Testing Components Toward a Remote-Sensing-Based Decision Support System for Cotton Production

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Abstract
American cotton producers face rising production costs, falling prices, minimal yield increases, and increased competition from overseas markets and artificial fibers. Many producers are looking toward technology to gain an advantage in the only two variables that are within their control: reducing production costs and increasing yield. ITD-Spectral Visions and the NASA Commercial Remote Sensing Program are working with cotton producers Kenneth Hood of Perthshire Farms, Mississippi and Jay Hardwick of Newellton, Louisiana to test remote sensing and precision-agriculture technologies to solve some of these problems, with the eventual goal of integrating successful techniques into a Decision Support System (DSS) for cotton production. Components of the envisioned DSS currently being tested through field experiments include variable-rate seeding, spatially variable insecticide, spatially variable plant-growth regulator, variable-rate nitrogen, and others. The objective of these tests is to reduce costs and/or increase yield in an economically feasible manner. The eventual goal—integration of these and other components into a DSS—may occur only after the components are field-tested to show positive and repeatable results that justify the costs of such a system.

Introduction
American cotton producers face the challenges of rising costs, declining prices, and plateau-level yields at the turn of the new century. A well-designed Decision Support System (DSS) that integrates key data—from remote and *in situ* perspectives—may serve to improve at least some of these variables. The goal of this research is to test components of this envisioned DSS for cotton through field trials that reflect actual conditions on functioning farms. Experiments that pass this verification phase will be candidates for inclusion in a DSS that will ingest timely data from a variety of sources and output reliable prescriptions in near-real time.

According to the USDA Economic Research Service, U.S. cotton production returns (total gross value of production minus total economic costs) fell from $18.36/acre in 1975 to a below-zero level of −$35.44/acre in 1997. The single largest factor contributing to this decline is the increase in variable cash expenses—from $141/acre in 1975 to $304/acre in 1997—during that 22 year period. Although yield increased by 51 percent in this era, harvests have leveled off at about 600 lbs/acre nationally since the early 1990s. Price has increased by only 25 percent from 1975 to 1997, and 1998–1999 have seen some of the lowest prices in recent memory (under $0.50/lb in late 1999). These figures reflect a number of global trends that have affected American cotton production for the past few decades: competition from China, India, Pakistan, and Uzbekistan; increased demand for synthetic fibers; surpluses from recent harvests; changes in government involvement in the industry; and, most significantly, increases in variable costs of production, comprising the elements listed in Table 1 (USDA ERS, 1999).

Individual producers are subject to the vagaries of the marketplace but exert some control over their own production costs and yield. Many are looking toward technology to exert this control, in the form of transgenic seed varieties, ultra-narrow row cropping techniques, and the recent trend toward "precision agriculture," also known as "site-specific agriculture" or "prescription farming." Precision agriculture may be thought of as the allocation of scarce farm resources to areas where they are needed and to the extent they are needed, rather than at a constant rate across the entire field, with the goal of minimizing input costs and maximizing yield. It is the logical extension of economics—the efficient allocation of scarce resources according to societal demand—to the farm. Gardeners practice precision agriculture on a micro-scale when they spray herbicide only where weeds exist, or when they water only those plants in need of water. On a production-agriculture scale, the spatial component of precision agriculture is usually delivered by an integration of a tractor-mounted geographic information system (GIS) and the Global Positions System (GPS), which communicate a location and a prescribed rate to the mechanical components of the operation: specialized equipment which regulates the amount of application through a series of valves and nozzles. This quantity is recorded separately as "as-applied" data, used to track the accuracy of the target prescription. At harvest, GPS-enabled yield monitors are mounted on harvesters to measure within-field yield variability, to provide feedback on the effectiveness of the operation.

The most critical element in this precision agriculture process is the data analysis that forms the cost-saving prescription. An effective prescription can save significant amounts of money and increase yield, but an erroneous one can have the exact opposite effect. The Institute for Technology Development-Spectral Visions (ITD-Spectral Visions) and the NASA

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Table 1. Cash Expenses per Acre, U.S. Cotton Production

	1975	1997	Absolute Increase	Relative Increase
Seed	$5.88	$15.99	$10.11	172%
Fertilizer, lime, and gypsum	$18.41	$43.73	$25.32	138%
Chemicals	$29.83	$57.26	$27.43	92%
Custom operations	$7.19	$20.64	$13.45	187%
Fuel, lube, and electricity	$16.36	$35.24	$18.88	115%
Repairs	$22.75	$30.11	$7.36	32%
Hired labor	$12.52	$43.96	$31.44	251%
Ginning	$25.14	$51.27	$26.13	104%
Other variable cash expenses	$3.00	$6.21	$3.21	107%
Total, variable cash expenses	$141.08	$304.41	$163.33	116%

Source: Economic Research Service, USDA http://www.econ.ag.gov/briefing/farmincome/car/cotton3.htm

Table 2. Cotton-Production Requirements (1999 Focus Group)

	Description of Requirement
Insects	Manage insects to reduce pesticide costs and inputs.
Soils	Identify soil management zones for improved decision-making.
Next-season preparation	Assess physical properties of fields after harvest to support planning of upcoming crop.
Irrigation	Optimize soil water resources and improved management of irrigation water.
Vigor/stress	Determine crop response to varying field and weather conditions to improve decision-making process.
Herbicide	Detect and manage weeds to reduce herbicide costs and inputs.
Nutrient application	Allocate fertilizer to reduce input costs and improve production efficiency.
Marketing	Improve knowledge of macro-scale market parameters to improve cropping decisions.
Maturity/termination	Improve knowledge of crop progress to support harvest

Source: NASA CRSP (1999)

Commercial Remote Sensing Program (NASA CRSP) are verifying the role of remote sensing in the generation of selected cotton prescriptions, from technical and economic perspectives, on two cotton farms in the lower Mississippi Valley: Kenneth Hood's Perthshire Farms of Gunnison, Mississippi and Jay Hardwick's Hardwick Farms of Newellton, Louisiana. The near-term objective of this effort is to test the effectiveness of specific variable-rate applications, based in part or wholly on remote sensing. The long-term goal, dependent on the success of the near-term work, is to integrate these components into a Decision Support System that outputs a series of cost-saving, yield-maximizing prescriptions based on recent remotely sensed data and previously collected field data. While this long-term goal is a number of years away, the component-testing stage of this envisioned DSS is already underway.

