2004 BELTWIDE COTTON CONFERENCES, SAN ANTONIO, TX – JANUARY 5-9

IMAGE-BASED, VARIABLE RATE PLANT GROWTH REGULATOR APPLIED BY AIR TO CALIFORNIA COTTON

Matthew Bethel, David Lewis, and Susan White
The Institute for Technology Development
Stennis Space Center, MS
Ted Sheely
Sheely Farms
Lemoore, CA
Bruce Roberts
University of California Cooperative Extension
Hanford, CA
Roger Hewitt
Blair Air Service, Inc.
Lemoore, CA
Mechel Paggi
California State University, Fresno
Fresno, CA
Nick Groenenberg
Nick Groenenberg Consulting
Hanford, CA

Abstract

Plant Growth Regulator (PGR) is commonly used in cotton plant management. When applied to the crop, it redirects plant growth from the vegetative leaves to boll production and as a result can increase yield. In the 2000 and 2001 growing seasons experiments were performed in Mississippi to study the effect of PGR application across different Normalized Difference Vegetation Index (NDVI) regions of a field. NDVI measurements were extracted from remotely sensed data acquired over the field. In the2000 experiment, the field was segmented into two types of treatment strips. One type received blanket applications of PGR according to traditional methods. The other treatment strips received no PGR. The treatment strips contained three different NDVI groupings to research if plants with different NDVI measurements respond differently to PGR. The 2001 experiment replicated the 2000 experiment, but added treatment strips as Spatially Variable plant Growth Regulator (SVPGR) applications to the design. The intent of this study was to determine if SVPGR application methods could be used as a technique to reduce PGR application costs and at the same time maintain or increase yields over the traditional (100%) method of applying PGR. The results of this research indicated that a cost savings of approximately 24% was realized in using the SVPGR method as compared to the traditional method.

In 2002, the image-based PGR application experiments were also conducted in the San Joaquin Valley of California. The San Joaquin Valley was chosen because of its different growing conditions from Mississippi, as well as the availability of a cooperating producer (Ted Sheely) and concurrent collaborative research on-going by USDA and University of California researchers at the farm. The 2002 PGR experiment incorporated plant height variance analysis following the PGR prescription application to determine any treatment effects on crop canopy management. The 2002 study experiment design consisted of three treatments; the untreated control, Site-Specific PGR (SSPGR), and Variable-Rate PGR (VRPGR). The SSPGR treatment consisted of strips that received two rates (0% and 100% of the scout prescribed rate for the field) of plant growth regulator based on the image data. The additional image-based treatment included in the experiment design, VRPGR, included five different PGR rates based on image analyses for those treatment strips. The results of the 2002 study (ITD Final Report, 2002) showed that the SSPGR treatment resulted in a 19% cost savings from using site-specific PGR applications as opposed to traditional (100%) applications of Pix. The results also showed that there was a 51% reduction in chemical applied with the SSPGR treatment with no adverse effect on yield. The comparison of the VRPGR and 100% applications of Pix indicated that VRPGR applications were, on average, 27% more costly. There was no statistical difference in plant height variance among the treatments, which indicated no negative impact on crop canopy management from using the image-based techniques.

The 2003 image-based PGR experiment incorporated the knowledge gained from the results of the 2002 study and attempted to implement new aspects to the experiment that would lead to more practical adoption of this technology in California. Specifically, the 2003 experiment included one image-based treatment that consisted of three rates based on the imagery and the field scout's recommendations, and because of the practical limitations of the application of PGR by ground sprayer in an area dependant on furrow irrigation, the study was designed around the aerial application of the PGR prescription. A Pima cotton field was included in the 2003 study because of the large amount of cotton acreage in California devoted to this crop.

Background

PGR—in this case Pix® (Mepiquat Chloride), is applied to cotton in order to inhibit cell elongation, restrict vegetative growth, and promote earlier and heavier boll production on lower node branches, and thereby increase lint yield (Weir and Kerby, 1988). It is usually applied in a blanket fashion based on factors such as height, height-to-node ratio, average length of top five internodes, internode length, and moisture status (Kerby et al., 1990). Plant height is widely recognized as a strong indicator for PGR application, by Weir and Kerby (1988), Kerby et al. (1990), and by Munier et al. (1993). These studies showed that plant height was "related to plant vigor and early fruit retention and this is a good indicator of the need for Pix®." Kerby et al. (1990) cited plant height prior to first bloom as the premier of six indicators for triggering PGR application. These factors are commonly checked in the field by consultants, sometimes aided by global positioning systems (GPS) (Thurman and Heiniger, 1998). Kerby (1985) observed yield benefits through the use of PGR. Cothren and Oosterhuis (1993) found that maintenance of a uniform cotton crop benefits insect management, crop termination, and harvest. Blanket (100%) applications of PGR based on a constant rate often results in the application of chemical to areas of a field that may not require treatment and as a result, may decrease yields. Likewise, insufficient application may also decrease yields in excessively leafy areas.

ITD observed these patterns in 1998-1999 when yield was quantified corresponding to five levels of the Normalized Difference Vegetation Index (NDVI) during 23 image dates in two different fields at Perthshire Farms in Mississippi (ITD Final Report, 1999). The patterns showed that the highest-20 percent of the NDVI areas became increasingly indicative of lower-yielding areas as the season progressed, indicating that these areas may be ideal candidates for site-specific PGR application. These observations resulted in a more formal PGR experiment at Perthshire Farms in 2000.

Variable rate applications of PGR have been discussed in studies by Weir and Kerby (1988), Munier et al. (1993), and Thurman and Heiniger (1998). Most studies had generally positive results with the potential of minimizing the use of the chemical, if not increasing yield. Other research explored adjustments in the timing and quantity of PGR applications. However, we have not found any specific references to the use of imagery for site-specific PGR application in cotton. Thurman and Heiniger (1998) briefly mentioned the use of aerial photographs "to assist in identifying areas of the field which differed in growth and development" in the context of a PGR study, but the photos were not directly germane to the study. Thurman and Heiniger (1998) did, however, determine (through grid-based field samples) that the variability in key cotton indicators was "wide enough to justify variable rate technology practices and application of Pix", and that "spatial analysis would improve the decision process of PGR application timing". Thurman and Heiniger (1999) identified growth areas and soil types in fields using aerial photography, GPS scouting, digital soil surveys and field histories. They also demonstrated that height control in rapid growth situations is critical to high boll retention and yield in variable cotton fields.

Research has shown that plant growth and development in crops can be effectively mapped with remotely sensed reflectance data (Moran et al., 1997; Senay et al., 1998; Plant and Keely, 1999). There have been numerous studies that showed high correlations between certain vegetation indices developed from spectral observations and plant stand parameters such as plant height, percent ground cover by vegetation, and plant population (Weigand et al., 1991). Some of the vegetation indices that Weigand et al. (1991) used in estimating crop vigor and yield prediction in salt-affected cotton near Weslaco, Texas were the NDVI, the GVI (Green Vegetation Index), and the PVI (perpendicular vegetation index). Holben (1980) found significant correlations between linear combinations of red and near-infrared bands, as well as vegetation indices, and green leaf biomass of a soybean crop canopy. Other studies have found these relationships between reflectance and plant biomass for a variety of crop cover types (Deering, 1978; Tucker, 1979). Coupled with ITD's past investigations (ITD Final Report 1999, 2000, 2001, and 2002), previous research points to the use of imagery to identify vigorous areas within a crop canopy, which are likely to exhibit excessive plant height, and thus may serve as a sound basis for an image-based PGR application.

Goal

The goal of this study was to successfully correlate remotely sensed image data to specific plant characteristics indicative of plant vigor that are normally sampled when scouting for PGR applications. Given the relationship between scout data and image data, this study attempted to reduce chemical input of PGR while maintaining or exceeding yields of normal 100% PGR application through site-specific applications based on imagery and the field scout's recommendations. The success of this study is measured by an increase in the producer's net profit resulting from the image-based treatment. Another goal of this study was to maintain or improve crop canopy management by minimizing variations in plant height as compared to the 100% treatment with image-based applications.

