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Predicting Cotton Lint Yield Maps from Aerial Photographs

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Abstract. It is generally accepted that aerial images of growing crops provide spatial and temporal information about crop growth conditions and may even be indicative of crop yield. The focus of this study was to develop a straightforward technique for creating predictive cotton yield maps from aerial images. A total of ten fields in southern Georgia, USA, were studied during three growing seasons. Conventional (true color) aerial photographs of the fields were acquired during the growing season in two to four week intervals. The aerial photos were then digitized and analyzed using an unsupervised classification function of image analysis software. During harvest, conventional yield maps were created for each of the fields using a cotton picker mounted yield monitor. Classified images and yield maps were compared quantitatively and qualitatively. A pixel by pixel comparison of the classified images and yield maps showed that spatial agreement between the two gradually increased in the weeks after planting, maintained spatial agreement of between 40% and 60% during weeks eight to fourteen, and then gradually declined again. The highest spatial agreement between a classified image and a yield map was 78%. The highest average agreement was 52% and occurred 9.9 weeks after planting. The visual similarity between the classified images and the yield maps were striking. In all cases, the dates with the best visual agreement occurred between eight and ten weeks after planting, and generally, during July for southern Georgia. This method offers great potential for offering cotton farmers early-season maps that predict the spatial distribution of yield. Although these maps can not provide magnitudes, they clearly show the resulting yield patterns. With inherent knowledge of past performance, farmers can use this information to allocate resources, address crop growth problems, and, perhaps, improve the profitability of their farm operation. These maps are well suited to be offered to farmers as a service by a crop consultant or a cooperative.

Keywords: cotton, yield maps, predictive, aerial photographs, image analysis, remote sensing

Introduction

It is generally accepted that aerial images of growing crops provide spatial and temporal information about crop growth conditions and may even be indicative of crop yield (Yang and Everitt, 2002; Vellidis *et al.,* 2001). Because of this, research teams are evaluating a multitude of remote sensing techniques for assessing the status of growing crops. These techniques vary from hyper-spectral imaging to detect plant stress to infrared imaging for irrigation scheduling. Much of this work has focused on using the visible and near-infrared wavelengths to develop vegetation indices such as the normalized difference vegetation index (NDVI) to estimate the nitrogen status of growing crops (Filella *et al.,* 1995; Li *et al.,* 2001a; Read *et al.,* 2002; Tarpley *et al.,* 2000; Thenkabail *et al.,* 2000; Walburg, *et al.,* 1982).

More recently, remotely-sensed imagery has been used to estimate yields for corn (Shanahan *et al.,* 2001; Yang *et al.,* 2001), grain sorghum (Yang and Everitt, 2002; Yang *et al.,* 2001) and cotton (Plant *et al.,* 2000; Yang *et al.,* 2001). In most cases the NDVI or similar vegetation indices were used to estimate plant stress or vigor and thus indirectly infer expected yields. Yang *et al.* (2001) found that yield maps generated from regression equations for yield as a function of a spectral band or a vegetation index corresponded closely with yield monitor data maps for corn and grain sorghum. The relative error between regression estimated yield and cotton gin yield was near 34%. The date of data acquisition appeared to have an effect on relative errors (Yang *et al.,* 2001). Boydell and McBratney (2002) used eleven years of remotely-sensed cotton yield estimates to establish within-field management zones. They found that the fields exhibited a high degree of temporal stability. These techniques all require the ability to collect high quality multispectral images and also require a high level of analysis which makes them difficult to implement by most crop consultants and farmers.

Because of this body of work, the University of Georgia Precision Agriculture Team has routinely commissioned low-level (below 3000 m) aerial photographs of fields in which precision agriculture research is conducted. When we compared cotton yield maps to color photographs of the crop taken early during the growing season, we observed impressive similarities in spatial patterns. Following several such observations, we hypothesized, like other researchers, that it might be possible to create representative yield maps from aerial photographs. However, we were interested in developing these maps with a simple technique that did not require specialized equipment and software and that could be readily used by crop consultants, cooperatives, and farmers. The ability to create these maps would benefit farmers in a number of ways. For small farmers without the resources to purchase yield monitors, the technology could provide yield maps at an acceptable cost. For all farmers, however, this technique has the ability to predict yields early in the season and enable management decisions that may positively affect profitability.

To test if there is a scientific underpinning to our hypothesis, we began a three year study that entailed photographing cotton fields at two to four week intervals during the growing season and comparing the photographs to yield maps created from picker-mounted yield monitors. This article describes our findings.

Materials and methods

A total of ten fields were studied—three during 1998, two during 1999, and five during 2000. The fields were located in southern Georgia, USA, ranged in size from 8 ha (20 ac) to 26 ha (63 ac). Slopes were less than 5% and soils ranged from sandy loams to loamy sands. All fields were strip-tilled and irrigated with center pivot systems. Cotton varieties were the same within fields but varied from field to field. Rows were planted on 0.91 m (36 in.) or 0.96 m (38 in.) centers. All decisions on crop management were made exclusively by the farmers so that planting dates, application of agrochemicals, and harvest dates varied from field to field.

Aerial photography

Color aerial photos of the fields were acquired beginning about week four of the growing season and in two to four week intervals thereafter. The photographs were taken with single lens reflex 35 mm cameras equipped with autofocus and mounted in the underside of a single-engine aircraft that is routinely contracted by the United States Department of Agriculture Farm Services Agency (USDA-FSA) for compliance photography. The images were exposed onto color slide film and the resulting slides were generally of good quality.

The aerial photos were taken at altitudes between 1000 and 3000 m. Altitude was a function of fitting the entire field within a single slide frame. Once developed, the slides were digitized at high resolution (2700 dpi) with a Polaroid SprintScan 35 slide scanner. The digital images resulted in files 12–20 Mb in size with three spectral bands (red, green, blue). With the concurrent decrease in price and increase in available resolution, the conventional 35 mm camera and slide scanner can now be replaced with a high-resolution digital camera. When the study began however, the cost of a high-resolution digital camera precluded its use in the study.