Developing a Cotton-Production Decision Support System

A number of Decision Support Systems are already on the market for agriculture. For example, TASC, Inc. and WSI Corporation produce mPower[3]®, described as "a knowledge-based service designed to maximize productivity [through] critical, accurate, and site specific information" about production environments (TASC and WSI, 2000). This DSS integrates yield, weather, soils, and multispectral imagery data to support farm-level decisions delivered via the World Wide Web. Some academic, government, and private organizations are developing agricultural DSSs, exemplified by the Agricultural Farm Analysis and Comparison Tool (AgriFACTs), which supports cropping decisions at the regional scale (Thomas, 2000). There are a number of expert systems and growth-simulation models specifically for cotton, developed in research environments and made available to cotton producers. Among them are the Gossym Comax model, which simulates cotton growth based on weather, soils, and management practices; the Cotton_qual model, a similar model for Acala cotton in California, and the OZCOT model, developed in Australia (**http://www.wiz.uni-kasse/.de/model_db/mdb/ozcot.html**).

The DSS envisioned here attempts to build upon these and other existing capabilities in a manner that (1) integrates remotely sensed imagery and (2) addresses the most critical requirements of American cotton producers. A focus group convened by ITD-Spectral Visions and NASA CRSP in August 1999 prioritized these top requirements, which serve to point researchers toward key areas that should be addressed in a cotton-production DSS (see Table 2). Using the information in Tables 1 and 2 adapted to the practical limitations of the participating farmers, the researchers have focused their efforts in testing (1) variable-rate seeding, (2) spatially variable insecticide, (3) variable-rate plant-growth regulator, and (4) other areas from 1998 to 2000.

Test 1: Variable-Rate Seeding

Introduction

This variable-rate seeding test addressed the question, What seeding rate produces the maximum cotton yield at the minimum seed cost, and in what geographical zones did this occur? The results provide empirical evidence that a relatively lower seeding rate (1) produces more lint-cotton yield, (2) minimizes seeding costs, and (3) that certain patterns between seeding rates and yield emerge when crossed with remotely sensed datasets, but not enough to indicate the basis for an imagery-based variable-rate seeding prescription.

Need

Technology fees associated with transgenic varieties have nearly tripled the cost of cottonseed, making it one of the highest input costs to American cotton farmers. These fees are designed to recoup the research-and-development investment made by seed companies in creating genetically altered varieties; while these new varieties produce high yield and save in herbicide and insecticide costs, they nevertheless represent a financial burden to the producer. The same is true for other crops: "With tech fees and the high cost of soybean seed these days, it's important to use the lowest population that produces the best yield possible" (Finck, 2000). A 50-pound bag of transgenic cottonseed (containing about 270,000 seeds) costs roughly $231, about a quarter of which represents seed costs and three-quarters ($177/bag in this case) comprises the technology fee. If seeded at a rate of 39,000/acre (three seeds per foot in 40-inch rows), a 50-pound bag would cover 6.92 acres and cost $33/acre; at 65,000 seeds/acre (five seeds per foot), the same bag would cover 4.15 acres and cost $56/acre. While a lower seeding rate minimizes costs, the researchers sought to investigate which rate would maximize yield while minimizing cost, and in which geographical zone this may occur. Such data would determine what role imagery may play in a DSS that included a component on seeding prescriptions.

Experiment Design

The test comprised 12 plots covering 58 acres laid out across a 200-acre field north of the town of Cleveland, Mississippi in the alluvial floodplain known as the Mississippi Delta. Seventy percent of the study area crosses Robinson fine sandy loams (higher elevations representing the natural levee of the nearby

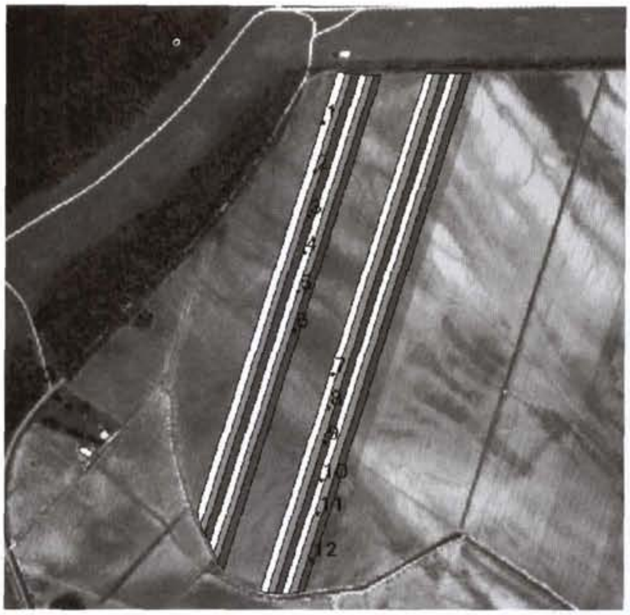


Figure 1. Seeding plots on Perthshire Farms, Gunnison, Mississippi.