Hypotheses

Analyses were conducted on the data collected during this experiment to draw conclusions for the following three hypotheses:

1) There are significant relationships between image reflectance and one or more plant parameters tested.

   H_O: There are no significant relationships between image reflectance and any plant parameters tested.

H_A: There is a significant relationship between image reflectance and one or more plant parameters tested.

2) There is an economic advantage to using image-based PGR applications as opposed to the traditional 100% PGR application as evidenced by net profit (defined as the crop revenue – PGR input costs) to the producer.

Ho: There are no significant differences in net profit to the producer between the treatments.
H_A: At least one is significantly different.

If the researchers fail to reject Ho, then analysis shows that there is no economic advantage to using image-based application of PGR as opposed to the traditional 100% application to a field.

If Ho is rejected, and Net Profit $_{\text{image-based areas}}$ > Net Profit $_{\text{100\% spray areas}}$ then the analysis shows that image-based PGR applications significantly increases a producer's net profit over traditional methods.

3) There is no adverse effect on crop canopy maintenance in using image-based PGR applications, as evidenced by a comparison of plant height variance measurements sampled within each treatment.

Ho: Plant height variance for the all are equal (i.e. Plant height variance $_{\text{image-based areas}}$ = Plant height variance $_{\text{100\% spray areas}}$ = Plant height variance $_{\text{Spray-Off areas)}}$
H_A: At least one treatments plant height variance is statistically different from the others.

If Ho is rejected, then the plant height variance differs for at least one of the treatments.

Experiment Design

This experiment consisted of a randomized complete block design replicated twice (Figure 1). The design allowed for testing of the underlying concept that image-based applications of PGR can increase net profit to a producer through a reduction in applied chemical and maintenance or increase in yield from the traditional method. The 2003 treatments were as follows:

1) No PGR
2) PGR 100% application (traditional method)
3) Site-specific, image-based PGR (SSPGR) application

Each of four blocks contained three field strips; one strip for each treatment. The No PGR treatment areas were unsprayed. The traditional method was a 100% blanket spray at a constant rate designated for that field by the field scout. The SSPGR treatment consisted of three rates determined appropriate by the field scout based on the relationship between field sampling and the image data. The spray threshold was determined by the field scout. The image processing technique that proved to have the strongest relationship with the field scout's data was used to develop the SSPGR prescription.

The SSPGR treatment was determined based on the statistical relationship between reflectance and the field scout's rate recommendations at GPS designated sampling points within the image-based treatment strips for each field. Plant mapping data as measured by plant height, internode distance (between the 4^{th} and 5^{th} nodes for typical PGR application in the San Joaquin Valley), internode distance of the top five internodes, and total node count were also analyzed for statistical relationships with reflectance to compare and relate to any relationship found with the field scout's data. These plant measurements were taken at six GPS designated sampling points within each treatment strip (each treatment strip is approximately .8 kilometers or .5 miles in length). The six sampling points were spaced equidistant from each other along each treatment strip. There were five random samples at each of the sampling points taken within a four-square meter area, then averaged to get a single value for each plant parameter sampled at each point. Analysis from the data collected was performed to ensure a relationship exists with the imagery, and given that relationship, the image processing technique determined to have the strongest relationship with the field data collected was used to create the prescription for the image-based PGR (SSPGR) application treatment strips. The SSPGR prescription was generated according to a regression equation created from the correlation between the image processing techniques tested and the field scout's rate recommendations at the sampling points.

The regression equation from the image processing technique that had the highest correlation was then applied to the image data, and thus inferred crop canopy PGR rate requirements for the SSPGR treatment strips. The output raster coverage was vectorized into polygons. The prescription was then converted into a digital geographic information system (GIS) format that was uploaded into the AutoCal variable-rate controller of the aerial applicator. The prescription for the image-based treatment contained spatially accurate PGR rate recommendations for the research area in pixels that were approximately 21.3x61 meters (70x200 feet) (the width of the applicator boom and the length of the ability of the aerial applicator's equipment to modify PGR application rates along track). The rates of Pix used in the mixed product for the PGR application were 0, 0.048, and 0.096 litres/hectare (0, 4, and 8 ounces/acre) for the Acala cotton field (5-3), and 0, 0.096, and 0.192 litres/hectare (0, 8, and 16 ounces/acre) for the Pima cotton field (31-3) as recommended by the field scout and Ted Sheely.

The scout determined when the experiment field was ready for the PGR application to the treatment strips based on normal methods. A prescription was generated directing the aerial applicator to apply PGR based on the image processing technique that best correlated to the field data collected for the SSPGR treatment. The prescription also included the 0% and 100% PGR application areas.

The study area (Figure 2) consisted of two fields, a Pima and an Acala cotton variety, approximately 65 hectares (160-acre) each in size at Sheely Farms (Fields 31-3 and 5-3 respectively) that the producer made available to the researchers. The fields were sprayed by air (as opposed to a ground-based sprayer). The study fields were chosen according to recommendations made by the grower and UC Cooperative Extension personnel. Factors involved in site determination included the potential for highly variable crop canopy field conditions and absence of any additional research occurring in conjunction with this study that may have confounded the experiment. We utilized 288 rows, each 96.5 centimeters (38" wide), spanning the length of the field to form a whole plot. There were 24 rows in each treatment strip, and 4 blocks of the three treatments listed above (Figure 1). Four-row pickers were utilized at harvest, and GPS equipped yield monitor data was collected for each picker pass within the study area.

Study Area

The research study area was a portion of two contiguous fields (field 5-3 and field 31-3) each totaling 64.75 hectares (160 acres) on the main ranch of Sheely Farms near Lemoore, California (Figure 2). Located in the San Joaquin Valley, the region represents a major cotton production area for the Western United States. Agriculture in this area of California is completely dependent on irrigation. Area producers grow such varied crops as tomatoes, spring wheat, and garlic in rotation with cotton.

Methodology

This experiment relied upon airborne three-band (830nm-70nm bandwidth, 660nm-30nm bandwidth, and 560nm-40nm bandwidth) multispectral imagery flown at 1-meter resolution by Precision Aviation, Inc. This spatial resolution allowed for the experiment field to be completely contained in one frame of the imagery when flown according to the prepared flight lines over Sheely farms, as well as provided ample spatial resolution for assessment of the imagery during the experiment. The sensor used was the RDACS multispectral sensor developed by the Institute for Technology Development. Imagery for the PGR prescription generation was collected on July 11th, just prior to PGR application. Image data was also acquired throughout the growing season (June 19th, June 26th, July 25th, and August 11th) to facilitate the investigation of the relationship between imagery and plant parameter data during the maturation of the cotton crop.

Field Data

Using measurements collected at different locations in the study field, the scouts involved with this study made decisions as to what PGR rate was best suited for each specific sampling area in the Variable-rate PGR treatment strips. Image analysts attempted to correlate image data to field sampling data and consequently created a variable rate prescription using this relationship to infer rates across the variable rate PGR strips. The researchers hypothesized that by applying plant growth regulator only to the areas that correspond with high vegetation indices values, significant savings in cost for PGR application may be achieved by reducing the amount of chemical applied in the field. Another aspect of the 2003 California PGR study was to assess crop canopy management with Pix. The value of a PGR application to a crop is not simply yield dependent, but the uniform control of cotton crop canopy is essential for proper crop management throughout the season (Shaw, 2001). Uncontrolled and highly variable crop canopies may result in the inability to properly apply chemicals with ground-based applicators, as well as adverse effects to farm equipment from driving through rank, tangled vegetation.

Plant characteristics were measured by field scouts to determine optimal PGR application timing. Once the date of PGR application was set for the study fields, field data was collected to aid in the creation of the prescription map. These measurements included plant height, total main stem nodes, internodal length, and the broader experience of the field scout for rate recommendations. Pix does not effect the total number of nodes, just the internodal length. Therefore, nodes are normally counted along with plant height to calculate height to node ratios. This is a good representation of plant vigor (Kerby and Hake, 1996). The field scout determined the particular rate of PGR to be applied to the Image-based PGR and 100% PGR treatment strips based on the normal methodology while scouting. Six GPS designated sampling points within each treatment strip spaced at equal-distances were designated at the beginning of the season and were visited at the sampling dates throughout the growing season, including just prior to the PGR application. Plant data collected at these points was compared to the scout's recommendations for the prescription, and was used to verify the results of the PGR application for the crop canopy management hypothesis.

