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# Remote Sensing of Sulfur Dioxide Effects on Vegetation

## Photometric Analysis of Aerial Photographs

## Interagency Energy/Environment R&D Program Report

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# REMOTE SENSING OF SULFUR DIOXIDE EFFECTS ON VEGETATION--PHOTOMETRIC ANALYSIS OF AERIAL PHOTOGRAPHS

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## DISCLAIMER

ABSTRACT

Spectral reflectances were measured by tri-band densitometry of aerial color-infrared photographs of soybean [Glycine max (L.) Merr.] fields that had been affected by sulfur dioxide ($SO_2$) emissions from large, coal-fired power plants in northwestern Alabama and western Tennessee. The photographs were photometrically calibrated.

Results indicate that, at very light levels of foliar injury, the infrared-to-red reflectance ratio decreased with increasing injury. This behavior was in accordance with theory. However, at moderate and severe levels of injury, the ratio increased with injury. The infrared component increased, and the red component decreased as injury level rose. Two other ratios of reflectance (infrared-to-green and red-to-green) did not correlate significantly ($\alpha = 0.05$) with injury. The best indicator of crop yield was green band reflectance, but the red and infrared bands were nearly as good. Ratios produced no significant correlations with yield. The yield variable actually increased with the level of injury, apparently because of field-to-field variations in canopy density.

This report was submitted by the Tennessee Valley Authority, Office of Natural Resources, in partial fulfillment of Energy Accomplishment Plan 80 BDJ, under terms of Interagency Agreement D8-E721-DJ with the Environmental Protection Agency. Work on this phase of the project was completed as of September 1978.

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SECTION 1

# INTRODUCTION

## GENERAL

The purpose of the project is to study the acute effects of sulfur dioxide ($SO_2$) emissions from large, coal-burning power plants on vegetation. The technique of remote sensing--a term used by earth scientists to describe the study of phenomena from a distance, without having the sensor in direct contact with the phenomena being sensed--is the tool chosen to accomplish this purpose.

Problems encountered during traditional field surveying include the time-consuming nature of field surveillance, inaccessibility of many areas, and subjectivity of descriptions of foliage color. Remote measurement of reflectance with calibrated instruments, followed by objective analysis of data in the laboratory, may bypass some of these problems.

The color of a leaf may be described merely as a hue, or it may be defined objectively by measuring reflected radiation. A spectral plot of radiant energy reflected by either a plant canopy or an individual leaf can define (1) the color of the leaf or canopy in the visible spectrum and (2) its radiant energy characteristics in the adjacent near-infrared spectrum. When a plant is stressed by $SO_2$ or some other agent, the shape of its radiant energy curve changes.[1]

The classical procedure for acquiring radiant energy data in the field involves making measurements at discrete points with a portable spectroradiometer.[2] Comparable data may also be obtained directly by making point measurements of the optical density of aerial photographs. With appropriate calibrations, calculations, and corrections, either technique can yield spectral reflectance data that may indicate $SO_2$-induced stress. This report describes "photometric analysis," the aerial photographic technique for acquiring reflectances.

This report is the first of two reports on remote sensing of reflectance characteristics of $SO_2$-affected vegetation. The second report describes spectroradiometry, in which a radiometer is used for laboratory-based measurements of stressed soybeans, winter wheat, and cotton plants. Research on a third technique, concerning close-range overhead photography of test plots of $SO_2$-stressed soybeans, was also undertaken. However, results of these close-range photographic experiments were inconclusive, and further work is being done before publishing them.

The primary hypotheses to be tested in this study are that (1) spectral reflectances are related to the levels of foliar injury to soybeans under the experimental conditions imposed on the study, and (2) reflectance is also related to yield of the crop.

# SECTION 2

# CONCLUSIONS AND RECOMMENDATIONS

## CONCLUSIONS

Overflights of two coal-fired power plants were made to photograph foliar effects of $SO_2$ emissions on soybeans. Spectral reflectance data were obtained from the color-infrared photographs, after which the statistical means and standard deviations for reflectance were compared with the levels of $SO_2$ injury for each field of soybeans.

Several statistically significant ($\alpha = 0.05$) relationships between reflectance and injury and between reflectance and yield were discovered.