TABLE 3. TARGET VS. ACTUAL SEEDING RATE

Plot Number	Target Seeding Rate/Acre	Actual Seeding Rate/Acre	Deviation
Plot 1	39000	43360	11%
Plot 2	52000	57621	11%
Plot 3	65000	55607	−14%
Plot 4	39000	43998	13%
Plot 5	52000	57467	11%
Plot 6	65000	62194	−4%
Plot 7	39000	40109	3%
Plot 8	52000	51074	−2%
Plot 9	65000	62679	−4%
Plot 10	39000	41324	6%
Plot 11	52000	51085	−2%
Plot 12	65000	63285	−3%

Mississippi River); Commerce silty loams account for another 25 percent; and the remaining areas are poorly drained Souva soils (USDA SCS, 1958). Each plot measured about 16 meters wide and 1220 meters long. Four of the 12 plots were seeded at a rate of 3 seeds/foot (39,000/acre), another four plots were seeded at 4 seeds/foot (52,000/acre), and the remaining four plots were seeded at 5 seeds/foot (65,000/acre) (Figure 1). These rates, which reflect adjustment for a 90 percent germination rate, were selected because they bracketed the seeding rate generally used by farm owner Kenneth Hood (approximately 52,000/acre) and reflected the typical range used throughout the Mississippi Delta. The seeding file, prepared using ESRI ARC/INFO and ArcView GIS software, was planted with 458 Bio-transgenic RoundUp Ready seed from 04 to 07 May 1999 using an eight-row vacuum planter equipped with a Rawson Accu-Rate controller and a Vision System controller/satellite receiver. To measure the extent to which actual seeding rate concurred with the target rate, "as-applied" ("actual") data were captured and compared to target rates (Table 3). An inspection of these data reveals some deviations that may

TABLE 4. YIELD-MONITOR VS. WEIGH-WAGON YIELD

Plot	Yield Monitor	Weigh Wagon	Deviation
Plot 1	3484	2568	−26%
Plot 2	2956	2740	−7%
Plot 3	3340	2662	−20%
Plot 4	2810	2666	−5%
Plot 5	2742	2726	−1%
Plot 6	2992	3028	1%
Plot 7	2856	2624	−8%
Plot 8	2384	2504	5%
Plot 9	2668	2622	−2%
Plot 10	2454	2514	2%
Plot 11	2680	2768	3%
Plot 12	2484	2584	4%

appear to interfere with the analysis of the experiment. However, it is noted that all analysis was done by specifically selecting the actual seeding data that fell within a range of ±3000 seeds from 39,000, 52,000, and 65,000 seeds per acre, regardless of plot. Because of the sheer number of points (13,400), there were many thousands that fell within the above ranges. Thus, we can say with certainty that the findings cited below reflect the ranges of 39,000, 52,000, and 65,000 seeds/acre, ±3000 seeds, regardless of the within-plot averages. For the remainder of the season, the test plots were treated under normal farm-management circumstances. All plots were irrigated and sprayed for insects and other applications in a broadcast (blanket) manner; no other variable-rate applications were conducted upon the plots.

The test plots were harvested on 11 and 12 October 1999 by a four-row cotton picker equipped with Micro-Trak cotton-flow sensors to monitor yield. To quantify the validity of the yield-monitor data, the harvest was weighed at the end of each plot. Table 4 shows that, in all but two plots, yield monitor data and weigh-wagon data fell within 8 percentage points of each other. A further inspection of the data revealed that there were no major spikes or troughs in the distribution of yield-monitor data.

Results at the Field Level

To determine the yield production of the three seeding rates, the "as-applied" data falling in the categories of 36,000 to 42,000, 49,000 to 55,000, and 62,000 to 68,000 (as described above) were isolated out and compared to their corresponding yield-monitor data points. This was done throughout the entire 28-acre study area, regardless of plots. In the following findings, "net" implies gross revenue minus seed costs only, and "marginal net gain" is the difference between (1) the deviation of seed cost at a given rate from the average seed cost, and (2) the deviation of revenue earned at that seeding rate from the average revenue produced at all three rates. These results assume a lint percentage of 38 percent, based on previous measurements at Perthshire Farms, and a price of $0.50/lb for lint cotton, based on the December 1999 market (see Figure 2).

- The lowest seeding rate (average 39,650/acre) produced the highest yield (1075 lbs/acre lint), highest net revenue ($503.59/acre), and highest marginal net gain (+$30.12/acre gain).
- The medium seeding rate (average 51,997/acre) produced the lowest yield (979 lbs/acre lint), lowest net revenue ($444.77/acre), and the lowest marginal net gain (−$28.70/acre loss).
- The highest seeding rate (average 65,856/acre) produced the medium yield (1057 lbs/acre lint), medium net revenue ($472.06/acre), and medium marginal net gain (−$1.42/acre loss).

The statistical significance of these differences was tested through a one-way analysis of variance (ANOVA): i.e.,

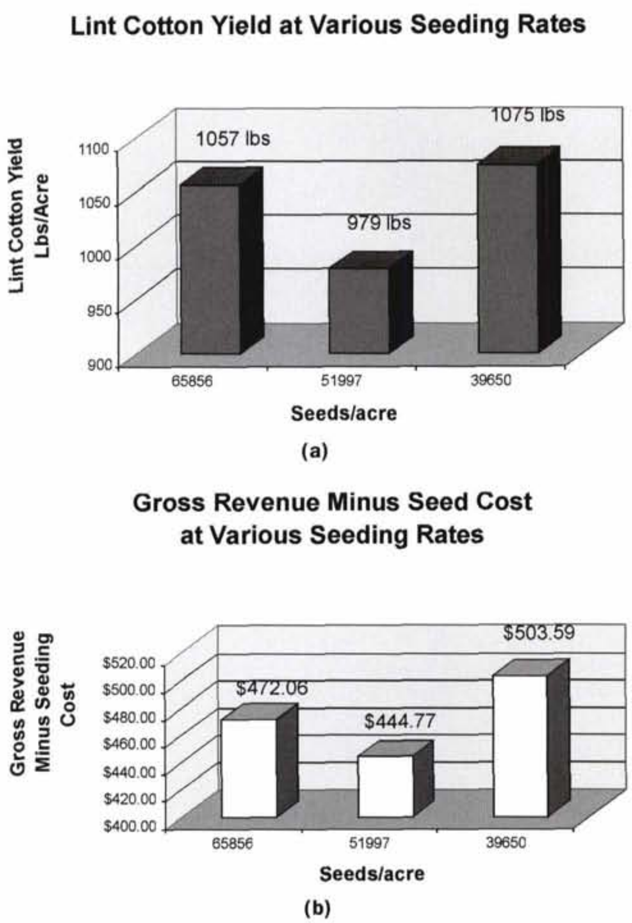


Figure 2. Comparison of (a) lint yield and (b) gross revenue minus seed costs, at the three seeding rates.

$$H_o: u_{39000/\text{acre rate}} = u_{52000/\text{acre rate}} = u_{65000/\text{acre rate}}$$

H_A: At least one mean yield is different

The results of this ANOVA are presented in Table 5.