Data collection conducted for the crop canopy management analysis was collected on August 11th (around the time of crop cutout for maximum plant height following PGR application), which allowed enough time for the crop canopy to show the effects of the Pix application (Roberts, 2002). This data consisted of plant height measurements at each sampling point along the treatment strips. At harvest, yield data was collected by GPS equipped yield monitors. The yield data was extracted from

80x8 meter areas (80 meters along the picker path by the width of two picker passes) around the sampling points for each strip to determine an average yield/acre for each treatment. Yield monitor data was collected for each picker pass in the study area at two-second intervals. The yield monitors were calibrated to a weigh wagon prior to harvest and were consistently within 5% of the yield weights as measured by the weigh wagon.

Image Pre-Processing Procedures

Preprocessing of the multispectral RDACS image data that was acquired for the study included band-to-band registration, georectification, and calibration to relative reflectance. Radiometric calibration utilized two permanent radiometric targets that were adjacent to the study fields at the time of data acquisition. These calibration targets varied in their reflectance values (the dark panel with a nominal value of 8%, and the light panel being 65%) and were 9.75x9.75 meter (32x32 ft) in size once opened up for data collection. The calibration panels were routinely cleaned before each image acquisition, but radiometer scans were collected during several image acquisitions to determine any significant reflectance change over the course of the growing season. This ensured proper calibration of the imagery for the day of image acquisition. Image calibration was performed using an empirical line equation between the digital numbers for the calibration panels retrieved from the imagery and the reflectance values for each target based on the radiometer scans collected (Moran et al., 1997). The image datasets were band-to-band registered and georeferenced using 1.22x1.22 meter (4x4 ft) white panels placed around Ted Sheely's farm at the corners of his fields. Each panel's position was recorded using a GPS with sub-meter accuracy.

Image Processing Procedures

Various techniques such as band ratios, vegetation indexes (NDVI, soil-adjusted vegetation index, NDVI change map, etc.), and linear band combinations were applied to the pre-processed image data to be tested for correlation with the ground truth data. The correlations were performed in order to derive the prescription for the variable rate treatment strips. The field scout's rate recommendation at each sampling point was used to assign estimated Pix rates to the variable-rate treatment based on the relationship with the image data.

Using discriminant analyses, a regression equation was derived for the image processing-technique that had the highest correlation to the scout's Pix rate values at the sampling sites. These techniques included the NDVI (Plant, 1999), a soil-adjusted vegetation index, an NDVI change map, and all combinations of bands possible with the three-band dataset. The resulting regression equation was applied to the imagery and a 'estimated Pix rate map' produced. The image was then converted into an ESRI Grid format and recoded to contain three discreet Pix rates (0, 5, and 10 gallons/acre) at two different Pix concentrations for the mixed product (one for Pima cotton and the other for Acala cotton) based on the scout's recommendations. These discreet Pix rates were defined by the field scout as typically assigned Pix rates, and the values of the continuous dataset were rounded to the nearest discreet value.

The prescription generation process involved generating a 21.3 x 61 meter (70x200 ft) spray grid that was overlaid on the ESRI Grid file. Each spray grid cell represented the width of the spray boom on the applicator (70 ft), and the distance by which the valves in the spray nozzles were able to effectively produce different rates (200 ft). Extensive testing was performed at Sheely Farms prior to the actual PGR application to assess the aerial applicator's ability to effectively change rates along a flight path. Test prescriptions were generated with rate changes at various distances along a flight path at various rates. For the test, water-sensitive cards were placed along the test strip (.5 mile long) at 50-foot intervals. The aerial applicator was loaded with water and flown over the test prescription. The water dispersion patterns on the cards collected after the test were analyzed by scanning the cards in digital form. The data was then run through the California Aerial Applicator's Association (CAAA) software to assess any rate changes evident on the cards. The rate changes were then compared to the test prescription generated to determine what distances along the flight direction of the applicator were acceptable. Based on the results of the testing, CAAA recommended effective rate changes at a minimum distance of 61 meters (Stoltz, 2003). The spray grid was aligned, centered on each treatment strip, and rotated to match the row orientation of the field. Once the alignment of the spray grid with the treatment strips was accomplished, the majority values of pixels in the estimated Pix rate map for each spray grid polygon in the variable rate treatment strips were used to create the variable rate prescription. The separate prescriptions for the variable rate, 100%, and 0 PGR treatments were then merged together to create a single prescription for each field (Figure 3). The prescription shapefile was created with a file format that was compatible with the AutoCal controller and SatLoc guidance system in the aerial applicator.

Field Data Collection

In-season field data collection for the PGR study in each field occurred in conjunction with each image acquisition given that the irrigation schedule in the field permitted sampling on that day. If the irrigation schedule did not allow for entry into the field on the same day then sampling occurred on the next possible day to enter the field. This field data was used to develop the prescription for the variable rate treatment strips. The field data consisted of plant height (as measured from cotyledon to terminal node along the main stem with a tape measure), total main stem nodes, and internodal distance between the 4^{th} and 5^{th} internode measurements, and was guided by Bruce Roberts of UC Cooperative Extension. Each GPS designated sampling point was flagged and labeled to facilitate field data collection. Once the cotton canopy grew tall enough to conceal the flags, painted wooded stakes were positioned at each sampling point that were higher than the crop canopy in order to help with sample point location. Five random measurements of each plant parameter sampled were taken at each sampling location from a four-square meter area around each flagged point, and then averaged to get a value for the plant parameters sampled at each sampling location. This data was collected using iPAQs equipped with GPS and sampling forms to record the data developed for ArcPad 6.0 by ITD.

Seed cotton yield was collected using cotton pickers equipped with sub-meter accuracy GPS receivers and AgriPlan yield monitors. A weigh wagon was used to weigh the cotton after each pass through a treatment strip. Bill Son, of Bill Son Cotton Picker Service, USDA-Shafter, and UC Cooperative Extension personnel calibrated the combine's yield monitor and weigh wagon scales just prior to harvest. The yield monitors were then calibrated by picking several passes of cotton and dumping into the calibrated weigh wagon until differences were consistently within 5%.

After harvest, the yield data files were downloaded from the PCMCIA cards and exported to shapefiles for further analysis and processing. Data points that were logged when the picker had stopped and/or momentarily reversed its direction of travel (i.e., due to plugging) were removed from the data set. After editing was complete, the file was saved and exported as a comma-delimited ASCII file.

Next, the yield data was processed using algorithms similar to those described by Birrell et al. (1996). These algorithms were implemented in software developed by the USDA-Agricultural Research Service (ARS) in Columbia, Missouri (Drummond, 2003). The software was used to correct the yield data for the time delay, removal of outliers, and to clean up the ends of the field were the picker entered and exited the crop. To maintain data integrity, yield data from each cotton picker (three pickers were used to harvest the study fields) was processed individually. After all the individual data files were processed for each study field, the files were merged for further analysis.

Statistical Analysis

The statistical analysis of the plant height sampling data following the PGR application was performed using the Chi-Square test in SAS (Cody and Smith, 1997) for variance differences among the treatments. An analysis of variance (the GLM procedure in SAS) was performed on the yield data to compare the average yield between treatments. The yield monitor data was analyzed using yield data extracted from an 80-meter long strip that was two picker-passes wide at each sampling point along each treatment strip. The yield data extracted at each point was averaged to get an average yield/acre for a particular point. There were a few points where misapplication of the PGR occurred as a result of intermittent GPS signal loss, and the data at these points were omitted for the statistical analyses. By only looking at the yield monitor data around each sampling point, the researchers ignored any yield variations that might be due to the picker starting up or slowing down at the end of a pass. The yield data was analyzed for any yield variance within treatment differences.