1. At very light levels of $SO_2$ injury to soybeans, where less than about 5 percent of the foliage was chlorotic,* the ratio of infrared to red (IR/R) reflectance decreased with the level of injury, as predicted. However, at higher levels of injury, where 20 percent or more of the foliage was chlorotic or necrotic,** the IR/R ratio increased with the level of injury. This behavior is the opposite of what was expected. The IR component increased and the R component decreased as percentage injury rose above 20 percent, thus raising the ratio. Two other reflectance ratios, infrared to green (IR/G) and red to green (R/G), did not correlate significantly with injury levels.

2. Single-band reflectances were not significantly related to injury. This includes the R, G, and IR bands.

3. The best indicator of yield was G reflectance, which was positively correlated (significant, $\alpha = 0.05$). The R and IR bands were nearly as good. Ratioing of the spectral bands produced no significant relationships.

## RECOMMENDATIONS

The experiments described in this report involved comparing the field-to-field variations in reflectance with levels of injury and yield for each field. The work should be repeated in more detail, concentrating on a few fields of mature soybeans within which detailed surveys of the patterns of reflectances and foliar injury are known. This procedure should isolate many of the masking variables described above.

Because the effects of the masking variables cannot be completely eliminated, future investigations should concentrate on fields of mature soybeans that have a nearly continuous canopy and little infestation by weeds.

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*Chlorosis is defined as a visible yellowing of leaf tissue. The markings may be acute or chronic, permanent or temporary.

**Necrosis is acute injury characterized by marginal or intercostal areas of dead leaf tissue.

The relationship of reflectance to yield needs further study. In particular, the increase in the IR/R reflectance ratio with increasing injury warrants further investigation, because the findings are the reverse of current theories published on the subject.

# SECTION 3

# METHODS AND INSTRUMENTS

## OVERFLIGHTS

Overflights of two of TVA's 12 coal-fired power plants were performed during the 1977 growing season when the foliar effects of $SO_2$ were still visible to ground observers. We were focusing on the effects on soybeans [Glycine max (L.) Merr.], an important cash crop in the Tennessee Valley, growing near Colbert Steam Plant, in northwestern Alabama; and Johnsonville Steam Plant, in western Tennessee (Figures 1 and 2).

Aerial color-infrared photographs were obtained from altitudes ranging from 500 to 1800 m above ground level. Large-format aerial mapping cameras equipped with 152-mm focal-length lenses were used. The resulting range of image scales varied from about 1:3000 for the low-altitude runs to 1:12,000 for the high-altitude runs. TVA used its Wild RC-8 camera to obtain coverage of Johnsonville, and EPA used one Wild RC-10 to fly Johnsonville and another to fly Colbert. EPA also flew a Daedelus multispectral scanner (MSS) over Colbert for TVA. The results of the MSS data analysis will be published later as a separate report.

## PHOTOMETRIC ANALYSIS

The objective of photometric analysis was to detect $SO_2$ effects in soybean fields by measuring differences in spectral reflectance. A second objective was to relate the reflectance measurements to yield of soybeans. To do this, systematic errors in the photographs were measured and eliminated through an image calibration process. The errors resulted from film processing, atmospheric effects, and variation in illumination. The reflectance patterns and trends were then compared with ground-truth data on $SO_2$ effects to ascertain whether any relationships existed.

Photometric analysis involved use of the Calspan Scene Color Standard (SCS) technique. Specific details of the SCS technique have been published.[5] The basics of photometric analysis have been described expertly by Lillesand in an introductory text.[4] Lillesand calls the technique photographic radiometry. The SCS procedure permits determination of the atmospheric and illumination variables directly from the photograph. One advantage is that no a priori knowledge of the reflectances of ground objects is necessary, because all the information for calculating reflectances is available from the photograph itself. Reflectances of specific objects, such as individual soybean plants on large-scale images or integrated spot canopy measurements on small-scale images, may be calculated from spot density measurements. Two densitometer apertures, 1.0 mm and 150 µm, were used. The 1-mm densitometer aperture was adequate for canopy sampling on the 1:12,000-scale photographs, where the spot covered a ground area 12 m in diameter. The 150-µm aperture was used to make density measurements in shadow areas. Also measured in the calibration process were images of asphalt surfaces (roofs and roads) and bare soil. Reflectances from these surfaces are