At $F = 7.14 > F_{critical} = 4.74$ (alpha = 0.01), the null hypothesis that all three rates produced the same average yield is rejected. That the lowest seeding rate produced the highest yield generally concurs with cotton seeding trials reported by the University of Georgia College of Agricultural and Environmental Sciences Cooperative Extension Service (2000), in which "rates as low as 2 seed/foot resulted in plant stands ranging from 1.2 to 1.9 plants/foot and [produced] maximum lint yield over the three-year study." Likewise, a three-year variable-rate soybean seeding study by *Farm Journal* found that the lowest seeding rate tested proved to be most beneficial (Finck, 2000).

Results at the Zone Level

The purpose of this test was to determine not just the optimal seeding rate but the geographical zones in which a certain seeding rate may excel. It is in this regard that remote sensing may be employed. The researchers analyzed the above data within the zones of four different data layers derived from remote sensing and field data: (1) soil-color classes based on a classification of a pre-season bare-soil image, (2) a normalized-difference vegetation index (NDVI) calculated from a previous-year image, (3) topographic curvature calculated from a digital elevation model, and (4) soil texture, based on soil samples. The goal was to observe relationships between seeding rate and yield within the zones of these four data layers, in the hope of determining a potential variable-rate seeding prescription based on remote sensing. This zonal analysis revealed that, when adjusted for the cost of seeds, the lowest seeding rate proved to be the most economical *regardless* of the four layers of geographical variation that were tested. These data are presented below.

Soil-Color Classes

An airborne multispectral image captured by ITD-Spectral Visions' Real-Time Data Acquisition Camera System (RDACS) sensor three weeks before planting (16 April 1999) at one-meter resolution and three spectral bands (840 nm, 675 nm, and 540 nm) was calibrated through the empirical line routine using field targets, georeferenced, masked to the limits of the study area, and processed through an unsupervised classification to break out ten classes. These classes depicted darker-colored soils in the lower classes to brighter-colored soils in the higher classes; beyond darkness (color), no other inference as to soil class, moisture, texture, or other property is made. The ten classes were then intersected with the seeding and yield data to determine what seeding rate produces what yield in each zone. The results are shown in Figure 3.

The data in Figure 3 show that the low seeding rate yielded the most in darker soils, while all three seeding rates yielded about the same in brighter soils. When adjusted for the costs of seeds incurred at the various seeding rates, it appears that the low seeding rate of 39,000 was the most economically sound, regardless of soil-color variation.

NDVI Zones

Next, an RDACS multispectral image captured a month prior to last year's harvest (08 September 1998) was processed into a normalized difference vegetation index (NDVI) with the goal of finding vibrant-vegetation zones in last year's crop that may produce extra yield if seeded at a certain rate. NDVI is a ratio between

Table 5. ANOVA to Test Significance of Yield Differences at Three Seeding Rates (alpha = 0.01)

SUMMARY Groups	Count	Sum	Average	Variance
Column 1	46	49058.50	1066.49	25100.21
Column 2	56	54714.22	977.04	12280.69
Column 3	64	67653.43	1057.08	19211.01

ANOVA Source of Variation	SS	df	MS	F	P-value	F crit
Between Groups	264066.30	2	132033.15	7.14	0.001068	4.74
Within Groups	3015241.12	163	18498.41			
Total	3279307.42	165				

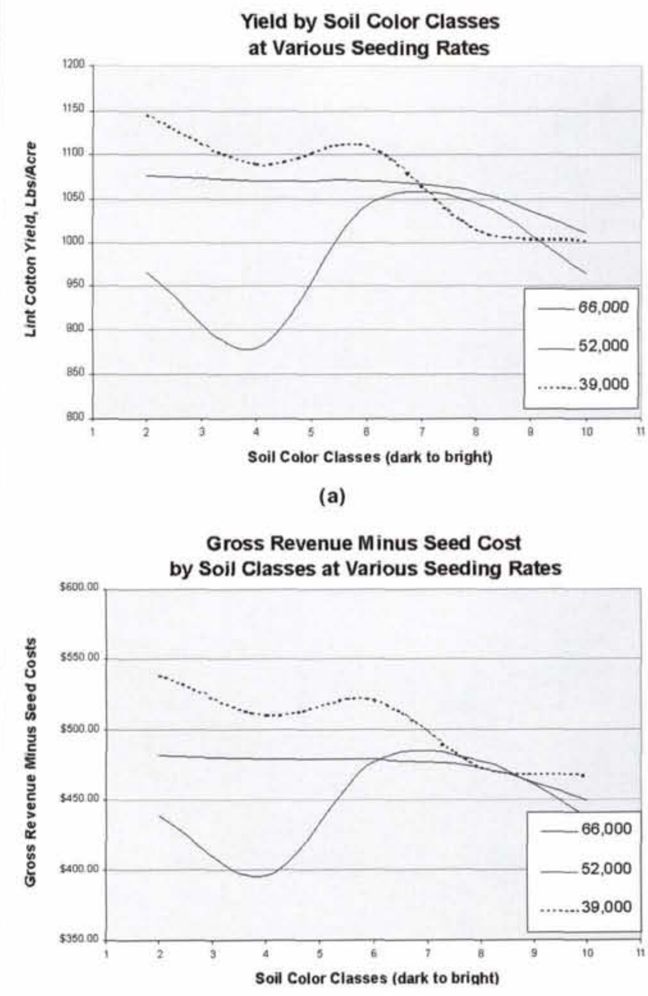


Figure 3. Relationships (a) between seeding rate and lint yield and (b) between seeding and revenue, within soil color classes.