Harvest

Conventional yield maps were created for each of the fields using the latest generation Agri-Plan (Zycom) yield monitor available on the market for each of the three years. The 1998 and 1999 maps were created with a yield monitor mounted on a University of Georgia-owned 4-row John Deere 9965 cotton picker with sensors mounted on each of the four chutes. The 2000 maps were created with a yield monitor mounted on a farmer-owned and operated 2-row John Deere 9930. Detailed information on the performance of the yield monitors and techniques used during harvest were presented by Durrence *et al.* (1999) and Vellidis *et al.* (2003a).

Image analyses

The digitized aerial photos were analyzed using the ERDAS® Imagine v.8.3.1 software which is a high-end image analysis package. The first step in the image analysis process consisted of importing the image and performing a first order polynomial geometric correction in order to rectify it. The rectification was accomplished by using the latitude and longitude (lat/long) of preestablished ground control points (GCP) on the perimeter of the field. The lat/long used for each GCP was the mathematical mean of 300 data points collected with an Omnistar 7000 C-band differentially corrected global positioning system (DGPS).

The next step consisted of defining an area of interest, which in our case, was the field boundary. An area of interest contained up to 3 million pixels with up to 60,000 colors. A pixel corresponded to an area of 0.09–0.25 m^2. Then, an unsupervised classification was performed on the area of interest. In an unsupervised classification, the objective is to group multiband spectral response patterns into clusters. The clusters are statistically different sets of multiband data—radiances expressed by their digital number (DN) values. DN values range from 0 to 255 in the red, green, and blue bands. Thus, a range of DNs can establish one cluster that is set apart from a specified range combination of another cluster (Sabins, 1987). In this work, unsupervised classification was used to group the pixels into a user-specified number of clusters.

Maas (1997, 1998) concluded from detailed measurements of cotton canopy reflectance obtained at different locations over several years that reflectance is driven by percent ground cover rather than canopy density. In practical terms, the classification process we selected was driven by canopy cover and reflectance in the green band. In early season cotton (twelve weeks or less since planting), pixels in which green was the predominant reflectance band represented areas in the field in which little or no bare soil was visible. These pixels were grouped together and assumed to represent higher yielding areas. Areas in which green was not the predominant reflectance band where characterized by bare soil and a sparse canopy. These were assumed to represent low yielding areas. An intermediate green reflectance represented medium yields. On the field, this classification method corresponded to percent ground cover and to the vitality of the cotton plants. The higher the leaf area and greener the plants within a pixel, the higher the yield category to which it was assigned.

The optimal number of yield categories that should be displayed on a yield map is a matter of debate. Our preference, and the preference of our farmer partners, is to display three or four yield categories. Consequently, our first attempts at classification were with three and four categories which created three or four non equally distributed clusters or classes.

To effectively compare the classified images to the yield maps, the yield map categories were modified to match the distribution of pixels in the images. For example, if the pixel distribution in a classified image resulted in 42% of the pixels assigned to low yield category, 28% in the medium, and 30% in the high, then the yield map yield categories were established so that lowest 42% of data were in the low yield category, 28% in a medium yield category, and 30% in a high yield category.

Despite our best efforts to ensure the pilot was taking good quality images, several full color aerial photographs were not usable. In some cases this was caused by cloud shadows on the field. In other cases, irrigation was in progress which had a major effect on the reflectance of the wetted area. On one occasion, haze resulted in an unuseable image. In all, we compared 53 images to the ten yield maps.

Spatial comparison

In the next step of the analysis, the spatial agreement between the classified images and the corresponding yield maps was determined quantitatively using ArcView's Spatial Analysis extension. The classified images for each field and date, along with the yield map data for each field, were imported into the ArcView® GIS 3.2 software. The classified images, which were produced in ERDAS Imagine and were cell based raster files, were converted to Arcview raster data called grids. The yield maps which consisted of georeferenced point data, were also converted to ArcView grid files. For easy comparison, both grid files were created with 2.5 m cell sizes using the nearest neighbor technique to aggregate cells. The cell size and aggregation technique was selected after evaluating a wide range of cell sizes and several aggregation techniques.

In both grid files, high yield cells were given a value of 1, medium yield cells a value of 2, and low yield cells a value of 3. To determine to what extent the yield values of the classified images *spatially* agreed with the yield values of the yield maps, an ArcView map calculation was performed. The calculation performed an overlay in which each yield map cell's value of 1, 2, or 3 was multiplied by ten and added to the value of the corresponding classified image cell (values of 1, 2, or 3). The resulting ArcView overlay map contained cells with values of 10, 11, 12, 13, 20, 21, 22, etc. Cells with values of 11, 22, or 33 indicated where the yield map cell values spatially aggreed with the classified image cell values. The percentage of cells with spatial agreement for each image were determined from these values.

Only areas for which both yield map and classified image coverages were available were included. By default, the first map listed in the map calculation, in this case the yield map, determined the area covered by the calculation because classified image cells outside of the area covered by the yield map are not included in the calculations. In addition, cells with values of 10, 20, and 30 were not included in the final percentage calculations because a zero in the value indicates there was no classified image cell at that location.

Hand-harvested plots

To ground-truth the predictive ability of the classified aerial images, small plots were selected in the Willis, Mangum, and Sumner 1998 fields and hand harvested the day before the mechanical harvest. The location of the plots was selected from the corresponding July, 1998 aerial photograph (not the classified image) which was taken nine, eight, and ten weeks after planting, respectively. Plot location in the Sumner and Willis fields is shown in Figure 1.

