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RELATIONSHIP OF FILM OPTICAL DENSITY TO YIELD INDICATORS[1]

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[1] Contribution from the Research and Development Branch, Standards and Research Division, Statistical Reporting Service, U.S.D.A. in cooperation with the Texas Agricultural Experiment Station, Texas A&M University. This study was supported in part by NASA Contract No. W12-996

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1. Introduction

A study was made to test the relationships between measurements of plant growth and development characteristics made using remote sensing techniques and yield determinants from actual field counts and measurements. This study was conducted in the Lower Rio Grande Valley of Texas. The crops were cotton, grain sorghum, carrots, cabbage, and onions.

The objectives were to study (a) relationships among optical densities of aerial Ektachrome[3/] infrared film and yield determinants and (b) methods of collecting ground data needed for analysis.

This project attempted to relate information available from aerial photography to crop yield. Research of this type is needed to fully utilize the vast amount of information soon to become available from satellites and supplementary aircraft flights.

2. Methods and Procedures

Sample fields were selected within existing flight test lines to provide variations in maturity, yield potential, plant population and soils. Field work on cotton and grain sorghum started in early July 1968 with a second observation on cotton about 30 days later. The vegetable work began in December 1968. Observations were made monthly until the crops were harvested. The last observation was made just prior to harvest and was the only one used in the analysis.

3/ The USDA neither guarantees nor warrants the standard of a product once the use of the name by the Department implies no approval of the product to the exclusion of others which may also be suitable.

Aerial photographs were obtained, when possible, to correspond with the date of the field observations. The plane was flown at 2,000 and 4,000 feet above ground level. A Zeiss aerial camera and Kodak Ektachrome infrared aero film was used.

Five cotton fields were observed in July and four of the same fields were observed in August. Each field was divided into quarters with two sample units or plots being randomly located within each quarter. Cotton plots were two adjacent rows 10 feet long. All cotton plants were counted within each plot. Cotton fruit counts such as squares, blooms, small bolls, large unopened bolls, partially open and open bolls, were made on the first and last plant of each row within the plots.

To locate the plots on the aerial photograph, fields were quartered on the photograph. The quarter became the sampling unit for the aerial survey. The estimated per acre fruit counts for each quarter were the ground truth variables compared with variables measured from the photographs. The photograph was scanned by quarters with an isodensitracer to get optical density readings. This method assumes that significant differences may exist between quarters. The field counts were analyzed using hierarchical classification. No significant differences were found among quarters within fields for total bolls used as yield indicators where the coefficient of variation within quarter was found to be 58.5 percent. Significant differences did exist in counts between the sample fields. The optical densities between fields also showed significant differences.

During the August observations, in two of the four fields, eight plots were marked for aerial identification by placing a 4-foot-square plywood marker in front of each plot. These markers were mounted on tripods about 5 feet high. The isodensitracer readings were then obtained for the area just behind the marker. This procedure for locating the plots on the photograph proved very satisfactory. The same counts and measurements were made in August as were made in July.

Grain sorghum was nearly mature at the time of the initial observations, so only one month's data were obtained. The grain sorghum fields were quartered also with two sample plots randomly located in each quarter. Sample units for grain sorghum were two adjacent rows 15 feet long. All the stalks, stalks with heads or shoots, heads and shoots, and heads with kernels were counted within each plot. The per acre counts for sorghum were analyzed in the same manner as for cotton.

The number of heads with kernels did not differ significantly between quarters within fields. The coefficient of variation within quarter was found to be 21.1 percent.

During December 1968, sample plots were laid out in three cabbage fields (one red cabbage), two carrot fields and two onion fields. In an effort to achieve a greater variation within fields than was observed for cotton and sorghum, five plots were randomly located in the field. In addition, within the same beds as the randomly located plots, an additional plot was located in an area where plant population differed considerably from the randomly located plot. Using this scheme it was possible to observe plots with large differences in plant densities in five out of the seven

vegetable fields.

