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IMAGE-BASED, VARIABLE RATE PLANT GROWTH REGULATOR APPLICATION IN COTTON AT SHEELY FARMS IN CALIFORNIA

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Abstract

Given the results of the 2000 and 2001 image-based PGR application experiments in Mississippi, ITD wished to attempt to replicate these results in a PGR experiment conducted in a different cotton production region. The San Joaquin Valley of California was chosen as the site to conduct a PGR experiment for 2002. 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.

Introduction

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. The 2000 experiment segmented the research field 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 were crossed with the three different NDVI groupings to research if plants with different NDVI measurements respond differently to PGR. The 2001 experiment replicated the design of 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.

Background

PGR—in this case Pix® (Mepiquat Chloride), costing $4.50/acre—is applied to cotton in order to inhibit cell elongation, restricting vegetative growth and promote earlier and heavier boll production on lower node branches, and thereby increasing 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), who 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-Spectral Visions 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 (Spectral Visions, 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.

The 2000 experiment conducted by ITD-Spectral Visions partitioned a cotton field at Perthshire Farms into treatment strips that were either 100% sprayed with PGR or treatment strips that were not treated with PGR. NDVI measurements were computed for the entire field during the season. Additionally, the field was divided into zones based on equal area thresholding of NDVI values derived from the July 5, 2000 data set, acquired prior to the first PGR application. This NDVI classification was segmented into equal area NDVI regions that consisted of the highest 20%, the middle 60% and the lowest 20%. The data analysis showed that the yield between the PGR 100% spray strips and the PGR untreated strips were not significantly different. However, when broken out by NDVI zones there were significant differences in the yield between some of the treatments (Spectral Visions, 2000). Therefore, the amount and cost of PGR used in a production field can be reduced by applying PGR to just the areas corresponding to a subset of NDVI values. This result reinforces the 1999 observations.

In 2001, the experiment was replicated and in addition, tests were performed to see whether yield was maintained, lost, or gained by using the spatially variable application technique to spray the PGR on treatment strips in the field. The yield was maintained within the SVPGR treatments when compared with the Blanket-Spray-On treatments. The 2001 growing season had more rainfall than in 2000 and the yields in general were greater. The 2001 analysis showed a significant difference in the yields in the middle 60% NDVI region. In addition, 2001 results showed that although the High-20%-NDVI/Blanket-Spray-On regions did yield higher than the High-20%-NDVI/Spray-Off region, it was not significant. This would seem to indicate that it is not always necessary to apply PGR to the highest NDVI areas, perhaps it is dependent on rainfall amount since the 2000 and 2001 studies differed greatly in that respect.

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., 1997a; 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-Spectral Visions' past investigations (Spectral Visions 1999, 2000, 2001), 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.

This year's PGR study attempted to verify some of the findings of similar work done in Mississippi (Spectral Visions 1999, 2000, and 2001) in a different region of the cotton belt. Specifically, the research team attempted to verify that image-based PGR applications do result in a net profit increase for the producer, as was the case in the studies at Perthshire Farms. The SSPGR and VRPGR treatment yields were compared with the 100% and no-spray treatment yields to determine the benefit of using image-based techniques for PGR application in the San Joaquin Valley. In addition, plant height measurements were recorded at each sampling site along each strip, and were analyzed for crop canopy management effects among the treatments.

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 this 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 and variable rate applications based on imagery. The success of this study is measured by an increase in the producer's net profit resulting from the SSPGR and/or VRPGR treatments. 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 SSPGR and/or VRPGR applications.

Study Area

The research study area was a portion of a contiguous field (field 5-4) totaling 64.75 hectares (160 acres) on the main ranch of Sheely Farms near Lemoore, California (Figure 1). 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.

Hypotheses

Analysis was 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 $_{\text{SSPGR, VRPGR areas}}$ > Net Profit $_{\text{100\% spray areas}}$ then the analysis shows that SSPGR and/or VRPGR 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 site-specific PGR, variable rate PGR, and 100% Spray PGR areas are at least equal, and plant height variance for spatially variable PGR, and/or the variable rate PGR treatments are significantly less than Spray-Off areas.

   Plant height variance $_{\text{SSPGR areas}}$ = Plant height variance $_{\text{VRPGR areas}}$ = Plant height variance $_{\text{100\% spray areas}}$

   Plant height variance $_{\text{SSPGR, VRPGR areas}}$ < Plant height variance $_{\text{Spray-Off areas}}$

   H_A: At least one is statistically different.

If the researchers fail to reject Ho, then analysis shows that SVPGR can reduce the cost of PGR applications while maintaining crop canopy uniformity.

If Ho is rejected, and Plant height variance $_{\text{SSPGR, VRPGR areas}}$ < Plant height variance $_{\text{100\% spray areas}}$ then the analysis shows that SSPGR and/or VRPGR may help increase crop canopy maintenance and also reduce overall PGR cost.

Experiment Design

This experiment consisted of a randomized complete block design (Figure 3). The design allowed for testing of the underlying concept that image-based, site-specific 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 2002 treatments were:

Treatment A: No PGR
Treatment B: PGR 100% application (traditional method)
Treatment C: Site-Specific (Spray On, Off) PGR application
Treatment D: Variable Rate PGR application

Each block contained four field strips; one strip for each treatment type. Treatment A (no PGR) area was unsprayed. Treatment B was 100% (blanket) sprayed. Treatment C used site-specific (on and off) spraying at a constant rate designated for that field by the field scout. The spray threshold was determined by the field scout. Treatment D used variable rate PGR within the treatment as designated by the field scout table (figure 2) as an appropriate rate to use based on field sampling. The PGR application in Treatments C and D was driven by vegetation indices created from remotely sensed data, and the correlation that this image data had with field scout data. Determining the statistical relationships between reflectance and crop biomass as determined by typical field scouting data collected for PGR applications, such as internodal length, was a critical component to this experimental design. Analysis from results of the field data collected was performed to ensure the relationship existed, and involved several techniques from the literature review for this study found to show a significant relationship between plant reflectance and crop biomass (various band ratios and vegetation indices). The image processing technique that proved to have the strongest relationship with the field data was used to develop the image-based VRPGR prescription.

The scout determined when the experiment field was ready for the PGR application to the treatment strips based on normal methods. The field scout determined an NDVI threshold to separate the spray/no-spray areas of the strips for Treatment C. A prescription was generated directing the spray rig to apply PGR only on the spray areas at a constant rate. Digital NDVI maps loaded onto handheld computers provided to the scout allowed the field scout to fine tune the actual threshold value used to delineate the spray/no-spray areas in Treatment C.