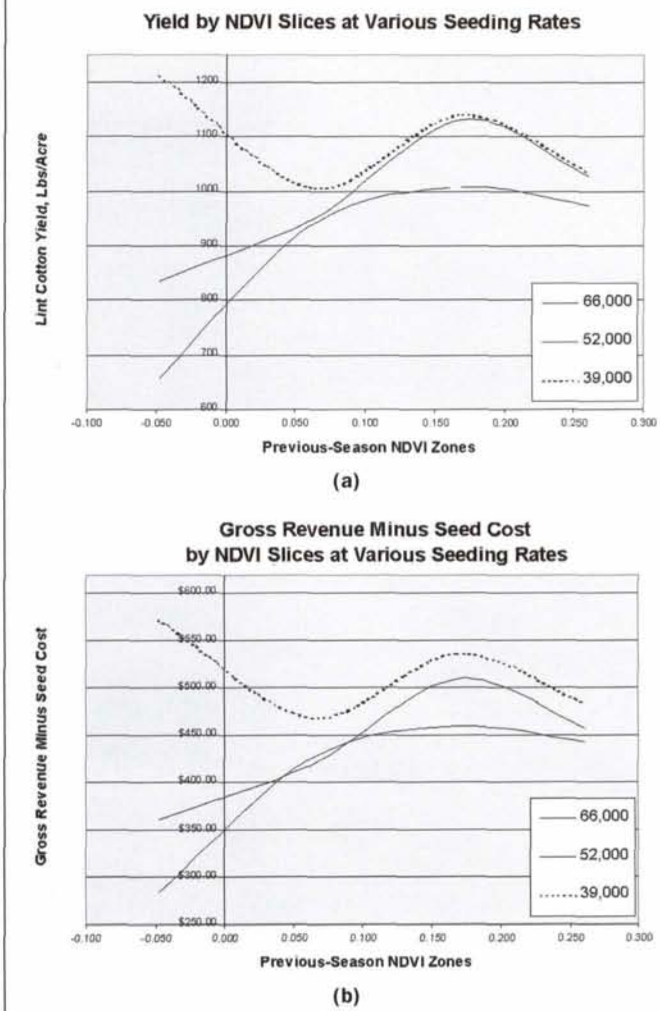


Figure 4. Relationships (a) between seeding rate and lint yield and (b) between seeding rate and revenue, within previous-season NDVI zones.

the near-infrared-band reflectance and red-band absorption of vegetation, producing values between -1 and $+1$, where values closer to -1 indicate less-vibrant areas and values closer to $+1$ mark areas that are most vibrant and green. In this case, the NDVI was sliced into five equal-interval zones, and the average NDVI value for each zone was computed (x-axis in Figures 4a and 4b). These zones were then crossed with the seeding and yield data to determine what seeding rate produces what yield in each zone. The results are shown in Figure 4. The low seeding rate of 39,000 in Figure 4a yielded highest in low-NDVI zones, and, to a lesser extent, in high-NDVI zones. However, when adjusted for seed cost, the low seeding rate was the most economically sound, regardless of previous-season NDVI zones.

Curvature Zones

Curvature measures the convexity and concavity of a topographic surface, and is calculated on a digital elevation model (ESRI, 1997). Lower negative values in a curvature model indicate more concave (water-collecting) surfaces; higher positive values reflect more convex (water-shedding) surfaces; zero is flat. Curvature was determined using the CURVATURE algorithm in ESRI ARC/INFO GRID upon a one-meter-resolution LIDAR digital elevation model ("bald earth," with vegetation removed), which was first coarsened and smoothed to remove excessive detail. The output curvature model was then categorized into five equal-interval zones, and the average curvature value was computed for each zone. These zones were then crossed with the seeding and yield data; the results are shown in Figure 5. Although Figure 5 shows little yield variation among the three seeding rates on various curvature zones, the low seeding rate again yielded the most, regardless of topography. When adjusted for seed costs, the low seeding rate was once again the most economical.

Soil Texture Zones

Soil texture was measured on a one-acre grid of field samples by researchers at Mississippi State University and were kriged to form a surface of average particle size, ranging from 0.23 mm to 0.71 mm in diameter (between silt and sand). This data layer was sliced into five equal-interval zones and intersected with the seeding and yield data to determine what seeding rate produces what yield in each zone (Figure 6). While certain soil-texture zones produced erratic yields, there appears to be no strong pattern among seeding rate, yield, and soil-texture zones. An overall yield benefit was produced by the low seeding rate, which became more apparent when the data were adjusted for seed costs.

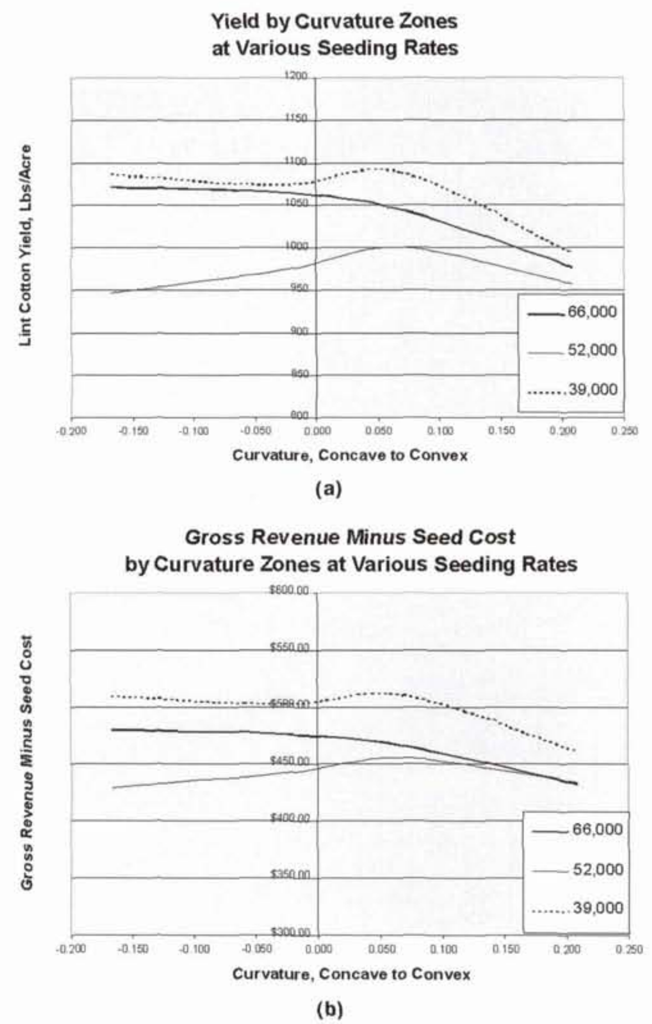


Figure 5. Relationships (a) between seeding rate and lint yield and (b) between seeding rate and revenue, within curvature zones (poorly to well-drained).