In the cabbage plots, the total number of plants in three adjacent beds 15 feet long were counted; average plant height, size and weight of head at harvest were determined from a random sample of 18 plants per plot. For carrots, the total number of plants were counted in three adjacent beds 9 feet long; height of plants and size of crown were measured for a random sample of carrots from each plot. Also weight of carrots per plot was obtained at harvest. Data collected for onions were similar to those collected for carrots, except the onion plots were three adjacent beds 15 feet long and the diameter of bulb was measured. The percent ground cover was estimated for all vegetable crops studied.

To locate the sample vegetable plots on aerial photos another scheme was tried. The length and width of each field and the distance to each plot from the edge of the field were measured. From these coordinates the exact location of the plots could be scaled on the photograph.

3. Photography

The photographs were made using 9 1/2-inch Ektachrome and Ektachrome infrared films, exposed in a K-17 or a Zeiss camera at scales of 1/3000 to 1/6000. Film densities of the sample plots were obtained by scanning the transparencies with an isodensitracer. Densities for each of the three layers of film were measured by using appropriate filters in the isodensitracer. Average density readings were then related to the plant counts and measurements obtained from the sample plots.

4. Results

Usuable photography was not always acquired for the same day as the ground data were collected. In several instances the time difference was as much as a week to 10 days for vegetables. Some of the yield indicators such as plant count, height of plant and number of heads with kernels are not critically time dependent so the relationships are limited only by the variation due to environmental effects on the photography. However, other yield indicators such as number of cotton bolls and open cotton bolls are greatly affected by time. Photographic coverage of some parts of the cotton and grain sorghum fields was unsatisfactory because of cloud cover or cloud shadows. These weather conditions and the small sample size limit the inferences that can be made from the relationships found.

Usable photography in July was obtained for just one of the grain sorghum fields. Sample line readings were obtained with the isodensitracer using no filter by quarters, with an average calculated for each quarter in the field. The simple correlation of the average film optical densities with the estimated number of heads with kernels per quarter (or per plot) was 0.429. This correlation was not significant.

July photography was usable for only one cotton field and coverage was not complete for that field. Simple correlation of the average densities without a filter and the number of large and small bolls (or total bolls) per quarter was -0.816. Again this correlation only suggests there may be a relationship. Since the number of plants is constant at this time of year, only the correlation of total bolls for July was calculated. The number of open bolls was negligible at this early date.

Density readings were obtained from the August photographs for each plot in the two cotton fields containing the 4 x 4 foot markers. The average of about 70 density readings of each layer of the film was obtained by using colored filters in the isodensitracer. Each colored filter measures the density of one of the three layers of aerial infrared film. Readings with no filter measure the density to "white" light through the three dye layers of the film. Therefore, each of the four densities could be sensitive to a certain phenomenon in a different way. To obtain a measure of filter effect, average readings with each filter were correlated with all other filters. All filter combinations were significantly correlated except red with blue and green with blue in cotton Field 2. When fields were combined, all combinations were highly correlated, with correlation coefficients ranging from .70 to .93 (see Table 1). The readings using (red, green or blue) filters were all highly correlated with readings when no filter was used. This indicates that the response of the film was similar in the colors produced in each dye layer.

Cotton yield indicators considered were per acre estimates of open bolls, number of open plus partially open bolls, the combined number of open, partially open and large unopened bolls, and number of plants derived for each plot. The estimates are products of the estimated number of plants per acre and estimated fruit counts per plant.

The estimated average number of plants per acre in Field 1 was 29,000, with individual plots ranging from 12,000 to 42,000. In field 2, the average number of plants was 43,000, with individual plots ranging from 26,000 to 46,000. The average number of open and partially open bolls was estimated at 20,000 in Field 1 compared with 30,500 in Field 2. Their respective ranges were 16,000 to 97,000 and 0 to 112,000. The average and range of optical densities for the two fields by filter were:

Cotton Optical Densities

Filter	Field 1		Field 2	
	Average	Range	Average	Range
No	.7363	.5653 - 1.0671	1.0152	.7496 - 1.2946
Red	.3900	.1868 - 1.0271	.5942	.2434 - 1.2968
Blue	.7163	.4566 - 1.0904	1.1392	.8062 - 1.4078
Green	.9938	.9216 - 1.1847	1.2957	1.1203 - 1.4611

Green filter readings were the highest. The red filter readings indicated the most variability.