Results

Regression analysis results for the field sampling data and a number of image processing techniques indicated in the Methodology section above showed some correlation. The results of the regression analysis performed on the field scout's Pix rates derived from the field sampling data and the green band for the Acala cotton field produced a coefficient of determination of 0.73. The resulting regression equation applied to the image data for the variable rate treatment strips in the Acala field was ((Red * 1.31) – 20.28). The regression analysis for the Pima field (31-3) showed much less correlation between the field data and the image data with a coefficient of determination of 0.21. The resulting regression equation applied to the image data for the Pima field was ((Green * 1.57) – 5.13. Discriminant analysis was used to determine the image processing technique that correlated best to the estimated Pix rates. The results of the correlation between what Pix rate was predicted with the imagery and the rate recommended by the field scout at the sampling points in the variable-rate treatment strips are shown in the frequency tables below (Tables 1 and 2). The table for the Acala field shows that predicted PGR rate at the sampling sites visited by the field scout match up well with the field scout's recommended rates at those sites (for the 10 times that the field scout recommended 5 gallons/acre, the predicted rate was correct 100% of the time). The table for the Pima field (31-3) shows much less accuracy in predicting the field scout's recommended rates with the imagery.

The Chi-Square test performed to analyze the pre and post-PGR application plant height sampling data showed different results between the Acala and Pima cotton studies. For field 5-3 (Acala cotton), there was significant difference between the treatments (alpha = 0.05) after PGR application. The variable-rate treatment provided the smallest variance of plant height. For field 31-3 (Pima cotton), the plant height variance of the 100% PGR treatment was significantly less than the other treatments at the end of the season. The plant height data analysis for the Pima field showed that the 100% PGR treatment was the most effective in reducing the plant height variance (Figure 5). The post-PGR application sampling showed that the 100% PGR treatment had a significantly more uniform crop canopy than the variable-rate or No PGR treatments. The summary statistics are depicted below in figures 4 and 5 by sampling date (PGR application occurred on July 23rd).

Results of the analysis of variance between the yield data from the treatment strips of the Acala cotton field (5-3) showed that a significant difference existed between the treatments (Pr > F = 0.0057; Table 3).

Duncan's Multiple Range Test was used to determine what treatments were significantly different. The result showed that the Variable-rate and standard (100%) treatment yields were not statistically different. The No PGR treatment yield, however, was significantly less than the other two treatments.

Results of the analysis of variance between the yield data from the treatment strips of the Pima cotton field (31-3) showed that a significant difference existed between the treatments ($Pr > F = 0.0241$; Table 4).

Duncan's Multiple Range Test was again used to determine what treatments were significantly different. The result showed that the Variable-rate and standard (100%) treatment yields were again not statistically different, and that the No PGR treatment yielded significantly less then the other treatments.

Economic Analysis

The economic analysis for this study was performed under the direction of the Fresno State University Center for Agricultural Business. The economic analysis compared the cost of traditional (100%) PGR applications to the cost of SSPGR applications. This cost includes equipment, human resource, imagery, prescription generation, and application costs.

Some of the costs factored into the economic analysis include $0.50/acre for the imagery, $2.50/acre for a consultant to create the prescription, $7.85/acre for the SSPGR application costs, and $44.50/gallon for the Pix chemical. These costs were supplied by local service providers currently working with area growers. Revenue for this economic analysis was based upon a return to the grower of $0.88/pound of Acala lint cotton harvested, and $1.25/pound of Pima lint cotton harvested. This is the price of lint cotton that the grower expects to receive for the 2003 crop.

The SSPGR treatment had the highest yield for both of the study fields, however, only slightly higher than the 100% PGR treatment. The No PGR treatment had yields that were much lower than the other two treatments in both study fields. The uniformity in yield between the 100% PGR and SSPGR treatments for this study accounted for the similarities in revenue from lint cotton per acre based on a 37% turnout that is typical for Riatta variety Acala cotton, and 35% turnout for Pima cotton in the San Joaquin Valley. The treatment strips where no PGR was applied yielded an average revenue of $1,220 per acre for the Acala cotton field, and $2,028 per acre for the Pima cotton field. The SSPGR strips yielded an average of $1,498 per acre in the Acala field, and $2,147 per acre in the Pima cotton field. This difference in average gross revenues was $83 per acre between the 100% treatment with the SSPGR treatment in the Acala field, and $5 between those treatments in the Pima field (Tables 5 and 6).

PGR chemical and application costs were different between the treatments. These cost differences are shown in Tables 7 and 8 for the Acala study, and in Tables 9 and 10 for the Pima study. The SSPGR treatment shows a slight increase in costs from the 100% PGR application for the Acala study, and a slight decrease in costs from the 100% PGR treatment in the Pima study. This difference in costs relative to the 100% treatment is due to the different concentrations of Pix chemical used for the two types of cotton. Pima typically receives a higher concentration of Pix than does Acala cotton. For this study the 5 gallon/acre rate (50% rate) used 4 oz/acre of Pix for the Acala, and 8 oz/acre for the Pima field. The 100% application used 8 oz/acre of Pix for the Acala, and 16 oz/acre for the Pima cotton. The majority of the acreage in the SSPGR treatment prescription for both fields was the 5 gallon/acre rate. This rate was 8 oz/acre of Pix chemical applied less than the 100% blanket rate for the Pima, but only 4 oz/acre of chemical applied less than the 100% treatment for the Acala field. Both image-based treatments resulted in a reduction in chemical applied when compared to the 100% treatment (Tables 8 and 10).

In summary, the comparison of SSPGR applications and a traditional (100%) application of Pix indicated that SSPGR applications resulted in an $82.36 average net revenue ($/acre) increase for the Acala study, and a $5.13 increase for the Pima study with very similar yield. The analysis shows that there was a reduction in chemical applied of about 65% in using SSPGR applications for Acala cotton, and a 52% reduction of chemical with SSPGR applications in Pima cotton when compared to the traditional (100%) method.

Conclusions

The results of the regression analysis performed on the image data with the estimated Pix rates derived from the field data indicated that a relationship exists (coefficient of determination= 0.73 for the Acala field and 0.21 for the Pima cotton field) with the red band for the Acala field and the green band for the Pima field. The scout's rate recommendations, that were the basis for converting the image data to actual Pix rates to be applied, incorporated typical scouting parameters such as plant height, internodal distance, and total nodes, as decision parameters. However, the field scout also incorporated his own innate experience to make the rate recommendations, so the imagery was correlated to the scout's experience and expertise. In the 2002 study (ITD Final Report, 2002), the field scout made the rate recommendations for the Site-specific PGR treatment, however, the Variable-rate PGR treatment prescription was based on the correlations with the plant parameters sampled. The strong correlation this season on the Acala cotton when compared to the much weaker correlations with the plant parameters sampled for the 2002 study (ITD Final Report, 2002) indicates that the innate experience of the field scout is a valuable addition to the process. The fact that the field scout data correlated very strongly with the image data in the Acala field, but not strongly in the Pima field suggests different conditions existed between the fields. A difference that was noted by the field scout was that there was much more variability in the study area of the Acala field than was present in the study area of the Pima field this season. Therefore, the field scout had to exaggerate the small variability that was present in the Pima cotton field in order to generate a variable rate prescription. The image data may have not been sensitive enough to the subtle variability in that field to correlate better with the field data collected. It may also be that Pima cotton reacts differently to Pix applications than does Acala cotton, and therefore exhibits less reflectance variability across the crop canopy.

The plant height data analysis indicated that crop canopy management was significantly improved by SSPGR applications in the Acala field. For that field, the variable-rate treatment showed a significantly smaller coefficient of variance in plant height following the PGR application when compared to the other treatments. While the variable-rate treatment did a superior job of evening out the plant heights, the 100% PGR (blanket) treatment did the worst job of creating a uniform plant canopy height (Table 3). However, for the Pima cotton field (31-3) the 100% PGR treatment did the best job of evening out the plant heights, and the variable-rate treatment had only slightly better results that the No PGR treatment in reducing plant height variability. It should be noted, however, that the differences in crop variability that existed this season between the Acala cotton field and the Pima field could have impacted these results. A more variable crop (which existed in the Acala field) might react more favorably to a variable-rate treatment than a more uniform crop (which existed in the Pima field). In fact, a more uniform crop would arguably benefit more from a uniform (100%) application, and would actually result in a more variable crop canopy when subjected to a variable-rate treatment for variability that is minimal.