In the Sumner field, a total of six $9 \text{ m} \times 11 \text{ m}$ ($30 \text{ ft} \times 36 \text{ ft}$) plots were selected—two replicates of anticipated low, medium, and high yields (Figure 1). The length of the plots was selected to coincide with the distance covered by a cotton picker in 5 s. The width coincided with 3 passes of the picker. Because of the large amount of labor required to harvest the Sumner field plots, fewer and smaller plots were selected in the Mangum and Willis fields. Five $3.7 \text{ m} \times 3.7 \text{ m}$ ($12 \text{ ft} \times 12 \text{ ft}$) plots were selected. Their size was chosen to coincide with 2 s of picker travel during one pass.

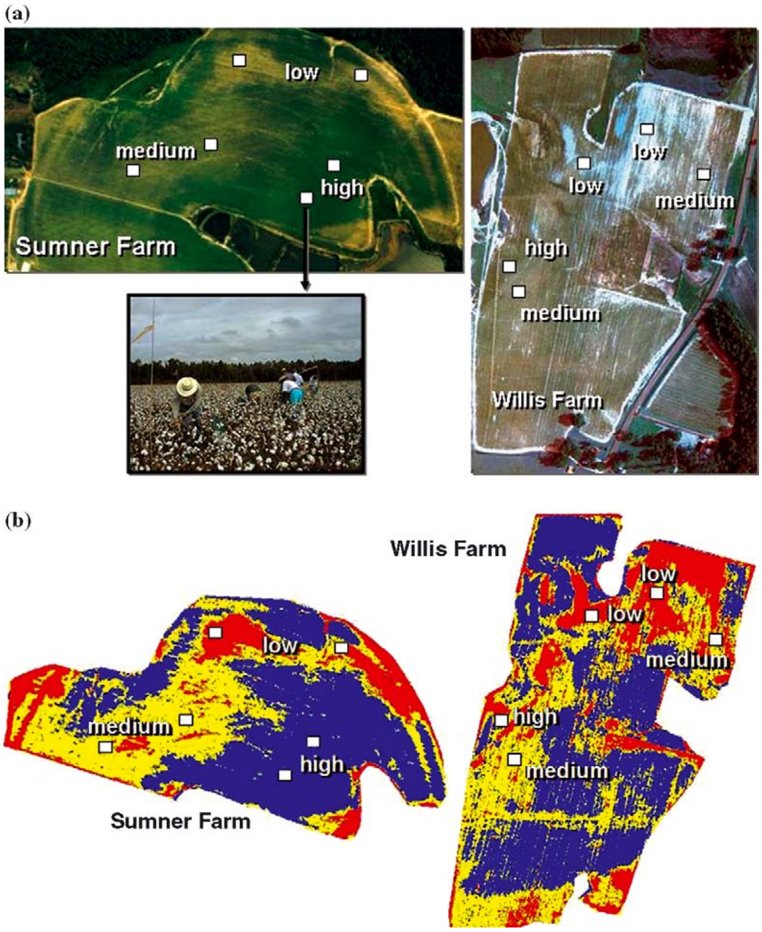

Figure 1. Hand-harvested plots were located by assigning them to what visually appeared to be areas with the potential for low, medium and high yields on the July 1998 photos of the Sumner and Willis fields (a). If the July 1998 classified images (b) which had the best visual agreement with the yield maps had been used, the placement of the plots on the Willis Farm field might have been different. The figure below shows the plots as placed using only the aerial photos.

The lat/long coordinates of the plots were identified from the rectified aerial photographs and the plots were physically located in the field using an Omnistar 7000 C-band DGPS. The yield from each of the plots was bagged separately and weighed. Because our hand-harvesting removed all lint from the stalks, the hand-harvested yield was reduced by 10% to match an average picking efficiency of the cotton picker (Valco, 2003).

To evaluate the placement of the plots, plot yields were compared to yield maps fitted to the pixel distributions of the July 1998 classified images of each field. Yield of the low, medium and high category plots was compared to the corresponding yield map ranges and to the average yield within those ranges.

It was evident from Figure 1 that the placement of the hand-harvested plots did not always coincide well with the low, medium, and high yield areas delineated by the classified image. In some cases, the plot was located in a transition area (Figure 1). To evaluate placement when using the classified images rather than the aerial photographs, we randomly selected a 2.5 m $\times$ 2.5 m cell centrally located within an homogeneous area of predicted low, medium, and high yield for each of the fields. Using ArcView, the classified image and the corresponding yield map were linked. A cell was selected randomly on the classified image and a query performed at the selection point. The query provided the yield from the yield map cell at that location. The yields of the randomly selected cells were compared to the corresponding yield map ranges and to the average yield within those ranges.

A paired two-sample student's t-test was used to determine whether the means of the plot yields were distinct from the means of the yield map ranges. A paired *t*-test is used when there is a natural pairing of observations. The test does not assume that the variances of both populations are equal.

Results

Many analyses were performed to identify the classification technique that resulted in the best agreement of the spatial patterns of the aerial photos and those of the yield monitor-created yield maps. We concluded that the most favorable comparisons were obtained using a 3-cluster unsupervised classification that directly resulted in a high, medium, and low class. The results are reported in Table 1.

For all fields, yield patterns were established early in the season. As the season progressed, the yield patterns were less evident, primarily because the canopy closed and masked spatial patterns as the crop matured. The best agreement between the classified aerial photos and yield maps was obtained with aerial photos taken between eight and fourteen weeks after planting. The average of the time since planting during which best agreement was measured for each field was 9.9 weeks.

For each overlay analysis conducted in ArcView, we obtained the percentage of cells that spatially agreed in each of the three yield categories as well as the percentage of overall agreement. Available results for the period of four weeks to fifteen weeks after planting are presented in Table 1. In general, overall agreement gradually increased in the weeks after planting, maintained an overall agreement of between 40% and 60% during weeks eight to fourteen, and then gradually declined again. The average of the best percent agreement measured for each field was 52%.