Correlations among average optical densities by filters and yield indicators by plots are given in Table 2. In Field 1, the relationships for the variables, number of open and partially open bolls to density readings were statistically significant for no filter and red filter but in Field 2 none of the yield indicators were significantly correlated with densities. When both fields were combined using a red filter and no filter, significant correlations $r = 0.73$ and $r = 0.64$, respectively, were found between open plus partially open bolls and optical density. The correlation coefficients between the two fields were not significantly different. The number of plants per acre was not significantly correlated with density in either field or the two combined.

Yield indicators for vegetables such as number of plants, size of head, size of bulb and weight per plot are directly related to yield. Percent of vegetative cover and height of plant may not be directly related to yield but may be indicators of plant vigor or condition of crop which are related to yield. Size of carrot crowns was assumed to be related to the size or weight of carrots. That is, a large crown should indicate a large or heavy carrot which would affect yield.

Carrot plant numbers per plot averaged 252 in Field 1 and 159 in Field 2 with ranges of 34 to 561 plants and 28 to 282 plants, respectively. The average and range of density readings for the two fields, respectively, by filter were:

Carrot Optical Densities

Filter	Field 1		Field 2	
	Average	Range	Average	Range
No	.8739	.7329 - .9616	1.1037	.8839 - 1.1481
Red	.6108	.5476 - .7063	.7707	.6952 - .8750
Blue	1.0482	.8073 - 1.1514	1.3590	1.0071 - 1.4445
Green	1.0238	.8029 - 1.1858	1.2535	.9549 - 1.3224

The ranges of the density readings indicate the variability found within fields. The weight per plot of harvested carrots averaged about the same in the two fields -- 26.0 pounds in Field 1 and 22.0 pounds in Field 2.

Significant correlations between optical density and yield indicators were observed for the plots in both carrot fields. When the two fields were combined, size of crown was the only yield indicator that was significant for all four filter readings (see Table 3).

The cabbage fields varied in maturity and variety. The red cabbage in Field 3 had matured about 45 more days than that in the other two fields. The average number of plants per plot was 61.9 in Field 1, 111.6 in Field 2 and 103.8 in Field 3. The average percent of cover for the three fields, respectively, was 76.3, 82.0, and 46.0. The average density for the three fields using a red filter was .5309, .3844, and .6808, respectively. The correlation between optical density and percent cover for fields combined was -.640 which was highly significant. In individual fields, the relationships among yield indicators and filters were not consistent regardless of crop maturity or variety. When fields were combined, six of the twelve correlations computed among filters and number of plants, weight per plot, and size of head were significant. The correlations for number of plants were -.630 with no filter and -.560 with a blue filter. Weight per plot had a correlation of .382 with no filter and .416 with a green filter. For cabbage, size of head had a relationship of .551 for no filter and .473 with a red filter (see Table 4).

Within the individual fields of onions, only a few correlations were significant. In Field 1 the correlation for number of plants with density was .913 with no filter, .914 with red filter, .882 with a blue filter and .902 with a green filter. In Field 2, which was the only field for which weight per plot was obtained, correlation of yield with density were .653 with a blue filter and .709 with a green filter. Part of the reason for the lack of correlation within the fields may have been the small amount of variation in the density readings. For example, the average and range of the readings by field and filter were:

Onion Optical Densities

Filter	Field 1		Field 2	
	Average	Range	Average	Range
No	.5476	.4765 - .5931	.8528	.6963 - .8928
Red	.6974	.5909 - .9339	.5620	.4765 - .6774
Blue	.5598	.4677 - .8462	.9294	.8018 - 1.0759
Green	.6286	.5420 - .8217	.9128	.8306 - 1.0426

When the onion fields were combined, all the correlations were significant for all yield indicators and filters. The correlations for number of plants were very good, ranging from .884 with a red filter to .910 with a green filter (see Table 5). The average number of plants was 387.6 in Field 1 and 753.7 in Field 2.