The yield data analysis results show that there was significantly less yield in the No PGR treatment group for both the Acala and Pima cotton fields. However, the yields for the SSPGR and blanket (100%) PGR treatments were not significantly different. This result clearly shows that the yield was not adversely impacted by image-based PGR applications when compared to blanket (100%) applications in either field. The exceptionally cool and wet spring that resulted in a later than normal planting time coupled with increased insect pressures for the 2003 growing season contributed to a greater need for PGR applications than was evident in the 2002 season. More square loss to insect damage and extreme temperatures during the growing season causes the effect of a Pix application to be much more pronounced as it reduces the energy the cotton is putting toward vegetative growth and focuses it on boll production (Roberts, 2002). Since the need for PGR applications were minimal in 2002, the No PGR treatment yield was not adversely affected (ITD Final Report, 2002). However, in 2003 the No PGR treatment yield was most likely impacted from not receiving any of the needed chemical.

The results of the economic analysis showed that the average cost of 100% blanket PGR treatments and SSPGR treatments are relatively similar for both fields, but the SSPGR treatment resulted in the highest net revenue for both Acala and Pima cotton because of higher yields. For both Acala and Pima cotton, the SSPGR treatment used much less chemical relative to the 100% blanket application. With increasing acreage, this reduction in chemical use becomes significant, especially for Pima cotton due to the larger Pix concentration requirement. These results demonstrate the potential economic benefit to a producer when SSPGR is incorporated into a farm management system. Also of note is that an economic gain can be realized by a producer with SSPGR applications while substantially reducing the impact of excess chemical runoff to the surrounding environment (Figures 8 and 9).

It is important to remember that these results represent a single trial of one growing season for the Pima cotton field, and the second season for the Acala cotton study. To be able to make definite conclusions as to the effectiveness and economic impact of using image-based PGR recommendations for Pix applications in cotton, similar data from several growing seasons needs to be analyzed.

Future Work Recommendations

There are some recommendations for subsequent work based on the experiences of this year's study. These recommendations are as follows:

1) Given the very different results from the two fields in this study, future work should incorporate fields that exhibit similar crop variability. A suggestion would be to expand the study to include a number of highly variable fields (Pima and Acala) and more uniform fields in order to determine any differences that are field variability dependent or cotton variety dependent.
2) Future work should incorporate growing seasons that are more typical of a 'Pix year'. A Pix year being a season with much greater insect pressures and extreme weather conditions that would cause shed squares and thus enhance the effect of a PGR application. 2003 was a 'moderate' Pix year with areas and fields where Pix was needed, and other areas that were not in need.

Acknowledgements

The authors would like to thank the following people for their invaluable assistance with this project. They include:

- Irma Dombrowski and Lauren King, Hanford Flight Center, LLC – data acquisition and delivery
- Dane Ehler and Jessi Sjoken, Precision Aviation, Inc. – data acquisition, training, and delivery
- Nick Groenenberg, Nick Groenenberg Consulting – agronomic expertise, field data collection, experiment design review
- Roger Hewitt, Blair Air Services, Inc. – sprayer and controller system expertise and PGR application
- John Ojala and Vic Penner, USDA-Shafter Field Station – field data collection, experiment design review
- Dr. Michel Paggi and Fumiko Yamazaki, Fresno State University – economic analysis, experiment design review
- Bruce Roberts, University of California Cooperative Extension, Kings County – agronomic expertise, experiment design review, field data collection, and harvest activities
- Ted Sheely, AZCAL Management Company – use of field site, experiment design review, agronomic expertise
- Bill and Clarice Son, Bill Son Picker Services – harvest activities, yield monitor data delivery

References

Birrell, S.J., K.A. Sudduth, and S.C. Borgelt. 1996. Comparison of sensors and techniques for crop yield mapping. Computers and Electronics in Agriculture. 14(2/3): 215-233.

Cody, Ronald P. and Jeffrey K. Smith. 1997. Applied Statistics and the SAS Programming Language. Prentice Hall, Inc., New Jersey. pp. 171-174.

Cothren, J.T. and D.M. Oosterhuis. 1993. Physiological Impact of Plant Growth Regulators in Cotton. Proceedings of the Beltwide Cotton Conference, pp 128-132.

Deering, D. W., 1978. Rangeland reflectance characteristics measured by aircraft and spacecraft sensors. Ph.D. dissertation. Texas A and M University, College Station, Texas, pp 338.

Drummond, S.T. 2003. Personal Communication.

Holben, B. T. 1980. Spectral Assessment of Soybean Leaf Area and Leaf Biomass. Photogrammetric Engineering and Remote Sensing 46(5): 651-656.

Institute for Technology Development. 1999. Image-Based, Variable-Rate Plant Growth Regulator to Cotton at Perthshire Farms in Mississippi. Final Report to NASA ESAD.

Institute for Technology Development. 2000. Plant Growth Regulator and Seeding Rate Experiment. Final Report to NASA ESAD. pp. 37-48.

Institute for Technology Development. 2001. Spatially Variable Plant Growth Regulator. Final Report to NASA ESAD. Section 2.

Institute for Technology Development. 2002. Image-Based, Variable-Rate Plant Growth Regulator in Cotton at Sheely Farms in California. Final Report to NASA ESAD. pp. 38-55.

Kerby, T.A. 1985. Cotton Response to Mepiquat Chloride. Agronomy Journal, 77(5):15-518.

Kerby, Tom, Dick Plant, Wallace Hofmann, and Dwayne Horrocks. 1990. Predicting Pix Response Using the Expert System Calex/Cotton. Proceedings of the Beltwide Cotton Production Research Conferences, pp. 658-659.

Kerby, T. A., and K.D. Hake. 1996. Monitoring Cotton's Growth. In, Cotton Production Manual. Hake, Kerby and Hake (eds). UC Division of Agriculture and Natural Resources Publication No. 3352. pp. 335

Moran, M. S., T. R. Clarke, J. Qi, E. M. Barnes, and P. J. Pinter Jr. 1997. Practical Techniques for Conversion of Airborne Imagery to Reflectances. Proceedings of the 16th Biennial Workshop on Videography and Color Photography in Resource Assessment. pp. 82-95.

Munier, D.J., B.L.Weir, S.D.Wright and T.A. Kerby. 1993. Applying Pix at Variable Rates When Plant Height Varies in A Cotton Field. Proceedings of the Beltwide Cotton Conference, pp. 1206-1207.

Plant, R. E., and M. Keely. 1999. Relationships among plant growth indices in Acala cotton. Journal of Production Agriculture. 12(1): 61-68.

Roberts, Bruce. 2002. Personal Communication. Director, University of California Cooperative Extension, Kings County, Hanford, California.

Senay, G. B., A. D. Ward, J. G. Lyon, N. R. Fausey, and S. E. Nokes. 1998. Manipulation of high spatial resolution aircraft remote sensing data for use in site-specific farming. Transactions of the ASAE. 41(2): 489-495.

Shaw, David. 2001. Personal Communication. Mississippi State University, Department of Weed Science, Mississippi State, Mississippi.

Stoltz, Richard, 2003. Personal Communication. California Aerial Applicator's Association, Clovis, California. Thurman, M.E. and R.W. Heiniger. 1998. Using GPS to Scout Cotton for Variable Rate Pix (Mepiquat Chloride) Application. Proceedings of the Beltwide Cotton Conference pages 1499-1503.

Thurman, M.E. and R.W. Heiniger. 1999. Evaluation of Variable Rate Pix (mepiquat Chloride) Application By Soil Type, Proceedings of the Beltwide Cotton Conference, Vol. 2: pages 524-526.