The best agreement occurred for the high yield category of field A012 (88%) on 18 July 2000. This field and date also had the best overall agreement (78%). The aerial photograph, the classified image, the yield map, and the overlay map for this field are presented in Figure 2. Although the overall agreement was high, the similarity between the classified image and the yield map is even more striking. The only area of major disagreement is the very bottom of the pivot circle which had medium yields but apparently good plant growth. The diagonal red patterns along the center of the

Table 1. Spatial agreement between yield map and classified images for each of the fields studied between 1998 and 2000

		Area			Spatial agreement between yield points and classified image pixels (%)				Average yield	
Field	Photo date	ac	ha	Weeks since Planting	High	Medium	Low	All	lb/ac	kg/ha
Willis	06/23/1998	63	26	7	42	50	41	46	2413	2709
	07/08/1998*			9	59	43	38	50		
	08/07/1998			13	46	55	23	50		
Mangum	06/23/1998	42	17	6	66	39	42	53	1887	2119
	07/08/1998*			8	65	40	49	54		
	08/07/1998			13	61	48	50	54		
Sumner	07/08/1998*	59	24	10	65	50	54	58	2408	2704
	08/07/1998			14	42	47	32	44		
Willis	06/05/1999	63	26	4	30	50	40	43	2316	2600
	06/19/1999			6	40	43	53	45		
	07/04/1999*			8	53	46	47	49		
	08/03/1999			12	80	40	27	66		
	08/19/1999			14	71	38	29	59		
Home	06/19/1999	42	17	7	28	48	37	40	2278	2558
	07/04/1999*			9	15	50	37	42		
	08/05/1999			13	51	51	28	50		
	08/19/1999			15	41	61	27	52		
A001	06/08/2000	57	23	4	17	48	52	47	2479	2783
	06/22/2000			6	35	50	31	42		
	07/05/2000*			8	36	68	22	56		
	07/18/2000			10	39	50	21	44		
A002	06/08/2000	36	14	5	30	45	30	37	2819	3165
	06/22/2000			7	29	57	14	45		
	07/05/2000*			9	65	40	38	55		
	07/18/2000			11	44	46	39	45		
A006	06/08/2000	27	11	5	30	56	27	43	2817	3162
	06/22/2000			7	54	55	44	54		
	07/05/2000*			9	60	42	49	53		
	07/18/2000			11	63	33	32	52		
A010	06/08/2000	20	8	5	21	44	25	32	3167	3555
	06/22/2000			7	44	50	9	47		
	07/05/2000			9	40	49	9	44		
	07/18/2000*			11	50	52	5	51		
A012	06/08/2000	53	21	4	31	39	28	33	2845	3194
	06/22/2000			6	37	49	32	42		
	07/05/2000			8	57	39	41	49		
	07/18/2000*			10	88	31	36	78		

*Denotes the date with the best visual agreement between a classified image and the yield map. This is a qualitative assessment.

field on the yield map were caused by the yield monitor continuing to collect data while the picker was traveling to, and emptying cotton into, the module builder.

Our worst results were for the 1998 Willis field for which the best overall agreement was 50% (08 July 1998 and 07 August 1998) (Figure 3). In contrast, the best

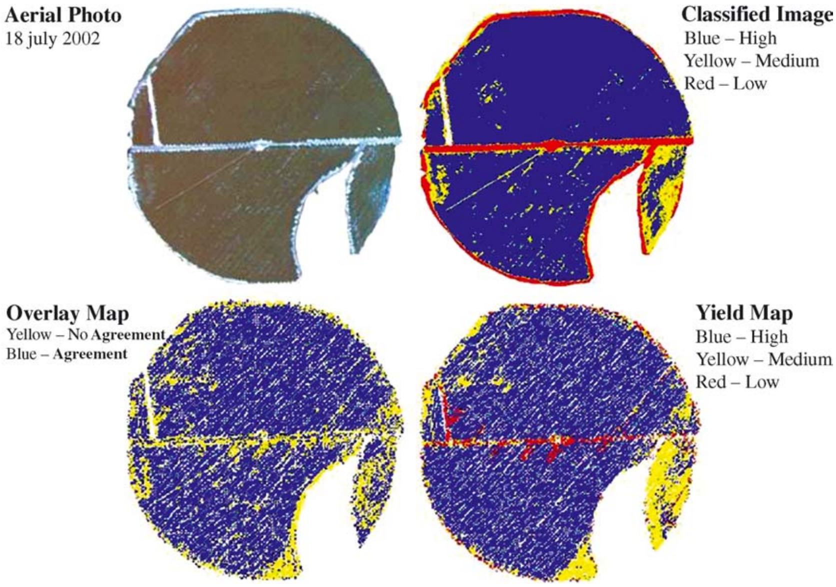

Figure 2. From top left in clockwise fashion—aerial photo, classified image, yield map, and overlay map of field A012. The overall agreement was 78% while the agreement for the high yielding areas was 88%. The visual similarity between the classified image and the yield map is striking. The only area of major disagreement is the very bottom of the pivot circle which had medium yields but apparently good plant growth. The diagonal red patterns along the center of the field on the yield map were caused by the yield monitor continuing to collect data while the picker was emptying cotton into the module builder.

overall agreement for this field during 1999 was 66%. This field is interesting to study because of the high degree of variability that it contains—both natural and management induced (Figure 3). Management induced variability includes incomplete coverage by the irrigation system, old fence lines, and portions of the field that were brought into production for the first time during 1998. The northwest section (top left) had been a pasture for more than a decade while the low, wet area in the eastern section (middle right) was wooded.

Natural variability includes topography and soil differences. The northeast (top right) of the field is very sandy but also suffers from crusting problems. The low wet area also has the lowest elevation in the field and receives substantial amounts of surface runoff, and potentially, subsurface flow from the adjacent areas of the field.