Treatment D was determined based on the statistical relationship between reflectance and plant vigor as measured by plant height, internode distance (between the 4th and 5th nodes for typical PGR application in the San Joaquin Valley), and total node count. These plant measurements were taken at eight GPS designated sampling points within each treatment strip (each treatment strip is approximately .8 kilometers or .5 miles in length). 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 variable rate PGR (Treatment D) application treatment strips. The variable rate PGR prescription was generated according to the PGR rate recommendation diagram which the crop scouts have historically followed to determine PGR rates to apply to a given field in the San Joaquin Valley (figure 1).

Using the field data collected, the researchers substituted values derived from the PGR recommendation diagram (Figure 2) to get estimated Pix application rates for each sampling point in the study, and created a regression equation based on the correlation of the estimated Pix application rates with the vegetation indices tested. The regression equation from the vegetation index that had the highest correlation was then applied to the image data, and thus inferred crop canopy PGR rate requirements for the VRPGR 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 Raven controller of the PGR applicator equipment. The prescriptions for the image-based treatments contained spatially accurate PGR rate recommendations for the research area in pixels that were approximately 14x10 meters (45x32 feet) (the width of the applicator boom and the length of the ability of the equipment to modify PGR application along track). The rates of Pix used for the PGR application ranged between 0 and .12 litres/hectare (0 and 10 ounces/acre) as recommended by the field scout and Ted Sheely.

The study area (Figure 1) was approximately 65 hectares (160-acre) in size at Sheely Farms (field 5-4) that the producer made available to the researchers. This field was tractor-sprayed (as opposed to aircraft). The study field was 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 448 rows, each 96.5 centimeters (38" wide), spanning the length of the field to form a whole plot. There were 28 rows in each treatment strip, and 4 replications (blocks) of the four treatments listed above (Figure 3).

Four-row pickers were utilized at harvest, and 16 rows in the center (four passes of a picker in each strip) of each treatment strip were harvested, weighed, and the weight recorded. The outer 4 rows on each side of each strip served as a buffer zone between treatment strips and were not weighed, however yield monitor data was collected for all of the picker passes within the study area.

Imagery and Field Data Specifications

Image Data

This experiment relied upon airborne three-band (850nm-40nm bandwidth, 660nm-10nm bandwidth, and 550nm-10nm bandwidth) multispectral imagery flown at 1.2-meter resolution by Opto-Knowledge Systems (OKSI), 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 flightlines over Sheely farms, as well as provided ample spatial resolution for assessment of the imagery during the experiment. The sensor used is the SAMRSS sensor developed by the USDA. Hyperspectral data acquired with OKSI's AVNIR sensor (60 bands ranging from 430nm to 1012nm at 10nm increments, each having a 10nm bandwidth) was not analyzed for the experiment given that the dataset could not accurately be georeferenced due to a high degree of distortion from the pitch, roll, and yaw of the aircraft. Imagery was collected just prior to PGR application on July 8th. Image data was also acquired in June to facilitate a practice run-through of the methodologies that were performed for this experiment.

Field Data

Using measurements collected at different locations in the study field, the scouts involved with this study made decisions as to what index threshold is best suited to delineate PGR-On and PGR-Off areas in the Site-specific PGR (SSPGR) treatment strips. Also, using the PGR rate recommendation diagram (Figure 2), 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 (VRPGR) strips. The PGR rate recommendation diagram was developed by Hutmacher et al. (2001) from research done by Juan Landivar at Texas A and M University (Landivar, 1998). Subsequently, this rate recommendation diagram has been widely distributed to field scouts in California at extension meetings, and has been adopted by the field scouts at the cooperating producer's farm. 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 2002 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. The 2002 California PGR experiment is much different in methodology than the previous PGR experiments conducted by ITD-Spectral Visions mentioned earlier, however, the intent of the research remains the same; to reduce the producer's input costs while maintaining or exceeding the yields of the traditional application method. A benefit of conducting this study in California as opposed to Mississippi is that in a dry climate where water availability to the crop is completely dependent on irrigation, such as the San Joaquin Valley, the unpredictable and confounding effects of rainfall on the experiment were removed.

Plant characteristics were measured by field scouts to determine optimal PGR application timing. Once the date of PGR application was set for field 5-4, data collection for analyses with the image data to create a prescription map was conducted on July 8th and 9th. These measurements included plant height, total main stem nodes, and internodal length. 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). For the SSPGR treatment strips, the field scouts were provided with NDVI maps in order to help determine threshold recommendations for prescription generation. The field scout determined the particular rate of PGR to be applied to the SSPGR and 100% PGR treatment strips based on the normal methodology while scouting with the image data loaded onto a GPS equipped iPAQ. Eight 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 prior to the PGR application. Plant data collected at these points was used to derive the VRPGR prescription, as well as to verify the results of the PGR application for the crop canopy management hypothesis.

Data collection conducted for crop canopy management analysis was collected on August 7th (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, weigh wagon yield data was collected from 4 picker passes in each treatment strip. The outer 4 rows on each side of a treatment strip were considered the buffer zone between treatments and were not weighed, as well as the middle 4 rows of each strip given that the sprayer made two passes in each strip (the boom width was half the width of a treatment strip), the effect of any spray overlap was reduced. Yield monitor data was also collected for each picker pass in the study area at two-secondintervals. The yield monitor data was used to assess the variability within each treatment. The yield monitors were calibrated using weigh wagon data just prior to harvest, and the yield monitor was continually checked for calibration throughout the harvest.

Methodology

Image Pre-Processing Procedures

Preprocessing of the multispectral SAMRSS image data that was acquired on July 8th, just prior to PGR application, 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 collected during several image acquisitions to determine any significant reflectance change over the course of the growing season 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., 1997a).

The image data was 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. This correlation was performed in order to derive the prescription for the variable rate treatment strips. The PGR rate recommendation diagram (Figure 2) was used to assign estimated Pix rates to the sampling areas based on the field sampling data. The field scout verified the accuracy of the estimated Pix rates by visiting 16 of the sampling sites to determine proper Pix rate assignments. Using discriminant analyses, a regression equation was derived for the image processing-technique that had the highest correlation to the estimated Pix rate values at the sampling sites. The average value of the pixels in a four-square meter area around each sampling point was utilized for the correlation with the field data. 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 an 'estimated Pix rate map' produced. The image was then converted into an ESRI Grid format and recoded to contain five discreet Pix rates (0, 5, 7.5, 10, and 12.5 gallons/acre). 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.