Tucker, C. J., 1979. Red and photographic infrared linear combinations for monitoring vegetation. Remote Sensing of the Environment 8(2): 127-150.

Weigand, C. L., A. J. Richardson, D. E. Escobar, and A. H. Gerbermann. 1991. Vegetation Indices in Crop Assessments. Remote Sensing of the Environment. 35: 105-119.

Weir, B.L., and Tom A. Kerby. 1988. The Effect of Pix Applied at Various Rates and Timings to 30 inch cotton in the San Joaquin Valley. Proceedings of the Beltwide Cotton Production Research Conferences. page 120.

Table 1. Frequency table showing the ability to predict the scout's recommended rate with imagery for the Acala field (5-3).

Predicted Rate Frequency Percent Column Percent	**Field Scout Recommended Rate 0**	**5**	**10**	**Total**
0	5	0	0	5
	27.78	0	0	
	83.33	0	0	
5	1	10	1	12
	5.56	55.56	5.56	
	16.67	100	50	
10	0	0	1	1
	0	0	5.56	
	0	0	50	
Total	6	10	2	18

Table 2. Frequency table showing the ability to predict the scout's recommended rate with imagery for the Pima field (31-3).

Predicted Rate Frequency Percent Column Percent	**Field Scout Recommended Rate 0**	**5**	**7.5**	**10**	**Total**
0	0	0	0	0	0
	0	0	0	0	
5	3	7	2	1	13
	100	87.5	25	20	
7.5	0	1	5	3	9
	0	12.5	62.5	60	
10	0	0	1	1	2
	0	0	12.5	20	
Total	3	8	8	5	24

Table 3. Weigh wagon yield summary statistics for treatments (in pounds of seed cotton).

Treatment	N	Mean
Variable Rate	24	4600.9
Standard (100%)	19	4364.5
No PGR	22	3735.2

Table 4. Weigh wagon yield summary statistics for treatments (in pounds of seed cotton).

Treatment	N	Mean
Variable Rate	24	4908.4
Standard (100%)	23	4899.4
No PGR	22	4633.5

Table 5. The Acala field average yield and revenue per acre for each treatment.

Treatment	Average Yield (lbs of lint cotton/acre)	Average Revenue ($/acre)	Average Cost ($/acre)	Average Net Revenue ($/acre)
1: 0% PGR application	1,386.57	1,220.18	0.000	1,220.18
2: 100% PGR application	1,608.29	1,415.30	8.52	1,406.78
3: Site-Specific PGR (SSPGR)	1,702.32	1,498.04	8.91	1,489.14

Table 6. The Pima field average yield and revenue per acre for each treatment.

Treatment	Average Yield (lbs of lint cotton/acre)	Average Revenue ($/acre)	Average Cost ($/acre)	Average Net Revenue ($/acre)
1: 0% PGR application	1,622.81	2,028.51	0.000	2,028.51
2: 100% PGR application	1,713.86	2,142.32	11.19	2,131.13
3: Site-Specific PGR (SSPGR)	1,717.93	2,147.41	11.15	2,136.26

Table 7. Percent cost difference among the treatments for the Acala field.

Treatment	% cost over traditional (100%)
No PGR application	0.00
100% PGR application	100.00
Site-Specific PGR	104.53

Table 8. Amounts of PGR chemical used for each treatment for the Acala study.

Treatment	PGR application	Total Acres	Pix chemical use (oz/acre)	Total Pix chemical use(oz)
1: 0% PGR application	0%	16.64	0	0.00
2: 100% PGR application	100%	16.64	8	133.12
3: SSPGR	0%	6.08	0	0.00
	50%	9.6	4	38.40
	100%	0.96	8	7.68
Total SSPGR		16.64		46.08

Table 9. Percent cost difference among the treatments for the Pima field.

Treatment	% cost over traditional (100%)
No PGR application	0.00
100% PGR application	100.00
Site-Specific PGR	99.67

Table 10. Amounts of PGR chemical used for each treatment for the Pima study.

Treatment	PGR application	Total Acres	Pix chemical use (oz/acre)	Total Pix chemical use(oz)
1: 0% PGR application	0%	16.64	0	0.00
2: 100% PGR application	100%	16.64	16	266.24
3: SSPGR	0%	4.80	0	0.00
	50%	7.68	8	61.44
	100%	4.16	16	66.56
Total SSPGR		16.64		128.00

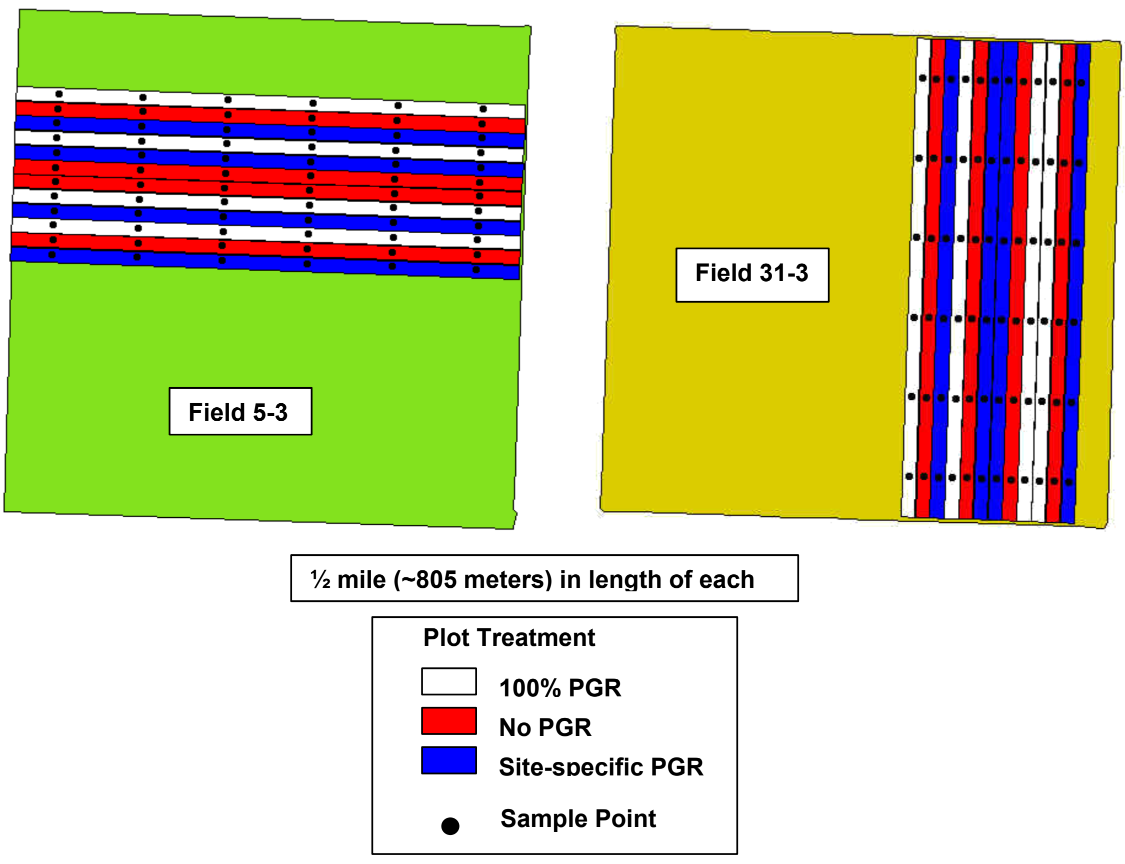

Figure 1. Treatment zones for the study fields (field 5-4 and 31-3) with sampling points overlaid.