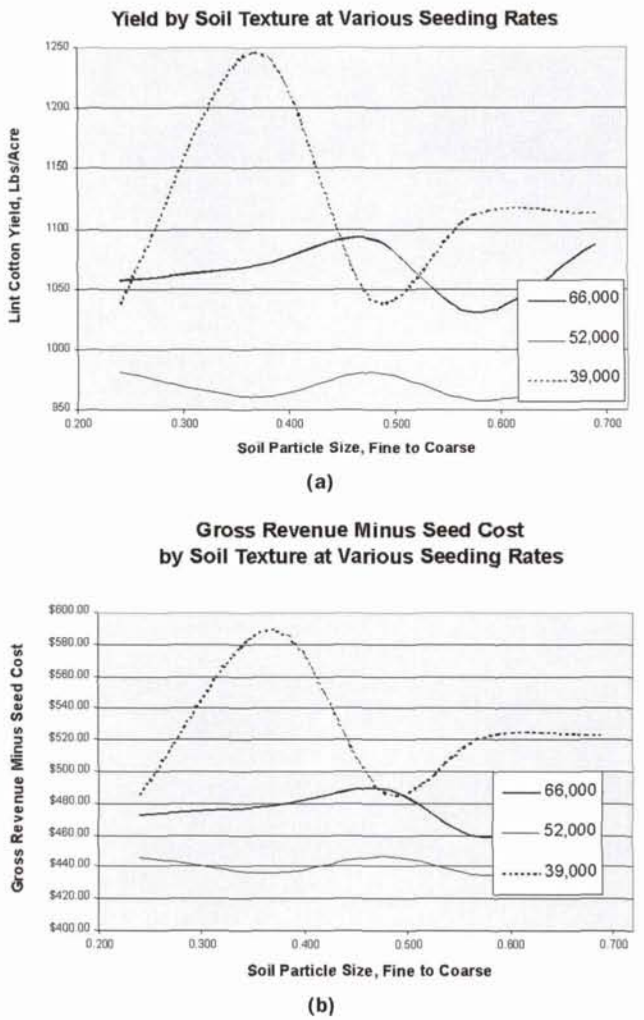


Figure 6. Relationships (a) between seeding rate and lint yield and (b) between seeding rate and revenue, within soil-texture zones (fine to coarse).

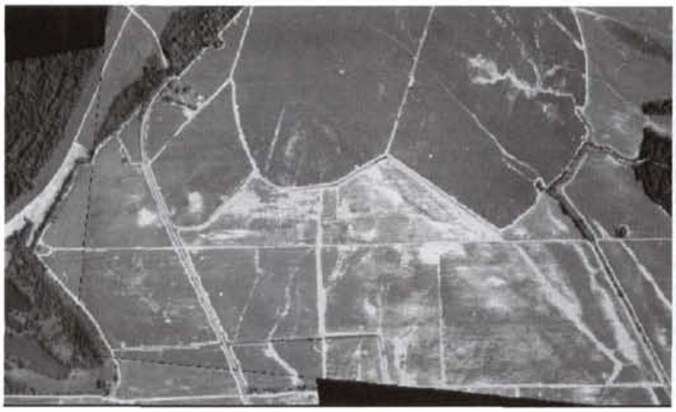
Conclusion: Variable-Rate Seeding

Testing this component of the envisioned cotton DSS revolved around the question, *What seeding rate produces the maximum cotton yield at the minimum seed cost, and in what geographical zones did this occur*? The 1999 field test indicated that the lowest seeding rate of 39,000/acre generally produced the most yield and incurred the lowest seed costs, regardless of geography—or at least regardless of the four geographical datasets that were tested in this study. The researchers will replicate this field test in 2000 and experiment with other data layers. If the 2000 test also fails to indicate a benefit to image-based prescriptions for seeding rates, this concept will be eliminated from the envisioned Decision Support System. This exercise shows the need to test such concepts prior to their inclusion in a DSS.

Test 2: Spatially Variable Insecticide

Introduction

Research by Dr. Jeffery Willers of the USDA-ARS in Starkville, Mississippi indicates that tarnished plant bugs (*Lygus lineolaris*) are drawn to fast-growing, vibrant cotton, which generally develop squares (buds) first, and that these areas may be detected through multispectral imagery and processed into "spatially variable" (on/off) insecticide prescriptions. Working with Dr. Willers, the research team employed this method for three applications over approximately 1000 acres in 1999, decreasing insecticide usage by about 60 percent. The procedure involved capturing three-band airborne multispectral images at 2-meter spatial resolution, radiometrically and geometrically processing them, and calculating Normalized Difference Vegetation Indices (NDVI) to estimate the greenness of the plants (Figure 7a). The NDVIs were then separated into vibrant cotton areas (spray-on) and less vibrant areas according to thresholds placed at three different levels, representing conservative, moderate, and liberal interpretations (Figure 7b). The NDVIs were then recoded according to these three thresholds and attributed to reflect the gallons of insecticide per acre to be sprayed (5 gallons for spray-on and 0 for spray-off). The resulting three raster files were vectorized, projected to the appropriate coordinate system, verified, documented, compressed, and e-mailed to the farm. The research team in the field then inspected the three prescriptions and selected the one that best addressed the distribution of plant bugs as they had observed in the field. This judgement was usually made on a basis of a general survey, not a point-by-point quantification.