An unsupervised classification was performed on an NDVI image of the study site to create a five-class image for scouting. The field scout used the image loaded into an iPAQ equipped with a GPS to scout the various class zones in the image and determine which classes needed to be sprayed (at the field prescribed 10 gallons/acre as determined by the field scout), and which classes did not need to be sprayed. Once this spray threshold was determined, the image was converted to an ESRI Grid and recoded for Pix application according to the scout's specifications.

The prescription generation process involved generating a 13.7 x 10 meter (45x32 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 (45 ft), and the distance by which the valves in the spray nozzles were able to effectively produce different rates (32 ft). The distance of 10 meters was recommended as the minimum distance of effective rate change by Bruce German of Blair Ground Service, Inc. (German, 2002) based on the sprayer type, speed of the sprayer at application, and the rates we were attempting to apply. 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 same process was utilized to create the prescription for the site-specific treatment strips, except using an NDVI scout map with the field scout's rate recommendation instead of the estimated Pix rate map. The separate prescriptions for the variable rate, site-specific, 100%, and 0 PGR treatments were then merged together to create a single prescription for the entire field (Figure 4). The prescription shapefile was created with a file format that was compatible with the Raven Viper controller in the sprayer.

Field Data Collection

In-season field data collection for the PGR study in field 5-4 occurred during the time of the July 8th image acquisition. 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 4th and 5th 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 identification. 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. Subsequent plant height sampling occurred on August 7th that followed the same procedures as the July 8th sampling. This sampling was performed to assess crop canopy variances among the treatments following the Pix application.

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. A five-pound sample of picked cotton from each treatment strip was bagged and tagged for gin turnout analyses (a measure of the amount of material other than lint cotton harvested by the pickers). 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 three load-cells on the weigh wagon were each calibrated with a standard 453.6 kilogram (1000 pound) standard weight, and then calibrated together with 1360.8 kilograms (3000 pounds), 453.6 kilograms on each load-cell simultaneously. The yield monitors were then calibrated by picking several passes of cotton and dumping into the calibrated weigh wagon until differences were consistently within 2%. Four rows of cotton at both edges of a treatment strip were not included in the data analyses, thus minimizing any treatment edge effects.

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 et al., 1997) for variance differences among the treatments. An analysis of variance (ANOVA) was performed on the weigh wagon yield data results. The weigh wagon yield data was compared between treatments with 16 observations per treatment (4 replications with 4 yield measurements taken per strip). The yield monitor data was analyzed using yield data from a 30-meter radius around each sampling point along each treatment strip with the Univariate procedure in SAS. 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. The yield data analyzed was picked from the 16 inner rows of each treatment strip, excluding the center 4 rows. These rows were picked for the yield analyses to reduce any edge effect due to overlapping spray from the applicator in adjacent treatments or the center of a treatment (since the applicator had a 13.7 meter (45 ft) boom width and thus two sprayer passes per 27.4 meter (90 ft) treatment strip).

Results

Regression analysis results for the field sampling data and a number of image processing techniques indicated in **Image Processing Procedures** above showed some correlation. The results of the regression analysis performed on the estimated Pix rates derived from the field sampling data and a linear combination of an NDVI and a red/NIR band ratio proved to have the highest correlation (a coefficient of determination of 0.44). The resulting regression equation applied to the image data for the variable rate treatment strips was ((NDVI Grid * 176.748) + (Red/NIR Grid * 227.055)) – 162.739). Discriminant analysis was used to determine the image processing technique that correlated best to the estimated Pix rates.

The Chi-Square test performed to analyze the August 7th plant height sampling data showed no significant difference between treatments (alpha = 0.10), although the variable rate treatment provides the smallest variance of plant height. It was noted that at an alpha = 0.16 the variable rate treatment yields a significantly lower variance than the other treatments. The summary statistics are reported below in table 1.

Results of the analysis of variance between the weigh wagon yield of the treatment strips showed that no significant difference existed between the treatments (Pr > F = 0.79; Table 2). The analysis of the yield monitor data shows that there was no statistical difference in yield between the treatments. Further analysis shows that there is little difference in the yield variance within the treatments as well (Figure 5). The treatment with the smallest variation in yield was, in fact, the treatment receiving no PGR at all.

An analysis was performed to determine if there were differences in yield between the treatments according to specific areas of the field using the yield monitor data. The field was divided into eight sections from the southern to the northern end. A yield comparison was made between the treatments of each of the four blocks and eight north/south sections from west to east. These results give an indication as to the yield difference within certain sections of the study area between each treatment and the untreated control (no PGR). In figures 6-8 the difference from the untreated control for each treatment in seed cotton yield for the various sections of the field are shown. Each section of the field is represented as a 'tier' in the figures below, 1 being the southernmost part of the field and 8 being the northern edge. The figures 6-8 show that the variable rate yield at the north end of the field was particularly less than the untreated control, and that the site-specific treatment yielded less near the middle and north end of the study area. The 100% PGR treatment appeared to have no noticeable trend when compared to the untreated control.

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 image-based PGR applications. This cost includes equipment, human resource, imagery, and prescription generation costs.

Some of the costs factored into the economic analysis include $0.80/acre for the imagery, $2.50/acre for a consultant to create the prescription, $7.00/acre for the application costs, and $53.10/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 $0.76/pound of lint cotton harvested. This is the price of lint cotton that the grower expects to receive for the 2002 crop.

The uniformity in yield between the treatments for this study accounted for the similarities in revenue from lint cotton per acre based on a 38% turnout that is typical for Riatta variety upland cotton in the San Joaquin Valley. The treatment strips where no PGR was applied yielded an average revenue of $1,421 per acre, and the VRPGR strips yielded an average of $1,393 per acre. This difference was $28 per acre between the treatment with the highest and lowest average gross revenues

(Table 3). That difference grows to about $41 per acre when the cost of the PGR chemical is factored into the analysis to compute average net revenue.

PGR chemical and application costs were different between the treatments. These cost differences are shown in Table 4. The SSPGR treatment shows a reduction in costs from the 100% PGR application due to the reduction in chemical applied. The VRPGR, however, shows a cost increase from the 100% application due to an actual increase in PGR chemical applied over the SSPGR treatment. Both image-based treatments resulted in a reduction in chemical applied when compared to the 100% treatment (Table 5).