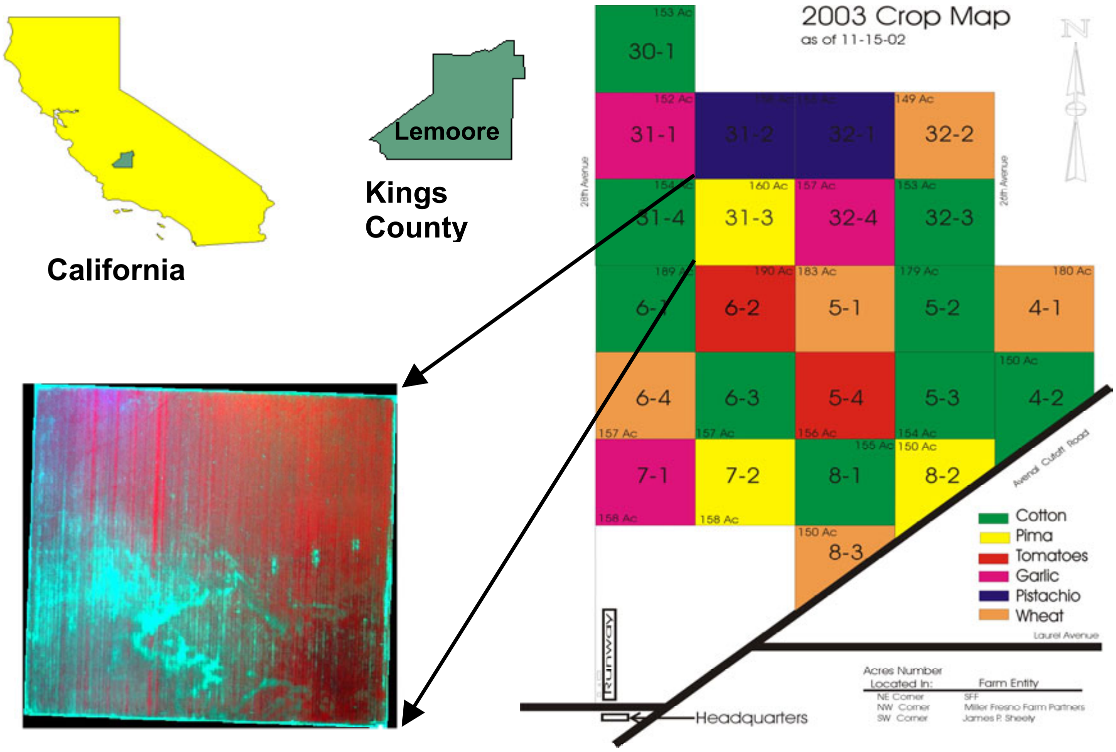

Figure 2. Multispectral image of field study area. Image acquired over Fild 31-3 on July 11, 2003.

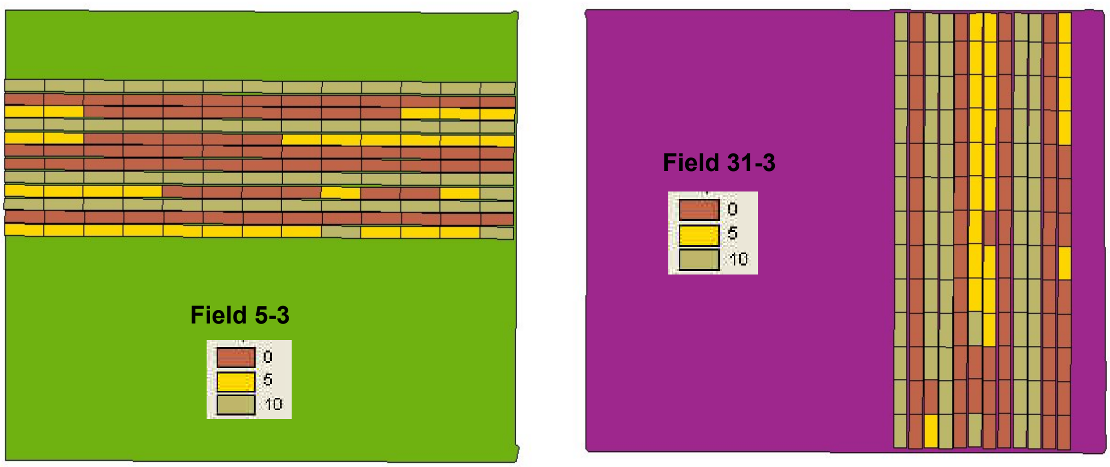

Figure 3. The Acala and Pima cotton study fields (Fields 5-3 and 31-3 respectively) Pix prescriptions with rates in gallons/acre of mixed product.

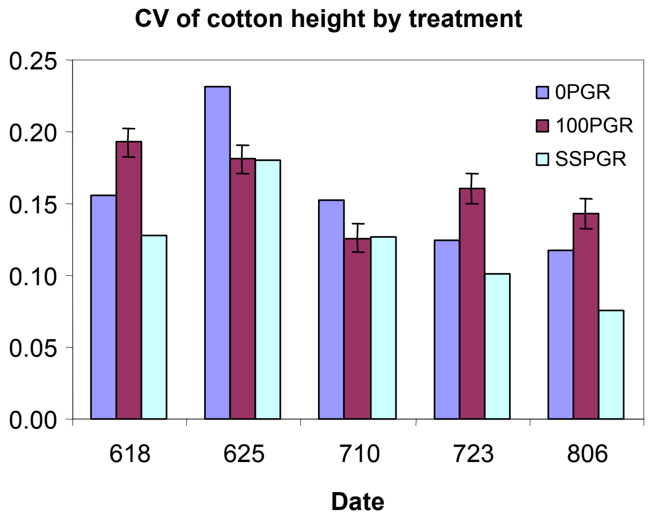

Figure 4. Plant height variance for the Acala field (5-3)

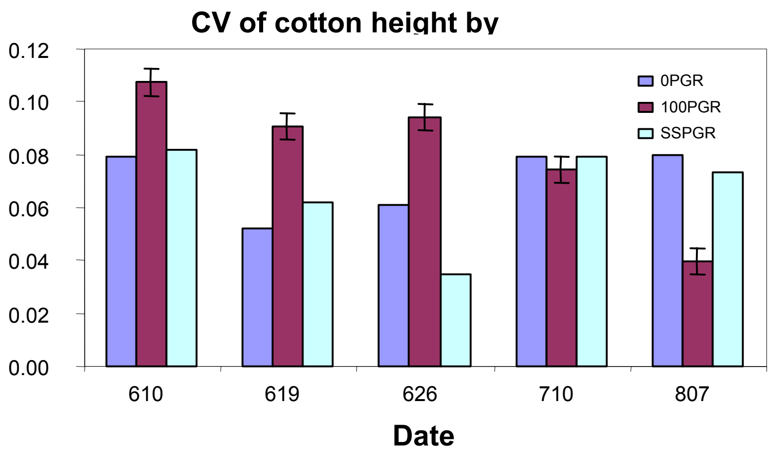

Figure 5. Plant height variance for the Pima field (31-3).

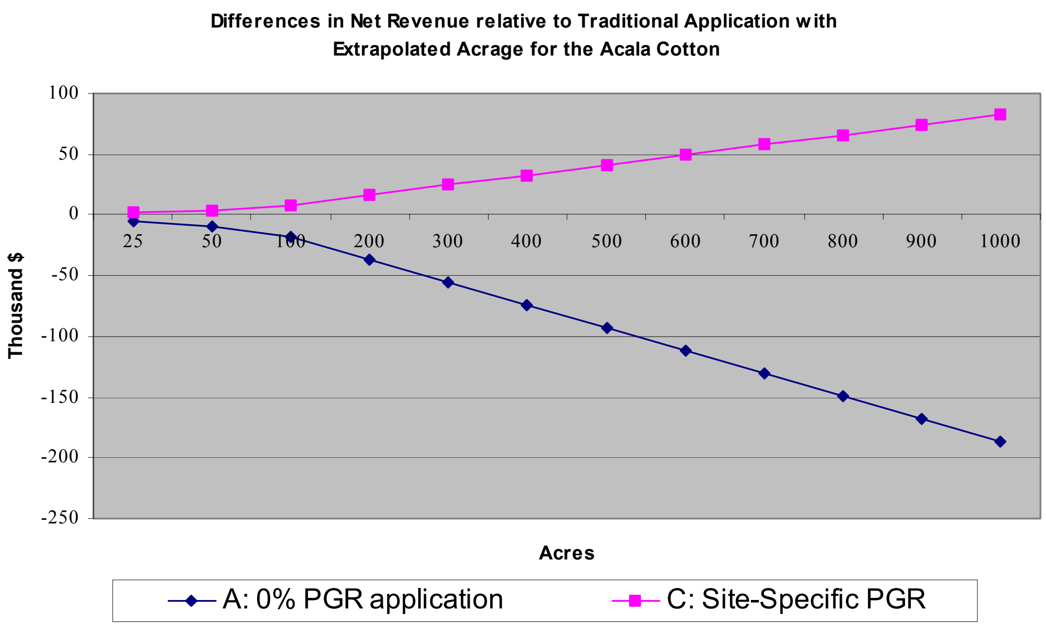

Figure 6. Plot of the extrapolated average net revenue for the SSPGR and No PGR treatments with increasing acreage with respect to the 100% application of PGR for the Acala field.