(a)

(b)

Figure 7. (a) NDVI calculated from multispectral image of Perthshire Farms. (b) The NDVI covering the spatially variable insecticide study area has been thresholded into two categories: vibrant, green cotton plants, which will be sprayed because they are more likely to attract plant bugs, and less vibrant cotton plants, which will not be sprayed (darker polygons).

Once a prescription was selected, it was loaded into the controller (an on-board GPS-enabled GIS) and applied. This process was repeated six times during the season, although a prescription was actually applied only three times. The insecticide, Bidrin®, costs about $4.30/acre; thus, a 60 percent reduction over thousands of acres represents a substantial financial savings, in addition to the environmental benefit. The cost of the imagery, processing, and application equipment must be figured into the cost-benefit analysis of remote-sensing-based spatially variable insecticide. But first the technique must be verified in terms of not solely its cost savings but also its effectiveness in killing plant bugs and its ability to maintain acceptable yield levels. Field data collected at 32 points during the 1999 season indicated that the reduced insecticide usage did not lead to increased numbers of plant bugs, and that yield was maintained at normal levels. However, before remote-sensing-based spatially variable insecticide is included in a cotton-production DDS, more field data are needed to verify effectiveness and yield maintenance, and more replications of the entire experiment must be executed in different geographical areas and under various farm-management systems. This is the thrust of the field campaign for the upcoming season.

Experiment Design to Verify Spatially Variable Insecticide

The research team plans to test the Spatially Variable Insecticide component of the cotton-production DSS through twin large-scale field tests at Hardwick Farms in Louisiana and Perthshire Farms in Mississippi. The tests will be designed as randomized block designs, in which neighboring fields of 50 to 200 acres each will be subjected to traditional blanket sprays and spatially variable sprays of insecticide. The researchers will count the number of insects (through the use of drop cloths) at points on a 2-acre grid throughout the study area before and after each spray for both the blanket and the spatially variable fields. These data will provide insight into the effectiveness of spatially variable insecticide with regard to killing plant bugs compared to traditional blanket sprays. Hand-picked cotton yield will also be collected on the 2-acre grid, providing data on the ability of this technique to maintain normal yield levels while decreasing insecticide costs. An economic analysis of the costs and benefits of spatially variable insecticide versus blanket spraying will then be conducted, taking into account insecticide usage/acre, total imagery costs/acre, total processing time costs/acre, straight-line depreciation for equipment needed to apply prescription/acre, specialized labor cost/acre, and any other items necessary to the comparison. These twin field experiments will be implemented during the 2000 growing season and reported in 2001.

Test 3: Spatially Variable Plant-Growth Regulator

Plant-growth regulator (PGR) is applied to inhibit cell elongation in cotton, restricting vegetative growth and promoting earlier and heavier boll production on lower node branches and thus increasing lint yield (Weir and Kerby, 1988). PGR is also used to make a field uniform in terms of plant height, to facilitate harvest. One popular PGR, Pix® (Mepiquat Chloride), costs $4.30/acre, representing a relatively small but nonetheless significant cost to cotton producers. While plant height is widely recognized as the main indicator to trigger a PGR application (Weir and Kerby, 1988; Kerby *et al.*, 1990; Landivar and Searcy, 1999), Munier *et al.* (1993) observed that plant height was "related to plant vigor and early fruit retention and this is a good indicator of the need for Pix®." Based on image analysis conducted in 1998 and 1999, the researchers noticed that the most vigorous plants (as indicated by the top 20 percent of Normalized Difference Vegetation Indices calculated from multispectral images) generally correlated to low-yielding areas. They hypothesize that the dual benefit of minimizing PGR application and increasing yield may be achieved by applying PGR only to the most verdant, robust cotton plants, as indicated by imagery. These leafy, green plants are probably utilizing an excessive amount of resources for leafiness and an insufficient amount for lint production. Empirically, this concept is based on the analysis of 23 multispectral images and yield-monitor data collected during the past two growing seasons over two fields at Perthshire Farms. An NDVI was calculated for each image and sliced into five equal-area categories. Yield-monitor data, captured at a 3-meter interval by a Micro-Trak cotton flow sensor mounted on the harvester, were intersected with the polygons derived from the NDVIs. The resulting graphs comparing NVDI slices at various dates throughout the growing season and their corresponding yields were plotted; these are displayed in Figure 8. The patterns provide empirical evidence that the highest 20 percent NDVI areas became increasingly indicative of lower- and lower-yielding areas as the season progressed, indicating that these areas may be ideal candidates for site-specific PGR application. Likewise, the lowest 20 percent NDVI areas became increasingly indicative of higher and higher yielding areas, and the middle 60 percent NDVI areas throughout the season generally concurred with highest-yielding areas.

The researchers plan to test this hypothesis in a factorial

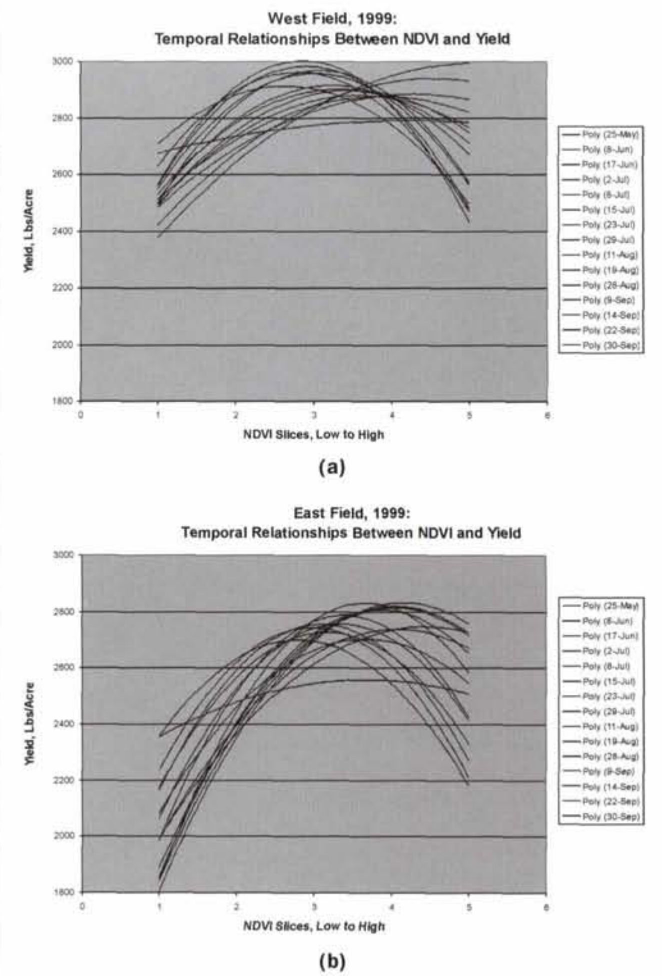


Figure 8. Temporal patterns between NDVI slices and cotton yield.