In summary, the comparison of image-based PGR applications and a traditional (100%) application of Pix indicated that SSPGR applications were, on average, 19% less costly than the 100% application with very similar yield. The VRPGR treatment, however, resulted in an overall cost increase of approximately 27% over the 100% application with similar yield. The analysis shows that there was a reduction in chemical applied of about 51% in using SSPGR applications, and a 12% reduction with VRPGR applications 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= 0.44) for the linear combination of NDVI and the red/NIR band ratio. Correlations directly to the image data were tried using the field data collected that is incorporated into the Pix rate recommendation diagram (Figure 2), being the total main stem nodes and the distance between the 4th and 5th internode. The correlations between the image data and each of these field data parameters were not strong. However, the correlation between the image data and the plant height data collected during the sampling proved to be strong (coefficient of determination= 0.77). The rate recommendation diagram, which was the basis for converting the image data to actual Pix rates to be applied, did not incorporate plant height as a decision parameter. The fact that the plant height data correlated very strongly with the image data suggests promise for incorporating this data into future image-based PGR recommendations.

The yield data analysis results show that there was no significant difference in the yields of the treatment groups. This result clearly shows that the yield was not adversely impacted by image-based PGR applications. The plant height data analysis indicated that crop canopy management was also not adversely affected by image-based PGR applications. It should be noted, however, that during this season there was little to no insect pressures or adverse weather conditions that would have made Pix applications more necessary to boll production. If there would have been more square loss to insect damage or extreme temperatures during the growing season the effect of a Pix application would be much more pronounced as it reduces the energy the cotton is putting toward vegetative growth and focuses it on boll production (Roberts, 2002).

The economic analysis performed by Dr. Paggi showed a cost savings of approximately 19% in using site-specific PGR applications as opposed to traditional (100%) applications of Pix during a similar growing season. The comparison of variable rate and 100% applications of Pix indicated that VRPGR applications were, on average, 27% more costly. 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 (Figure 11).

It is important to remember that these results represent a single trial of one growing season. 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. One definite conclusion can be made from this study, however, and that is that there is promise of a more effective and efficient application of Pix in cotton through the use of remotely sensed imagery.

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 strong correlation found with the plant height sampling data and image reflectance data, any future work should focus on testing the ability of processed imagery to relate directly to the plant height data, as well as the other field data, in cotton. This method is suggested as opposed to relating imagery to the field data indirectly through Pix rate estimation derived from the Pix rate recommendation chart. The estimated Pix rate method may still be tested as an alternative method, with perhaps plant height data being incorporated somehow.
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.

3) The economic analysis showed that if the yield of the VRPGR treatment were slightly increased (+ 0.2%) the VRPGR would have been more profitable, when extrapolated for increasing acreage, than the traditional (100%) method. Future work should investigate adjusting the rates applied for the VRPGR treatment to optimize boll development and thus perhaps realize a consistent slight increase in yield needed to make this treatment preferable to producers.
4) An aerial applicator with capabilities in variable rate PGR applications may improve the power of future research. Given the tight irrigation scheduling in the San Joaquin Valley, timing of a ground-based PGR application for a field-scale experiment is limited and a real inconvenience to the producer and his irrigation scout. An aerial PGR application can be performed at any time regardless of the irrigation schedule. The aerial applicator, however, should have the abilities and accuracy of variable rate application as was experienced with the ground-based sprayer during this study.

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Table 1. Summary statistics for the Chi-Square analysis of plant height variance.

Trt	Mean	Variance	df	cv
VR	31.54	28.53	32	0.90
SS	31.34	34.17	32	1.09
Off	33.49	38.47	32	1.15
100%	32.12	40.50	32	1.26
Average	32.12	35.29	128	1.10

Table 2. Weigh wagon yield summary statistics for treatments (in pounds of seed cotton).

Treatment	N	Mean	Standard Deviation
Variable Rate	16	3617.9	49771
Standard (100%)	16	3646.9	32370
Site-Specific	16	3648.8	55797
No PGR	16	3691.1	29722

Table 3. 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)
A: 0% PGR application	1,870.170	1,421.329	0.000	1,421.329
B: 100% PGR application	1,847.750	1,404.290	10.280	1,394.010
C: Site-Specific PGR (SSPGR)	1,848.700	1,405.012	8.454	1,396.558
D: Variable rate PGR (VRPGR)	1,833.088	1,393.147	13.093	1,380.054

Table 4. Percent cost difference among the treatments.

Treatment	% cost over traditional (100%)
No PGR application	0.00
100% PGR application	100.00
Site-Specific PGR	80.91
Variable rate PGR	126.66

Table 5. Amounts of PGR chemical used for each treatment.

Treatment	PGR application	Total Acres	Pix chemical use (oz/acre)	Total Pix chemical use(oz)
A: 0% PGR application	0%	24.8	0	0.00
B: 100% PGR application	100%	24.8	8	198.40
C: Site-Specific PGR	0%	12.14	0	0.00
(SSPGR)	100%	12.24	8	97.92
Total SSPGR		24.38		97.92
D: Variable rate PGR	0%	0.38	0	0.00
(VRPGR)	50%	6.75	4	27.00
	75%	3.90	6	23.40
	100%	6.07	8	48.56
	125%	7.56	10	75.60
Total VRPGR		24.66		174.56