There are clearly many discrepancies and many striking similarities between the classified image and the yield map (Figure 3). Very early during the 1998 season, the cotton plants were growing rapidly in both the old pasture area and the wet area. The pasture area resulted in high yields while the wet area resulted in rank growth of the plants and poor yields. Li *et al.* (2001b) made similar observations on how landscape variability associated with topographic features affects the spatial pattern of soil water and N redistribution, and thus N uptake and crop yield. The southern perimeter produced lower yields because it was not irrigated. The low-yielding crescent-shape in the top left is an eroded ridge top. The narrow, circular bands in

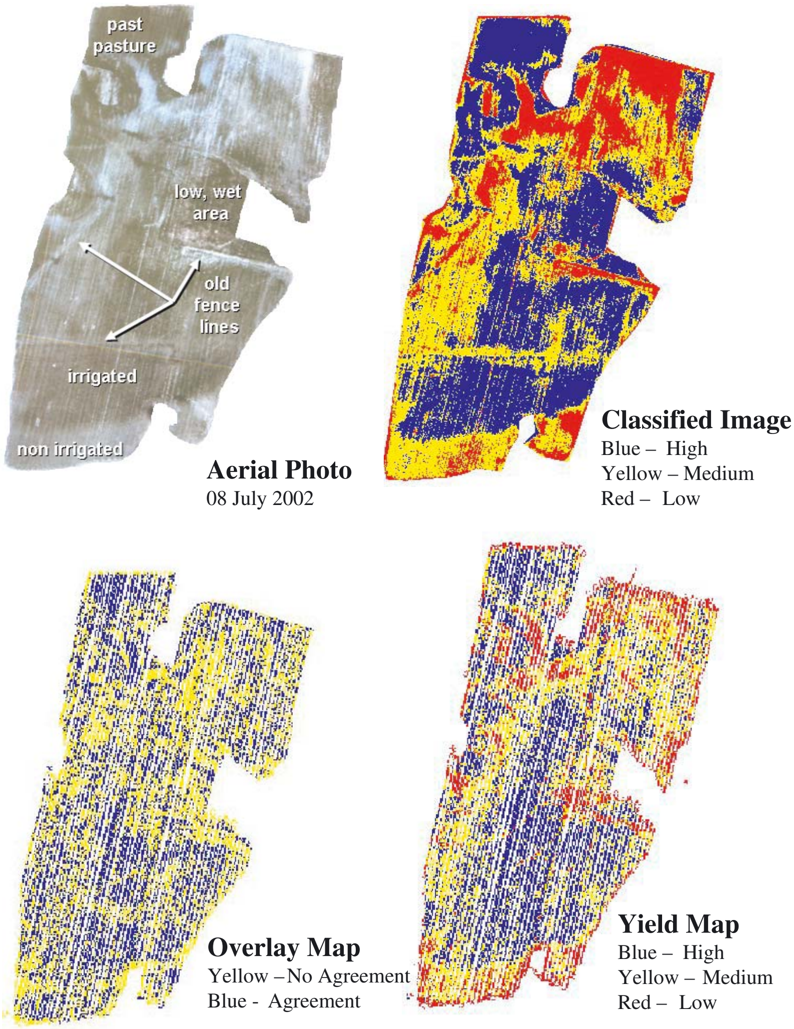

Figure 3. From top left in clockwise fashion—aerial photo, classified image, yield map, and overlay map of the Willis Farm field (1998). Although this date did not result in the best overlay map and numerical agreement, it did have the best visual agreement between the classified image and the corresponding yield map. The only major area of disagreement is in the low, wet area on the eastern edge of the field where rank growth was observed in the cotton plants.

the center of the field are the tracks of the center pivot irrigation system. Despite the poor overall agreement (50%), visually, the classified image appears to predict the final spatial distribution of yield fairly well.

Although the overall agreement numbers (Table 1) were not impressive and the average best overall agreement was only 52%, the visual similarities between the classified images and the yield maps were compelling. The best visual agreement was always found during July. Additional examples are given in Figures 4–7 and

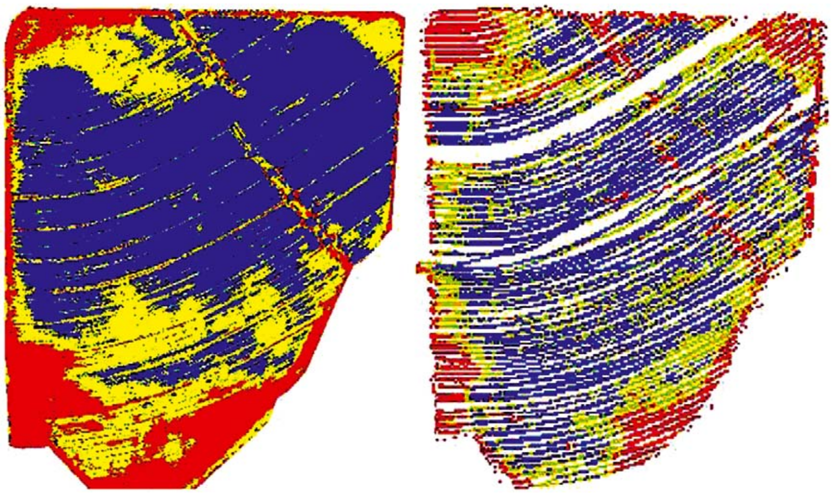

Figure 4. July 1998 classified image (8 weeks) and yield map of the Mangum Farm field.

by Vellidis (2003b). The Mangum Farm field (Figure 4) contains a severely eroded area (top left) and areas containing deep sands resulting from sediment deposition (bottom left and right). Poor yields in these areas are exhibited in both the classified image and the yield map. Blocked sprinklers caused parallel low yielding streaks in the Sumner Farm field along the right and left boundaries of