experimental design that combines on/off plant-growth regulator application with variable-rate seeding and analyzes the resulting yield within polygons delineated from in-season NDVIs sliced into five categories. (The variable-rate seeding component will serve to replicate the 1999 experiment discussed earlier. There will be a sufficient number of replications in the experiment to accommodate both the PGR and the variable-rate seeding components of this experiment.) Observations from this experiment will shed light on the relationship between PGR and yield when (1) PGR is sprayed on high, medium, and low NDVI areas and when (2) PGR is not sprayed on these areas. If successful and replicable, NDVIs from multispectral imagery may play a role for both Spatially Variable Insecticide and Spatially Variable Plant-Growth Regulator.

Other Potential Components of a Cotton DSD

The researchers are collaborating with soil scientists, agronomists, weed scientists and others at Mississippi State University, USDA-ARS in Starkville and Stoneville, and other organizations in investigating remote-sensing-based solutions to cotton-production problems. As these techniques are field-tested to a reasonable level of verification, they may become candidates for inclusion in the envisioned cotton-production DSS. This additional research, cited in the reference section, includes work in variable-rate nitrogen application by Dr. Jac Varco, soil characterization by Dr. Frank Whisler, and a wide range of projects by the new Remote Sensing Technology Center (RSTC) at Mississippi State University. Additionally, a new joint initiative called Ag20/20—sponsored by NASA, USDA, and the commodity organizations representing cotton, corn, soybean, and wheat—is designed to streamline the testing of field-scale remote sensing applications in agriculture over the next five years, with the specific goal of bringing successful tests to the marketplace as commercially available products and services. It is in this regard that the researchers strive to develop a Decision Support System integrating each tested component into a single, near-real-time, remote-sensing-based "digital crop consultant."

Remotely Sensed Data Sources

This project utilized an in-house airborne multispectral sensor, built by Dr. Chengye Mao of ITD-Spectral Visions and called the Real-Time Data Acquisition Camera System (RDACS), for most of its image needs. This sensor was selected because the requirements of rapid turn-around time and constant availability during the growing season precluded the use of other systems on the commercial market. The lack of appropriate satellite providers at the time prevented the team from using spaceborne platforms for data acquisition, although it is anticipated that this situation will be changing shortly. For these experiments, the RDACS was flown on a Cessna at 3700 meters (12,000 feet) above ground level to yield a 2-meter-resolution pixel. RDACS features three cameras with arrays of 1320 by 1028 pixels per scene; thus, a single image at this altitude covers a footprint of 2,640 meters by 2056 meters. RDACS' three bands capture reflected light at the 540-nm (green), 695-nm (red), and 840-nm (near infrared) portions of the electromagnetic spectrum (±5 nm). Images are stored on 8-mm tape and extracted at ITD-Spectral Visions' facilities at Stennis Space Center, Mississippi, where they are automatically band-to-band registered and manually georeferenced to GPS and other spatial data. Images are calibrated through the empirical line method, which uses 8-step gray-scale radiometric targets to map raw 8-bit digital numbers to percent reflectance. Image geometric and radiometric quality were constantly checked in a qualitative manner, such as comparison with high-accuracy datasets and minimization of mosaic seams, but rapid turn-around time and other circumstances precluded the consistent and quantified quality assurance/quality control (QA/QC) of the imagery. While this is not an optimal situation, it is noted that, because the applications being tested in this project involve relative differentiation of crop and field patterns rather than absolute identification of particular phenomenon, a rigorous QA/QC program is arguably not as critical as other issues in the execution of the experiments. At the laboratory level, the RDACS sensor is currently being tested and measured for optical and geometrical properties in the Sensor Lab managed by the NASA Commercial Remote Sensing Program at Stennis Space Center, Mississippi.

LIDAR (laser radar) data used for elevation modeling were captured by the helicopter-borne Aerial LaserMap™ system of Waggoner Engineering, Jackson, Mississippi. A LIDAR is a focused infrared laser system that sends thousands of pulses per second to the ground and measures their return, mapping the topography of the study area. The digital elevation model used in this project was captured at a resolution of 0.6 m (two feet) in the *x-y* direction and 0.15 m (six inches) in the *z* direction. Quality assurance/quality control of this dataset was carried out by the vendor.

Conclusion: An Envisioned Cotton DSD

With declining prices, leveled-off yield, and increasing costs, cotton producers are looking toward technology to recoup at least some of the losses of recent years. Precision agriculture, with remote sensing serving as a key and timely data source, may offer this solution, but conducting site-specific agriculture for each component of farm operation (seeding, herbicide and insecticide applications, fertilization, plant-growth regulator application, etc.) may prove too complex and cumbersome to be cost effective. A single DSS that outputs reliable prescriptions for many or most of these issues may reduce this complexity while minimizing costs and maximizing yield. Challenges abound in creating this DSS: differences in cotton production by soil class, geographical region, and cultural practices may make certain components limited in their applicability; field-testing of components may not account for all the variation that occurs at this macro scale; and sufficient confirmation of hypotheses and replication may not be achievable in the amount of time demanded by cotton producers. Nevertheless, the researchers are confident that the synoptical crop information depicted in timely multispectral images hold much promise for cost-effective cotton-farm management. Progress in the verification of components of this cotton-production DSS, as well as other remote-sensing-based precision agriculture experiments, may be tracked at *http://www.ag2020.org*.

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