Conclusions

Ground data on yield indicators from small plots can be related to film density of aerial photographs of the small plots. These relationships make it possible to estimate crop yields with remote sensing techniques. It may not be possible to estimate yields for small areas directly with the precision desired but small areas may be classified as to yield potential based on selected yield components. By using double sampling techniques acceptable current estimates should be possible, but will mean that for every forecast date a certain amount of ground data would have to be collected.

In these studies the reflectance was measured at a time of the season when the plants and pertinent yield characteristics were established. The possibility that similar relationships may exist earlier in the crop year is, of course, highly speculative, but it is generally believed that the important yield components become the sole or dominant factors in determining yield per acre as the crop approaches maturity. During the period just proir to maturity the crop nearly covers the ground and minimizes the effects of nuisance variables associated with soil.

It is recommended that direct readings for plots be used in order to measure more accurately the correlation between film density and yield components. If field quarters are used, more sample plots would be needed within quarters to provide an adequate estimate for the yield components in an area as large as a quarter.

Table I -- Cotton: Correlation coefficients among average optical density readings for red, green, blue and no filters by fields and fields combined, August 1968

Field number and filter type	Filter		
	Red	Green	Blue
Field 1:			
No.	.947**	.940**	.970**
Red.		.734*	.881**
Green.			.978**
Field 2:			
No.	.940**	.873**	.810*
Red.		.763*	.672
Green.			.589
Fields combined:			
No.	.898**	.926**	.913**
Red.		.806**	.696**
Green.			.820**

For individual fields: *Correlations $> \pm$ .707 are significant at the 5 percent level. **Correlations $> \pm$ .834 are significant at the 1 percent level.

For combined fields: *Correlations $> \pm$ .497 are significant at the 5 percent level. **Correlations $> \pm$ .623 are significant at the 1 percent level.

Table II -- Cotton: Correlation coefficients among average optical density readings and yield indicators by field and filter, August 1968

Field number and yield indicator	Est. ave. no. per acre (Thousands)	Filter			
		No	Red	Green	Blue
Field 1:					
Open bolls	21	.887	.768	.866	.829
Open and partially open	40	.787	.790	.643	.657
Open, partially open and large	205	-.388	-.417	-.452	-.458
Number of plants	29	-.229	-.146	-.460	-.364
Field 2:					
Open bolls	37	.176	.397	.029	-.132
Open and partially open	51	.495	.657	.344	.192
Open, partially open and large	161	.102	.268	-.063	-.145
Number of plants	33	.056	.008	.003	.036
Fields combined:					
Open bolls	29	.552	.578	.506	.449
Open and partially open	46	.640	.732	.517	.475
Open, partially open and large	183	-.238	-.127	-.326	-.363
Number of plants	31	.125	.040	.079	.090

For individual fields: *Correlations $> \pm$ .707 are significant at the 5 percent level. **Correlations $> \pm$ .834 are significant at the 1 percent level.

For combined fields: *Correlations $> \pm$ .497 are significant at the 5 percent level. **Correlations $> \pm$ .623 are significant at the 1 percent level.

Table III -- Carrots: Correlation coefficients among average optical density and yield indicators by field and filter, 1969

Field number and yield Characteristic	Average per plot	Filter			
		No	Red	Blue	Green
Field 1:					
Number of plants	252.3	+.509	-.696*	+.604	+.675*
Percent of cover	58.0	+.653*	-.374	+.678*	+.716*
Height of plant	12.4 in.	+.620	-.547	+.680*	+.735*
Weight per plot	26.0 lbs.	+.574	-.488	+.624	+.670*
Size of crown (diameter)	0.92 in.	-.263	+.658	-.338	-.374
Field 2:					
Number of plants	159.3	+.763*	-.057	+.857**	+.873**
Percent of cover	49.5	+.787**	+.053	+.799**	+.805**
Height of plant	12.6 in.	+.600	-.103	+.769**	+ 736*
Weight per plot	22.2 lbs.	+.744*	-.096	+.851**	+.844**
Size of crown (diameter)	1.07 in.	+.628	+.602	+.556	+.187
Fields combined:					
Number of plants	205.8	-.002	-.565**	+.369	+.198
Percent of cover	53.8	+.209	-.300	+.292	+.353
Height of plant	12.5 in.	+.426	-.138	+.544*	+.583**
Weight per plot	24.1 lbs.	+.235	-.324	+.348	+.404
Size of crown (diameter)	1.0 in.	+.632**	+.731**	+.580**	+.573**

For individual fields: *Correlations $> \pm$ .632 are significant at the 5 percent level. **Correlations $> \pm$ .765 are significant at the 1 percent level.