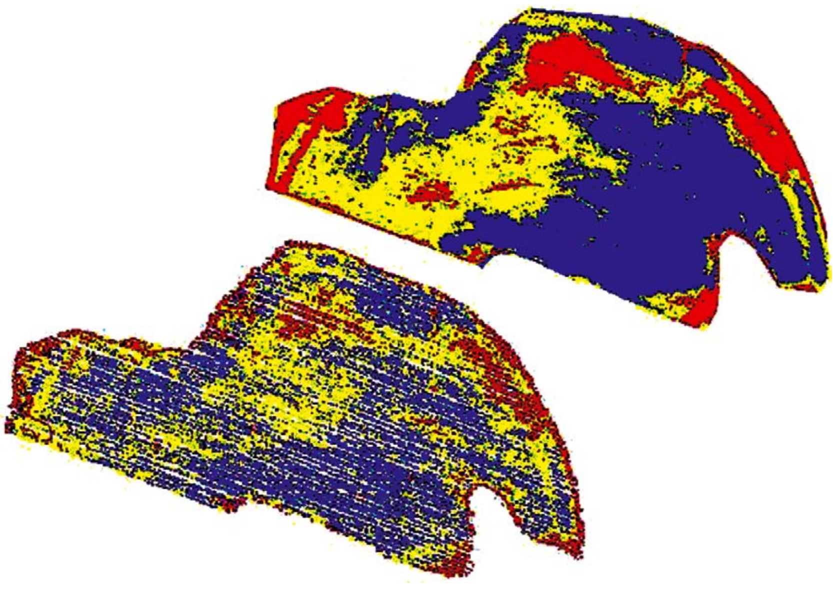

Figure 5. July 1998 classified image (10 weeks) and yield map of the Sumner Farm field.

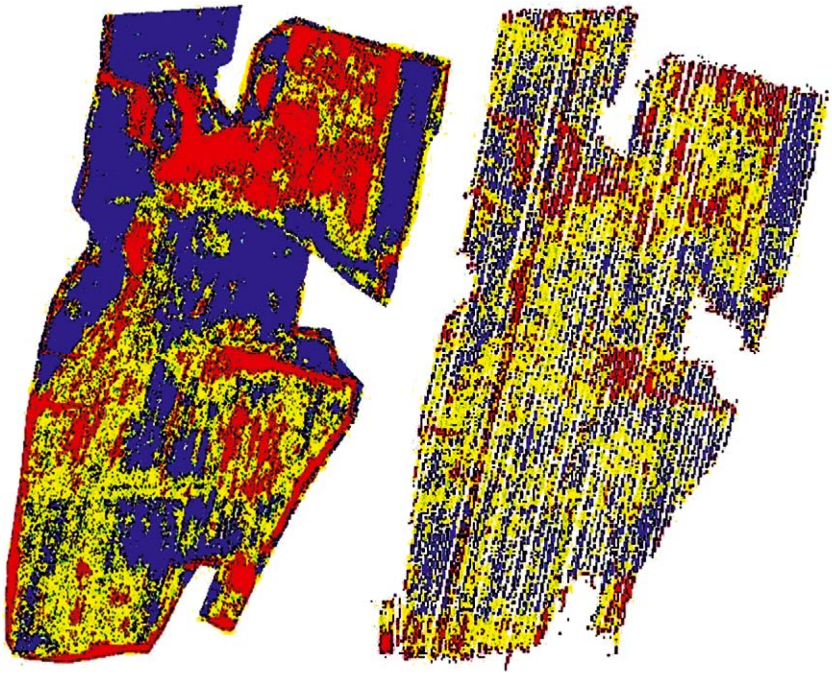

Figure 6. July 1999 classified image (8 weeks) and yield map of the Willis Farm field.

the field (Figure 5). The pattern is not exhibited along the entire length of the perimeter because the pivot occasionally extends beyond the field boundary. Because 1999 was a much drier year, the low wet area of the Willis Farm field (Figure 3) yielded well during 1999 (Figure 6) in contrast to 1998. The classified image and yield map of field A001 (Figure 7) shows good visual agreement in most areas of the field.

More variability is present in the yield maps than in the classified images which tend to contain relatively homogeneous areas. The ArcView overlay method used to quantify the spatial agreement between the image and the yield map was inherently biased towards expressing the variability of the yield map and resulted in relatively low agreement rates. There are also areas that deceived the classification algorithms. In most cases, the biggest discrepancies occurred in areas of the fields that exhibited good vegetative growth but produced poor yields (Figure 3).

In a few cases, the date with the best visual agreement between the yield map and the classified image was not the date with the best numerical agreement. In Table 1, the asterisk denotes the date with the best visual agreement. It should be noted that best visual agreement is a qualitative assessment which may be biased by conspicuously matching spatial features in both the classified image and the yield map. With one exception, the dates with the best visual agreement occurred between eight and ten weeks after planting. The best visual agreement for field A010 occurred 11 weeks after planting.