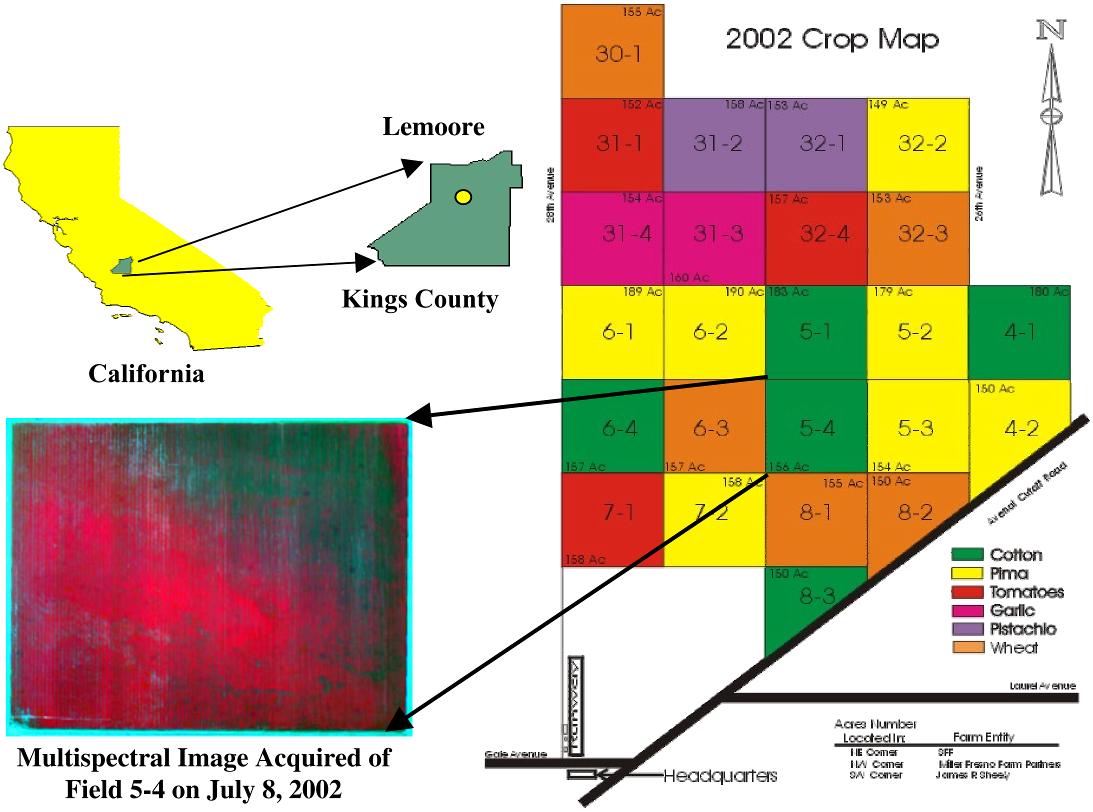

Figure 1. Field 5-4 Study Area Map.

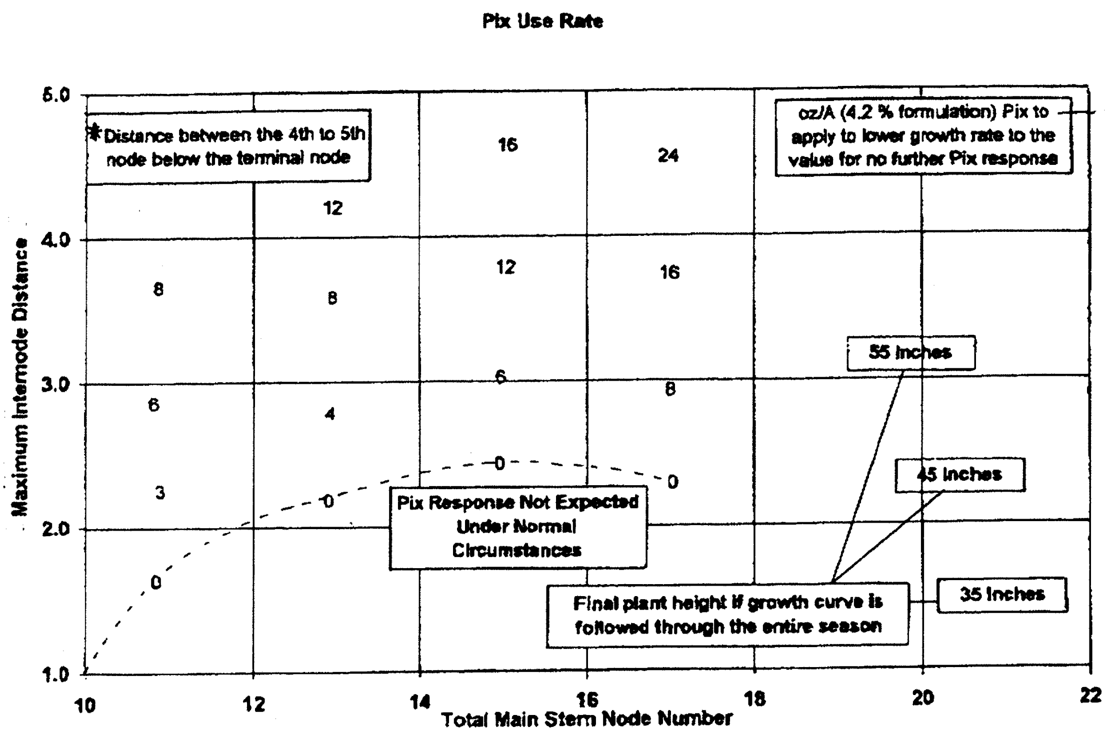

Figure 2. PGR rate recommendation diagram.

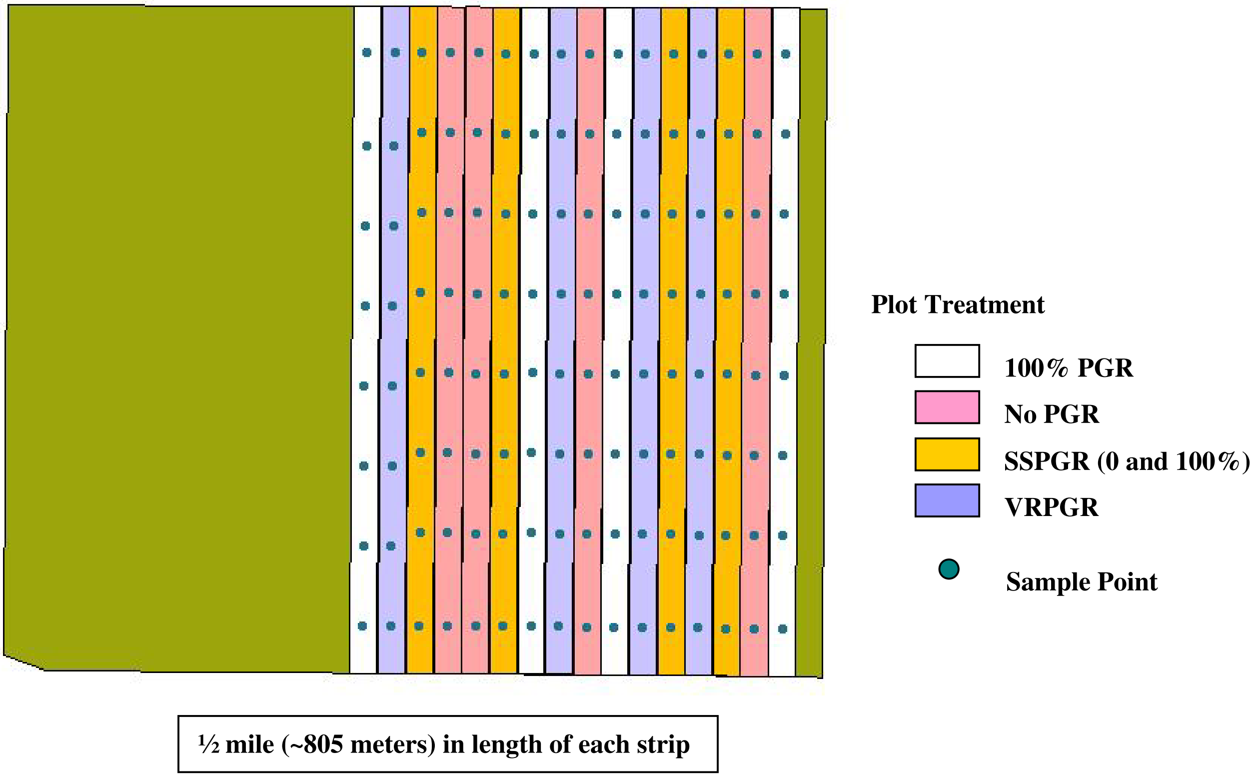

Figure 3. Treatment Zones for the Study Field (field 5-4).

