultants within the Downs region as such was successful in generating much interest in potential remote sensing applications. The trialling of Google Earth as a distribution host of derived imagery products was highly successful with most participants already have some experience with the free software. This result indicated the need to establish a similar system for the Australian cotton industry that has the capacity to host imagery data as well as offer growers, consultants and researchers

9. Extension Opportunities

Research and interest shown in this project supports the need for the development of a standardised internet based delivery system that can host and deliver remotely sensed imagery to all facets of the Australian Cotton industry. This framework could also provide an easy-to-use and safe interface for growers and researcher to record additional spatially referenced information including point source observations or measurements, EM soil layers, yield maps, irrigation scheduling etc. This tool has the potential of improving the sustainability, profitability and traceability of the cotton industry and its catchments, as well as to encourage industry collaboration to provide a strong, focused and committed research program. Such a framework offers many benefits including:

Expected economic benefits:

- Improve efficiencies – time savings for growers associated with view, entry and management of farm information at block level; also improved industry collaboration.
- Improve technology delivery – easier access to relevant technology layers for growers, including in-season imagery for variable rate applications to reduce input costs whilst still maintaining optimal crop production.

- Standardize information recording – improved efficiencies in the conversion, translation or interpretation of data for growers, industry and researchers, whilst still ensuring information security for growers.

Expected environmental benefits:

- Improve and standardise reporting practices, such as information regarding current management practices, accessible at a farm or regional level that can be linked to environmental outcomes.
- Reduce risk of off-site impacts by rapid delivery of technology layers including imagery and vigour maps to improve application efficiencies for crop inputs, potentially reducing farm run off.

Expected social benefits:

- Reduce inconsistent data management by providing a standardised interface for growers to view, enter and manage information relating to their management practices that will be protected as their own personal information.
- Improve data dissemination between stakeholders by enabling exchange and reuse of data by growers, gins, productivity services and research groups following grower approval.
- Provide platforms for ongoing use after research by developing an easy-to-use interface that will improve uptake and ensure continuation of use after research has completed.
- Traceability - provide a framework that will enable efficient recovery of current and historic crop data to enable improved traceability

Expected return on investment:

- Address the needs of growers, industry and researchers by offering the cotton industry a standardised data management interface that encourages uptake of efficient and sustainable land and nutrient management practices, a key achievement in fulfilling environmentally sustainable cotton cropping.
- The approach and tools will be transferable to other agricultural industries, both in Australia and overseas.

Furthermore this unprecedented collation of data and spatial information will enable:

- **Growers** to identify within-season and historically underperforming crop regions and allow for the improved the adoption of variable rate technologies; provide a spatially based nutrient and chemical application rate recording system (from tractor to database); allow for records (financial, crop history, irrigation regime etc) to be accessed with ease via spatial connectivity to each respective farm block; and enable reports of cotton management, harvest locations etc to be easily compiled for traceability requirements or to report on environmental stewardship.
- **Agronomists** to direct where in-season crop assessment should be taken (high and low vigour regions); identify locations to record and report in-season crop assessments and soil test results.
- **Gins** to provide harvest/ quality reports that are spatially linked to each respective crop.

- **Contractors** to identify location of crops prior to a job and then to report on job results.
- **Biosecurity** to identify changes in the spatial trends of crop vigour across seasons, therefore allowing for potential sites of concern to be identified and ground truthed; if identified to be a risk of concern, the framework could be used as a warning delivery system.
- **Research/ Consultancy groups** to direct where in-season surveys are taken, where to locate replicated trials so they are not influenced by inherent issues such as soil type etc., report results to growers and other collaborators and to compare results and locations from differing years.
- **Seed distributors** to locate trial sites, record and distribute results and promote varieties.
- **Industry** to identify cropping trends from season to season and to predict regional yield.

It is suggested that once this site is established and validated, it will be supported financially by contributions from each entity involved including growers, industry and research bodies.