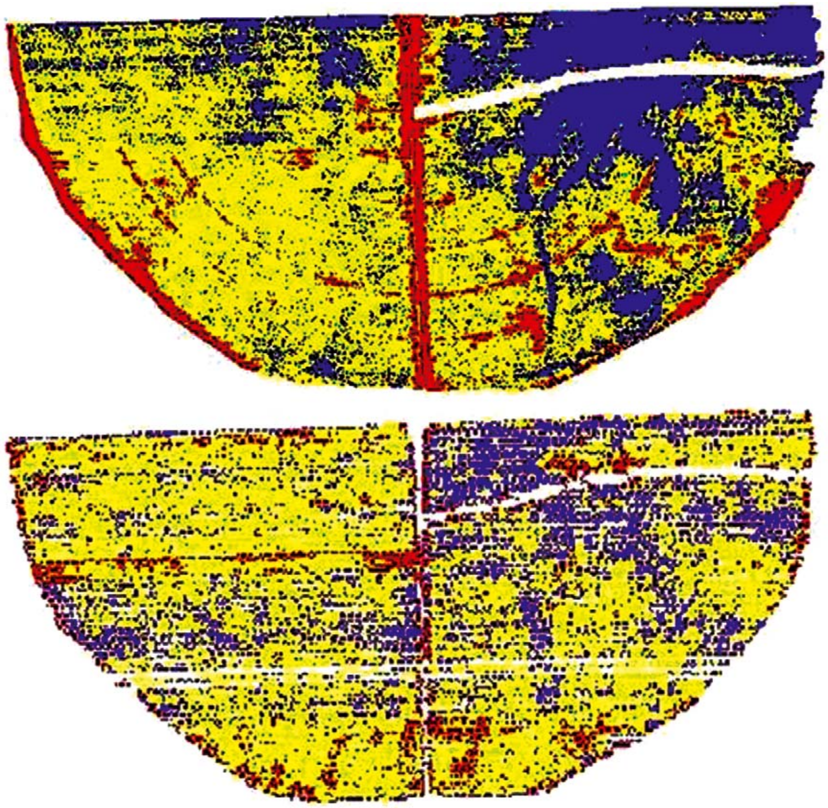

Figure 7. July 2000 classified image (8 weeks) and yield map of field A001.

Hand-harvested plots

Table 2 summarizes the results from the hand-harvested plots. Eight of nine corrected average plot yields fell within the appropriate yield ranges of the corresponding yield maps. The only exception being the high yield plot from the Willis farm. This amount of agreement was somewhat surprising as the plots were located by assigning them to what visually appeared to be areas with the potential for low, medium and high yields on the July 1998 photo of the three fields. When the location of the plots is overlaid onto the corresponding classified images, it is clear that the plots were not optimally placed (Figure 1).

Comparison of the corrected average plot yields to the average yield of the corresponding yield map ranges produced mixed results. The yield map averages of the low ranges at the Sumner and Mangum farms were much lower than the yields of the plots. Consequently, use of the plots to predict yields would have resulted in significant overestimation. In contrast, the relative error for the other seven comparisons were generally good and in three instances was within 10% (Table 2). Results of Student's *t*-test showed that the mean of plot yields was not significantly different

Table 2. Hand-harvested plot yields as compared to yield ranges of the corresponding yield map with the best agreement

	Plot yield (seed cotton)				Yield map (seed cotton) (kg/ha)		Relative[b] error	Plot yield seed cotton				Yield map seed cotton lb/ac	
Plot	Kg	Plots (kg/ha)	Avg. (kg/ha)	Picker[a] Equiv. (kg/ha)	Range	Range Avg.	(%)	lb	Plots lb/ac	Avg. lb/ac	Picker Equiv. lb/ac	Range	Range Avg.
Summer farm													
Low	19.6	1951	2257	2032	0–2133	368	452	43.1	1738	2011	1809	0–1900	328
Low	25.7	2563						56.6	2283				
Medium	32.0	3193	3349	3014	2133–3312	2641	14	70.5	2844	2983	2685	1900–2950	2352
Medium	35.2	3505						77.4	3122				
High	36.1	3595	3785	3407	3312–above	3568	−5	79.4	3202	3372	3034	2950–above	3178
High	39.9	3976						87.8	3541				
Means (*P*-value)[c]				2818		2192	($p=0.37$)				2510		1953
Mangum farm													
Low	2.2	1630	1630	1467	0–1684	638	130	4.8	1452	1452	1307	0–1500	568
Medium	2.9	2174	3023	2721	1684–3144	2572	6	6.4	1936	2693	2423	1500-2800	2291
Medium	5.2	3872						11.4	3449				
High	5.4	4008	4059	3653	3144–above	3823	−4	11.8	3570	3615	3254	2800—above	3405
High	5.5	4109						12.1	3660				
Means (*P*-value)[c]				2614		2344	($p=0.46$)				2328		2088
Willis farm													
Low	1.2	884	1070	963	0–1628	1172	−18	2.6	787	953	858	0–1450	1044
Low	1.7	1256						3.7	1119				
Medium	3.0	2276	2445	2201	1628–3088	2599	−15	6.7	2027	2178	1960	1450–2750	2315
Medium	3.5	2615						7.7	2329				
High	3.7	2784	2784	2506	3088–above	3498	−28	8.2	2480	2480	2232	2750–above	3116
Means (*P*-value)[c]				1890		2423	($p=0.15$)				1683		2158

[a]100% hand harvesting efficiency and 90% picker-harvesting efficiencies are assumed. Hand-harvested yields are reduced by 10% for comparison to yield map yields.
[b]Relative error = (picker equivalent of average plot yield−average yield map yield)/average yield map yield × 100.
[c]Based on Student's paired *t*-test.

from the mean of yield map ranges at Sumner and Mangum Farms. At the Willis Farm, however, mean yields were significantly different at the $P = 0.15$ level (Table 2).

Plots randomly selected from classified images

The comparison between the yields of the cells randomly selected from the classified images and corresponding yield map parameters resulted in 100% of cell yields being within the corresponding yield map ranges (Table 3). Of the 30 possible comparisons (3 cells × 10 fields), 25 were available because in some images a homogeneous area representative of given yield category was not available. For example, in fields A001 (Figure 7), A002, A010, and A012 (Figure 2), areas classified as low yielding were found only at the edges of the field or alongside roadways or waterways.

Comparison of the cell yield to the average range yield was also good, particularly in the medium and high categories. The average absolute relative error between cell yield and average range yield was 43%, 11%, and 8%, for the predicted low, medium, and high categories, respectively. Results of student's *t*-test showed that the mean of cell yields was not significantly different from the mean of yield map ranges in the low, medium, or high yield categories (Table 3). Consequently, it appears feasible to use small hand harvested plots for assigning yields to a classified image and thus replace a conventional yield map. It is prudent, however, to use the classified image to locate the plots rather than the raw aerial photograph.