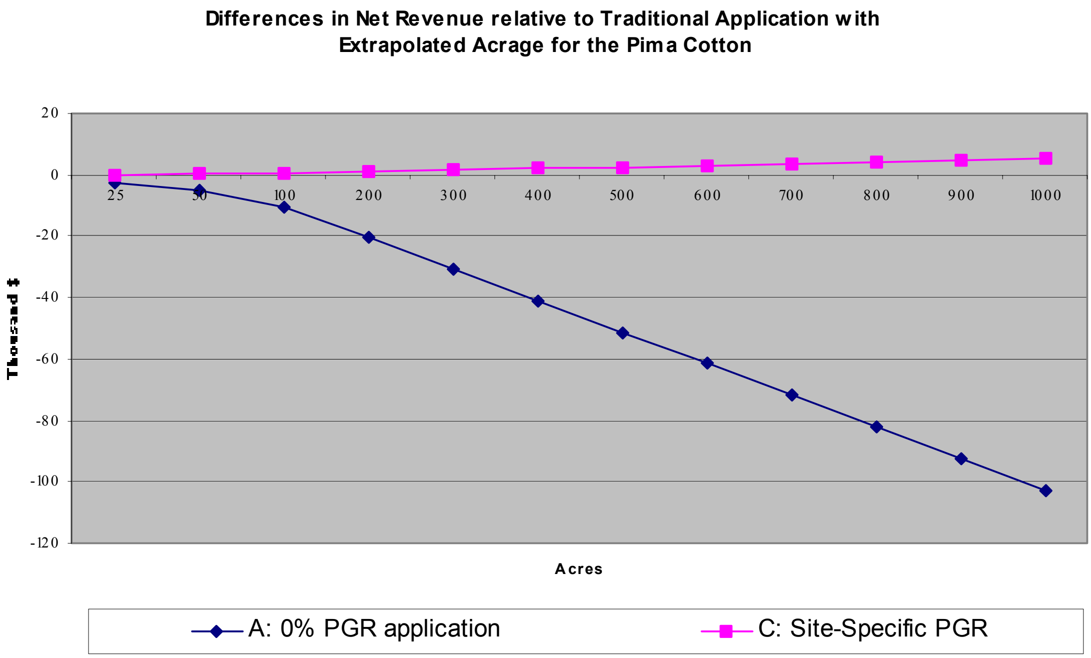

Figure 7. Plot of the extrapolated average net revenue for the SSPGR and No PGR treatments with increasing acreage with respect to the 100% application of PGR for the Pima field.

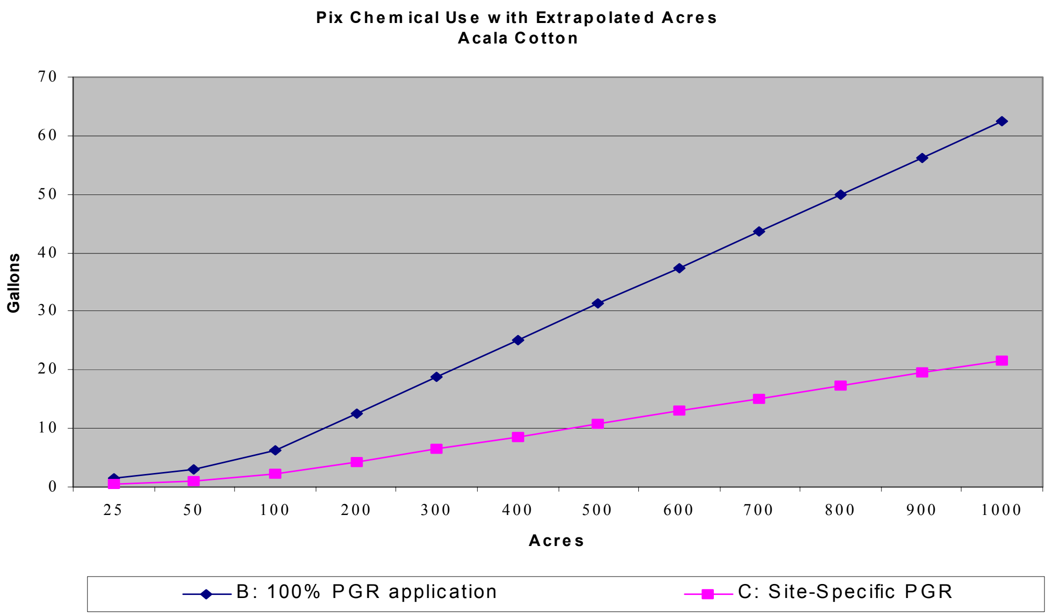

Figure 8. Plot of the extrapolated Pix chemical use for the SSPGR and 100% PGR treatments with increasing acreage for the Acala field.

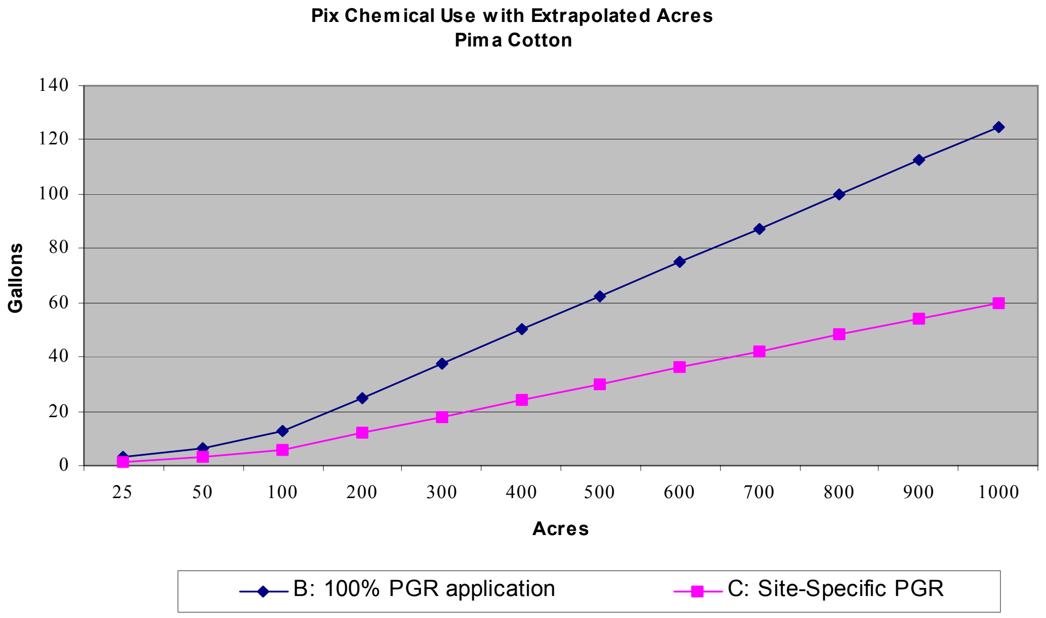

Figure 9. Plot of the extrapolated Pix chemical use for the SSPGR and 100% PGR treatments with increasing acreage for the Pima field.