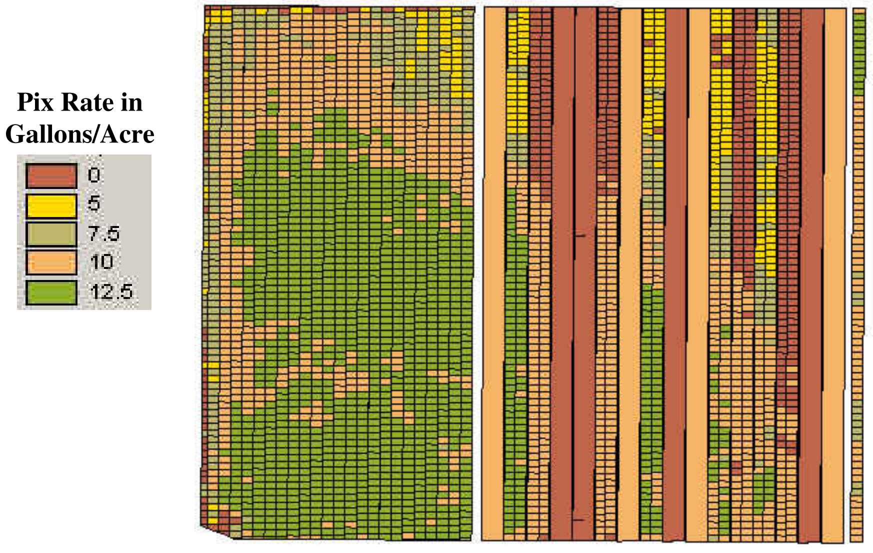

Figure 4. Field 5-4 Pix Prescription (Applied July 15).

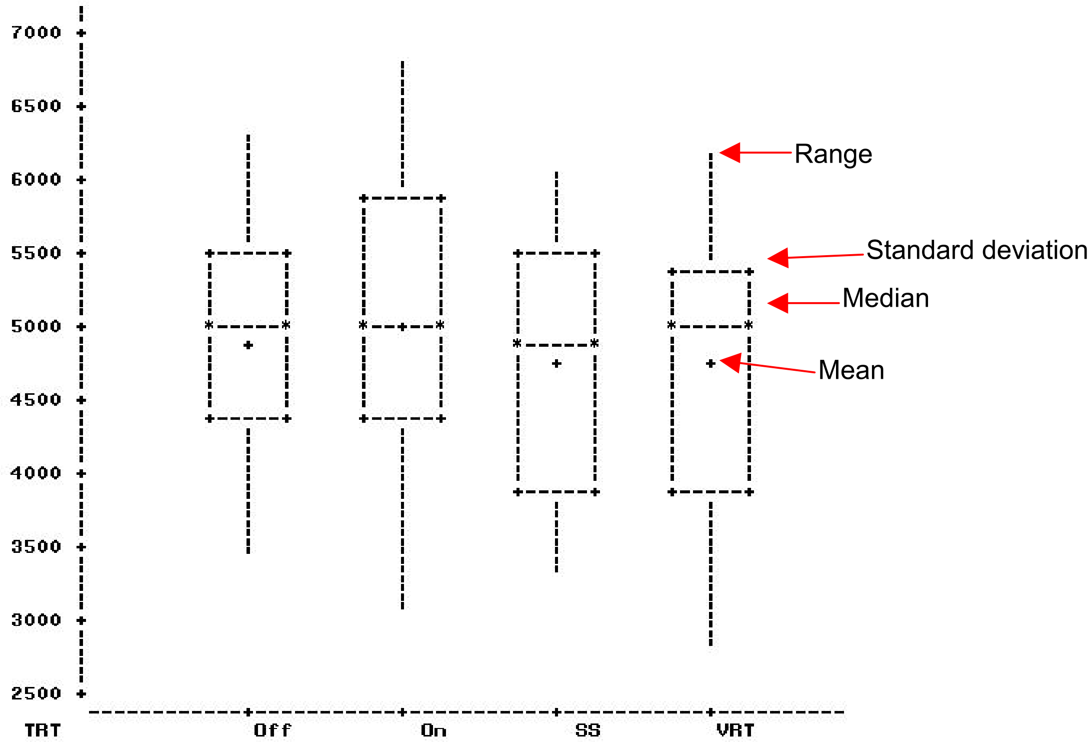

Figure 5. Plot of the yield monitor yield data range, mean, median, and variance for each treatment.

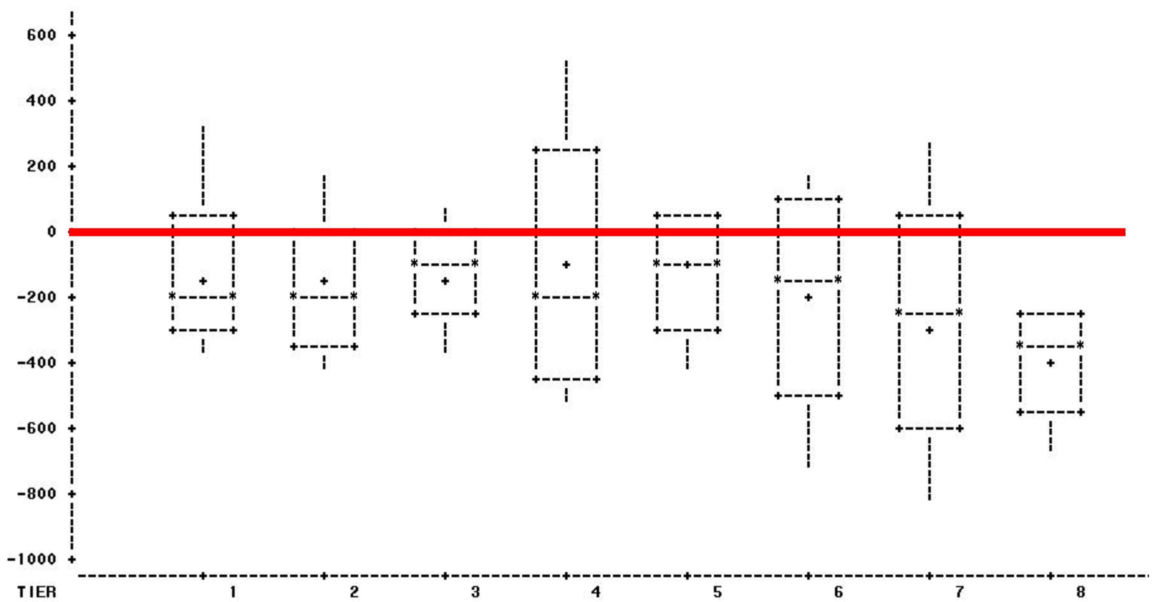

Figure 6. Plot of the summary statistics for the difference of the variable rate treatment yield from the untreated control according to regions of the study site (tiers 1-8).