Discussion and conclusions

This method offers potential for offering cotton farmers early-season maps that predict the spatial distribution of yield. Although these maps can not provide magnitudes, they clearly show the resulting yield patterns. With inherent knowledge of past performance, farmers can use this information to allocate resources, address crop growth problems, and, perhaps, improve the profitability of their farm operation.

Assigning magnitudes to the high, medium, and low yield categories is desirable, and perhaps could be accomplished with crop growth models in the early season. In the absences of a conventional yield map, projected yield values could also be assigned at the end of the season from representative hand sampling in delineated areas prior to mechanical harvesting provided these plots are properly located. Using a classified image in conjunction with the original image is probably the best way to locate plots.

On average, the best agreement between classified images and yield maps occurred 9.9 weeks after planting because yield patterns were established early in the season. As the season progressed, the yield patterns were less evident, primarily because the canopy closed and masked spatial patterns.

The best agreement was obtained with a 3-class unsupervised classification which separated the image into areas with high, medium, and low yield potential. Although

Table 3. Comparison of yields of cells randomly selected from classified images to yield ranges of the corresponding yield map

		Predicted yield–low (red)					Predicted yield – high (yellow)					Predicted yield – H (blue)				
Field	Photo date	Cell yield[a]	Range avg.[b]	Rel error(%)[c]	Range[d]	In range?	Cell yield	Range avg.	Rel error(%)	Range	In range?	Cell yield	Range avg.	Rel error(%)	Range	In range?
All values are in (kg/ha)																
Willis	7/8/1998	1080	1172	−8	≤ 2046	Y	2543	2599	−2	2046–3026	Y	3355	3498	−4	3026 ≤	Y
Mangum	7/8/1998	734	639	15	≤ 1606	Y	2409	2572	−6	1606–3099	Y	3775	3824	−1	3099 ≤	Y
Sumner	7/8/1998	1503	1077	40	≤ 2161	Y	3015	2728	11	2161–3079	Y	3431	3515	−2	3079 ≤	Y
Willis	7/4/1999	695	1235	−44	≤ 1941	Y	2610	2408	8	1941–2787	Y	2949	3200	−8	2787 ≤	Y
Home	7/4/1999	1390	1283	8	≤ 2004	Y		2299		2004–2563		2722	2864	−5	2563 ≤	Y
A001	7/5/2000		534		≤ 862		1074	1147	−6	862–1344	Y	1515	1513	0	1344 ≤	Y
A002	7/5/2000		138		≤ 455		848	1085	−22	455–1263	Y	1371	1555	−12	1263 ≤	Y
A006	7/5/2000	531	219	142	≤ 578	Y	1134	1131	0	578–1279	Y	2178	1602	36	1279 ≤	Y
A010	7/18/2000		27		≤ 73		1056	1203	−12	73–1517	Y	1792	1885	−5	1517 ≤	Y
A012	7/18/2000		58		≤ 225		966	719	34	225–988	Y	1608	1546	4	988 ≤	Y
means (P-value)[e]		989	638	($P = 0.37$)			1740	1789	($P = 0.91$)			2469	2500	($P = 0.68$)		
All values are in (Ib/ac)																
Willis	7/8/1998	962	1044	−8	≤ 1822	Y	2265	2315	−2	1822–2695	Y	2988	3116	−4	2695 ≤	Y
Mangum	7/8/1998	653	569	15	≤ 1430	Y	2146	2291	−6	1430–2760	Y	3362	3406	−1	2760 ≤	Y
Sumner	7/8/1998	1338	959	40	≤ 1925	Y	2685	2430	11	1925–2742	Y	3056	3131	−2	2742 ≤	Y
Willis	7/4/1999	619	1100	−44	≤ 1729	Y	2325	2145	8	1729–2482	Y	2627	2850	−8	2482 ≤	Y
Home	7/4/1999	1238	1143	8	≤ 1785	Y		2048		1785–2283		2424	2551	−5	2283 ≤	Y
A001	7/5/2000		476		≤ 768		957	1021	−6	768–1197	Y	1349	1348	0	1197 ≤	Y
A002	7/5/2000		123		≤ 405		756	966	−22	405–1125	Y	1221	1385	−12	1125 ≤	Y
A006	7/5/2000	473	195	142	≤ 515	Y	1010	1007	0	515–1139	Y	1940	1427	36	1139 ≤	Y
A010	7/18/2000		24		≤ 65		941	1072	−12	65–1351	Y	1596	1679	−5	1351 ≤	Y
A012	7/18/2000		52		≤ 200		861	641	34	200–880	Y	1433	1377	4	880 ≤	Y

[a]Yield map yield of 2.5 × 2.5 m cell randomly located within a uniform area of low, medium, or high yield on a classified image.
[b]Average yield of the yield range within which the randomly selected cell was located.
[c]Relative error = (cell yield−range avg)/range avg*100.
[d]Yield map yield range within which the randomly selected cell was located.
[e]Based on Student's paired *t*-test.

the overall agreement numbers were not impressive and the average best overall agreement was only 52%, the visual similarities between the July classified images and the yield maps were striking.

There is real potential for developing predictive yield maps from low-level aerial photographs. Because it appears that yield patterns are established early in the season, yield projections can be made as early as 10 weeks into the crop season. This technology is inexpensive and fairly straightforward, and ideally suited as a service to be offered to farmers by a crop consultant or a cooperative. The slide film and slide scanner used in the study can now be replaced by high resolution digital camera which would eliminate the cost of processing film and scanning images. The high-end image analysis package used during the project was necessary for evaluating the techniques presented here and is not necessary for conducting unsupervised classifications of digital images. Images can be classified using readily available desktop photo-editing software such as Paint Shop Pro®, Microsoft Photo Editor®, or other similar packages. Images that will be used only for classification need not be rectified.

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