For combined fields: *Correlations $> \pm$ .444 are significant at the 5 percent level. **Correlations $> \pm$ .561 are significant at the 1 percent level.

Table IV -- Cabbage: Correlation coefficients among average optical density and yield indicators by field and filter, 1969

Field number and yield Characteristics	Average per plot	Filter			
		No	Red	Blue	Green
Field 1:					
Number of plants	61.9	-.507	-.686*	-.186	-.140
Percent cover	76.3	-.041	-.358	+.162	+.182
Height of plant	11.4 in.	-.643*	-.637*	-.218	-.285
Weight per plot	100.6 lbs.	-.623	-.663*	-.343	-.405
Size of head (circumference)	14.9 in.	-.396	-.526	-.365	-.564
Field 2:					
Number of plants	111.6	-.174	-.380	-.073	+.490
Percent of cover	82.0	-.171	-.270	-.052	+.825**
Height of plant	11.1 in.	+.020	+.150	-.028	-.163
Weight per plot	120.6 lbs.	-.468	-.541	-.420	+.170
Size of head (circumference)	10.9 in.	-.089	+.055	-.118	-.164
Field 3:					
Number of plants	103.8	+.098	+.355	+.098	+.116
Percent of cover	46.0	+.377	+.450	+.375	+.370
Height of plant	8.2 in.	+.753*	+.708*	+.763*	+.767**
Weight per plot	8.9 lbs.	+.232	+.184	+.247	+.110
Size of head (circumference)	9.2 in.	+.114	+.217	+.045	+.170
Fields combined:					
Number of plants	92.4	-.630	-.190	-.560**	-.355
Percent of cover	68.1	+.071	-.640**	+.138	+.473**
Height of plant	10.2 in.	+.257	-.565**	+.288	+.488**
Weight per plot	76.7 lbs.	+.382*	+.308	-.089	+.416*
Size of head (circumference)	11.7	+.551**	+.473**	+.145	+.202

For individual fields: *Correlations $> \pm .632$ are significant at the 5 percent level. **Correlations $> \pm .765$ are significant at the 1 percent level.

For combined fields: *Correlations $> \pm .361$ are significant at the 5 percent level. **Correlations $> \pm .463$ are significant at the 1 percent level.

Table V -- Onions: Correlation coefficients among average optical density and yield indicators by field and filter, 1969

Field number and yield Characteristic	Average Number per plot	Filter			
		No	Red	Blue	Green
Field 1:					
Number of plants	387.6	+.913**	+.914**	+.882**	+.902**
Percent of cover	14.3	+.578	+.612	+.619	+.617
Height of plant (inches)	15.3	+.349	+.237	+.335	+.371
Size of bulb(diameter in.)	1.6	-.435	-.391	-.396	-.372
Field 2:					
Number of plants	753.7	+.209	+.136	+.170	+.191
Percent of cover	51.5	+.548	+.563	+.568	+.555
Height of plant (inches)	11.8	-.271	-.297	-.289	-.293
Weight per plot (lbs.)	103.6	+.612	-.361	+.653*	+.709*
Size of bulb(diameter in.)	2.0	-.197	-.140	-.065	-.126
Fields combined:					
Number of plants	570.6	+.908**	+.884**	+.896**	+.910**
Percent of cover	32.9	+.879**	-.512*	+.894**	+.914**
Height of plant	13.6	-.749**	-.757**	-.756**	-.750**
Size of bulb (diameter)	1.8	+.491*	-.591**	+.544*	+.556*

For individual fields: *Correlations $> \pm .632$ are significant at the 5 percent level. **Correlations $> \pm .765$ are significant at the 1 percent level.

For combined fields: *Correlations $> \pm .444$ are significant at the 5 percent level. **Correlations $> \pm .561$ are significant at the 1 percent level.