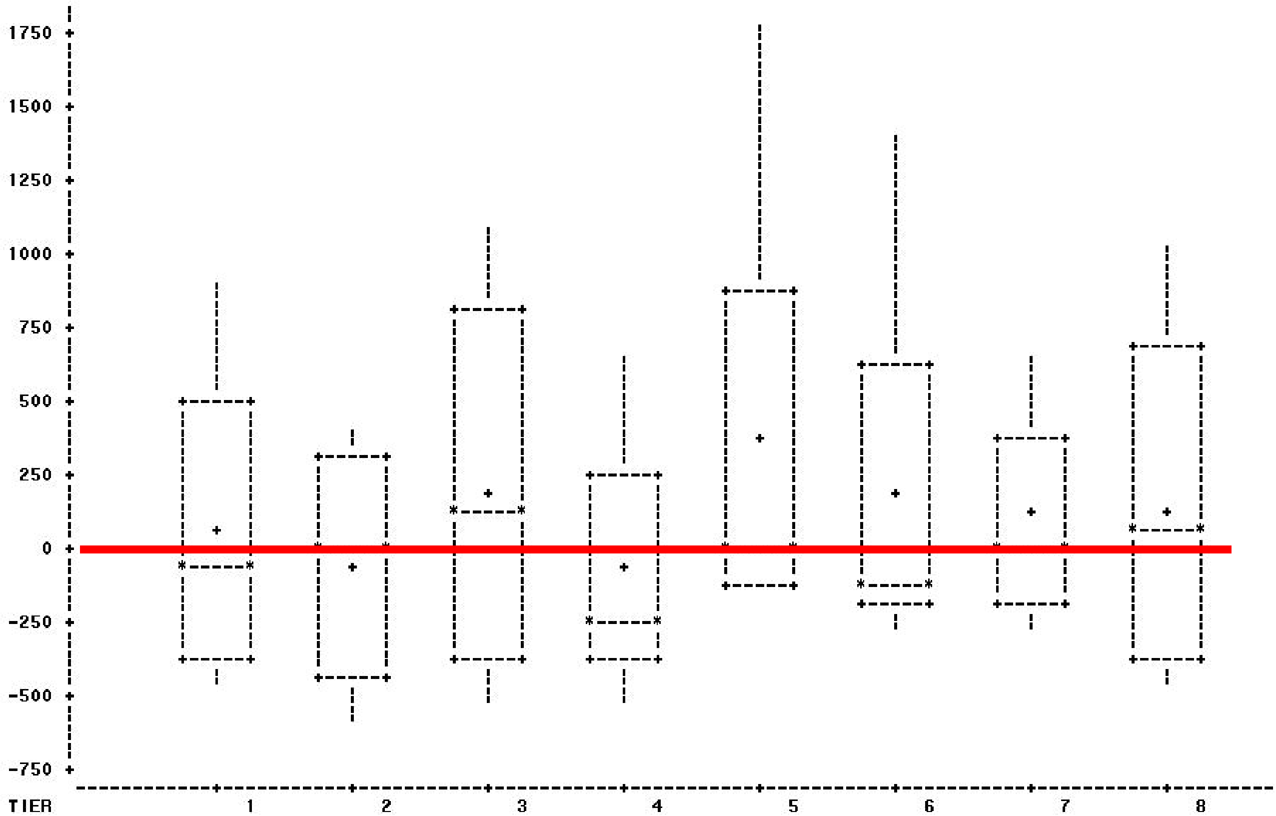

Figure 7. Plot of the summary statistics for the difference of the site-specific treatment yield from the untreated control according to regions of the study site (tiers 1-8).

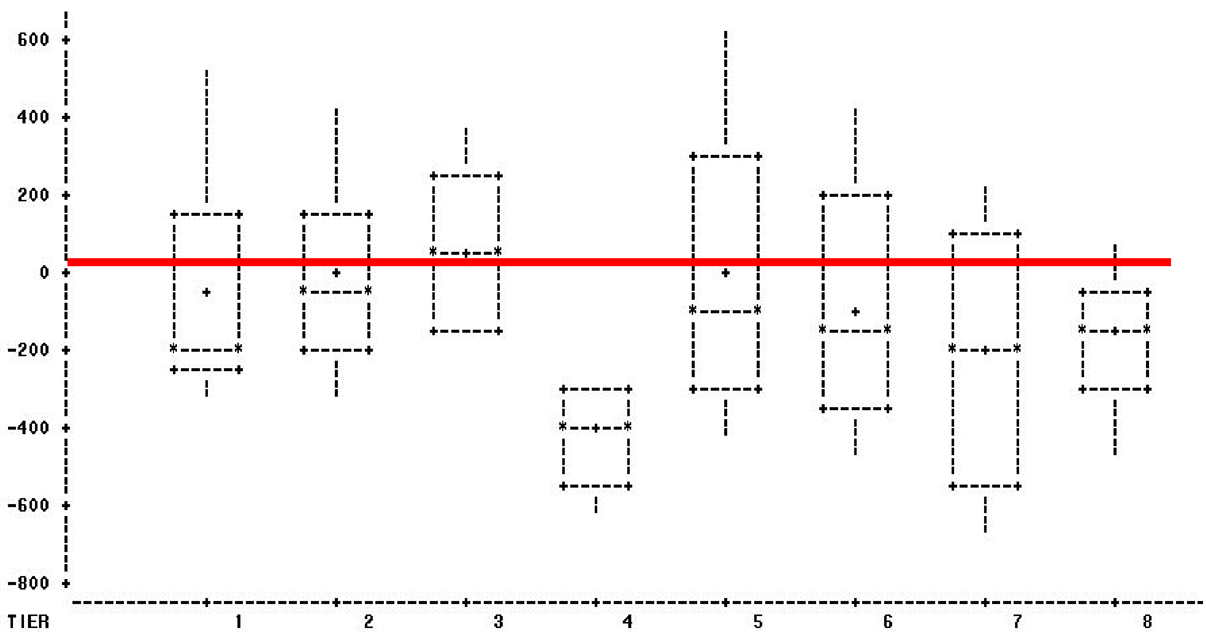

Figure 8. Plot of the summary statistics for the difference of the 100% standard treatment yield from the untreated control according to regions of the study site (tiers 1-8).

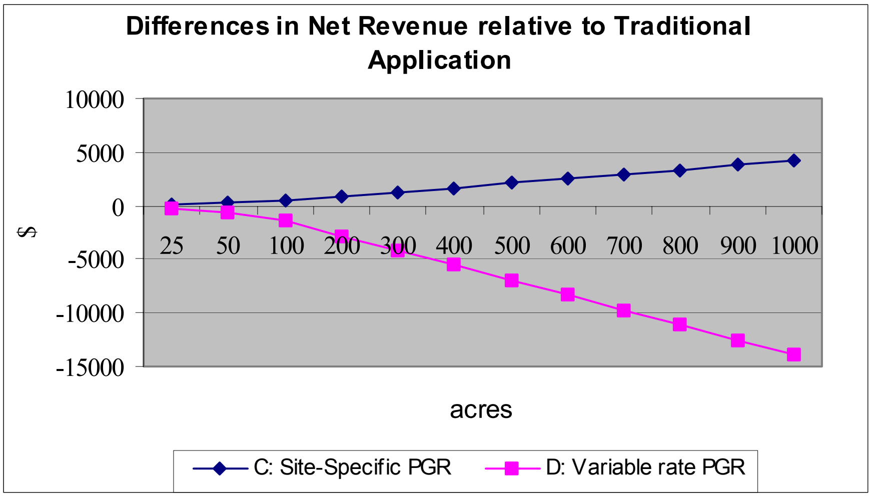

Figure 9. Plot of the extrapolated average net revenue for the image-based treatments with increasing acreage with respect to the 100% application of PGR.

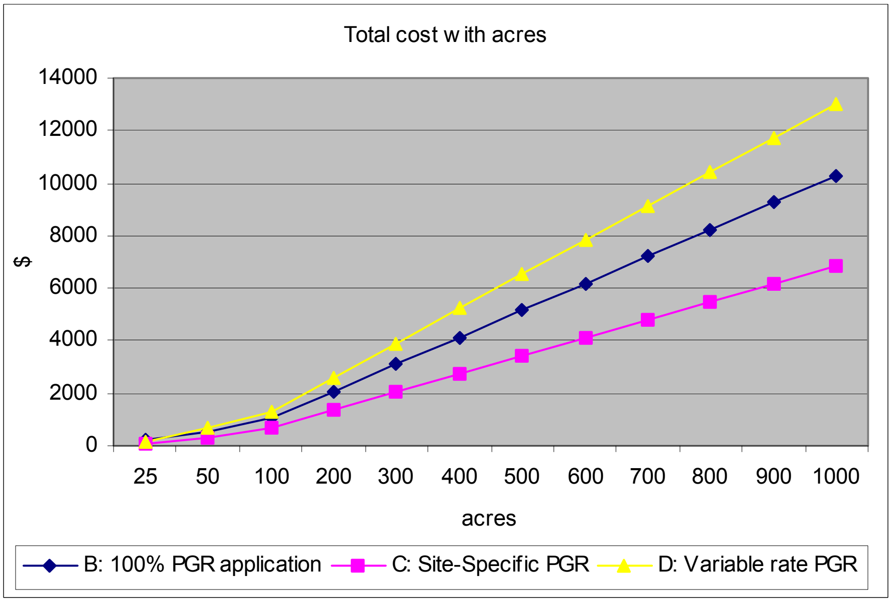

Figure 10. Plot of the extrapolated costs for the image-based and 100% PGR treatments with increasing acreage.

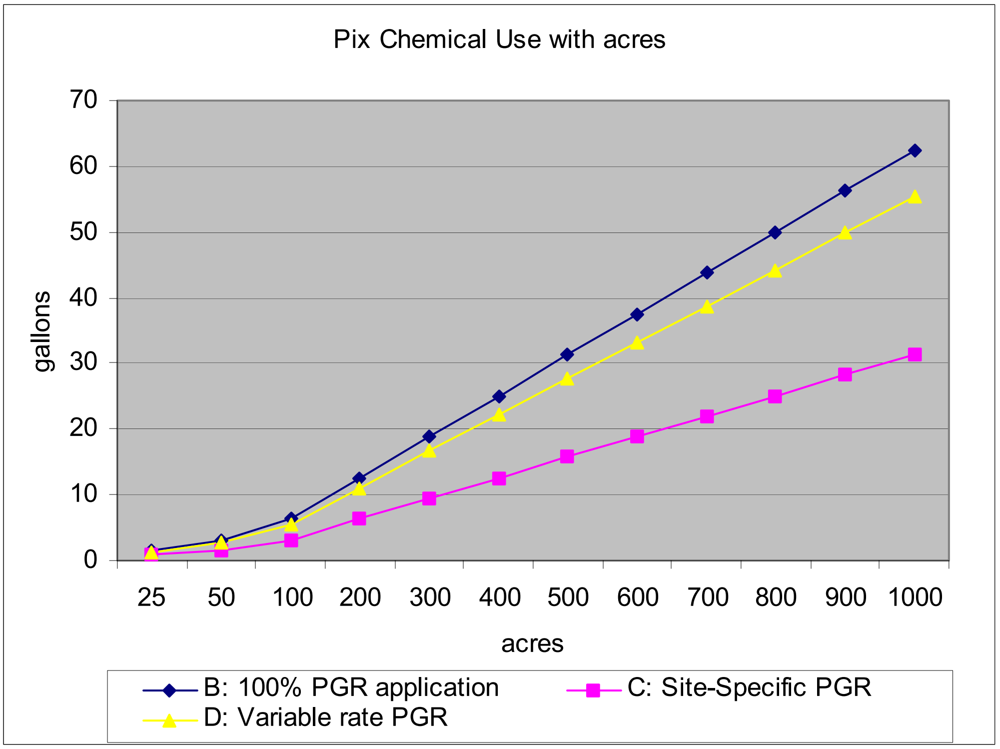

Figure 11. Plot of the extrapolated Pix chemical usage for the image-based and 100% PGR treatments with increasing acreage.