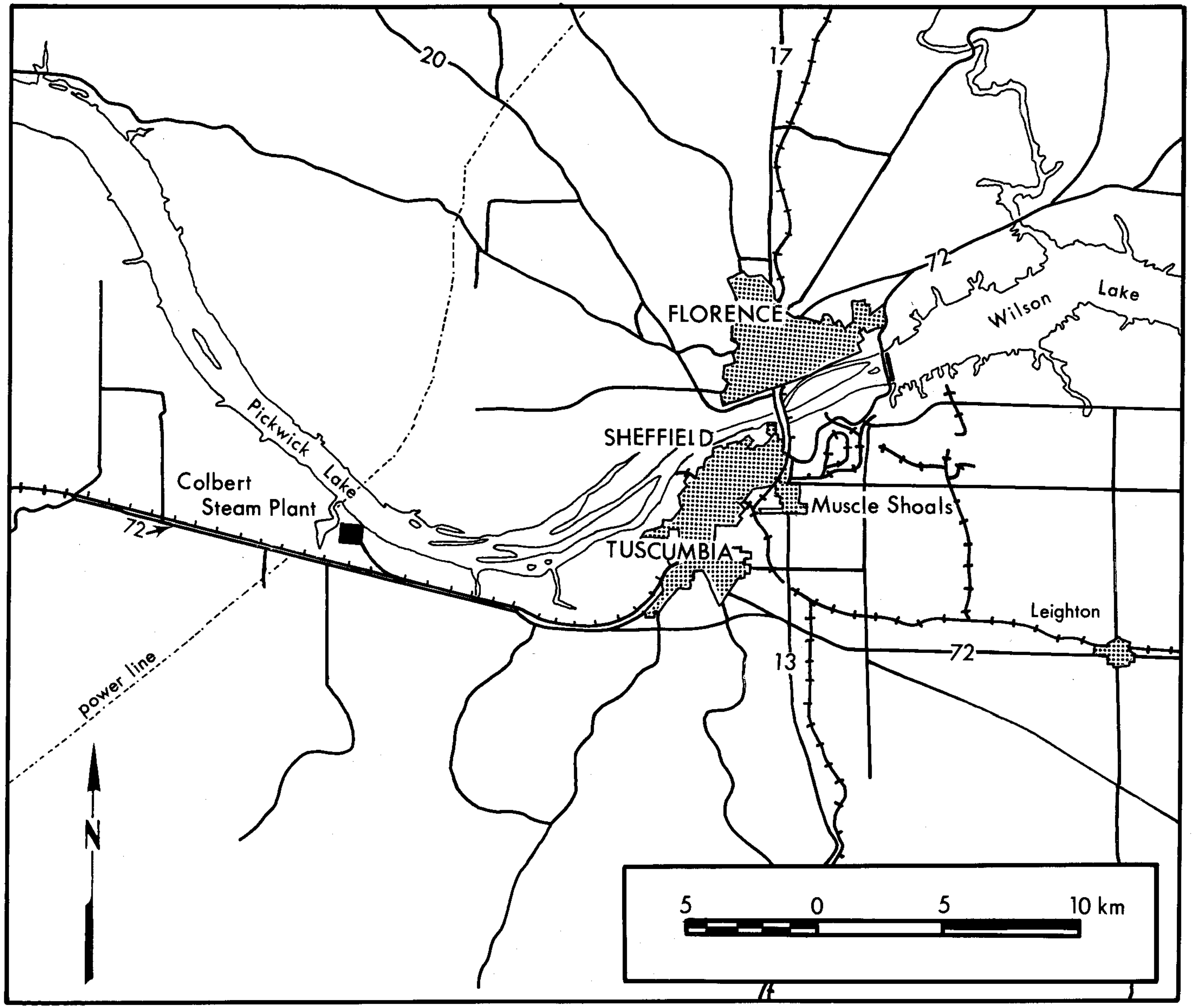


Figure 1. Colbert Steam Plant area in northwestern Alabama.

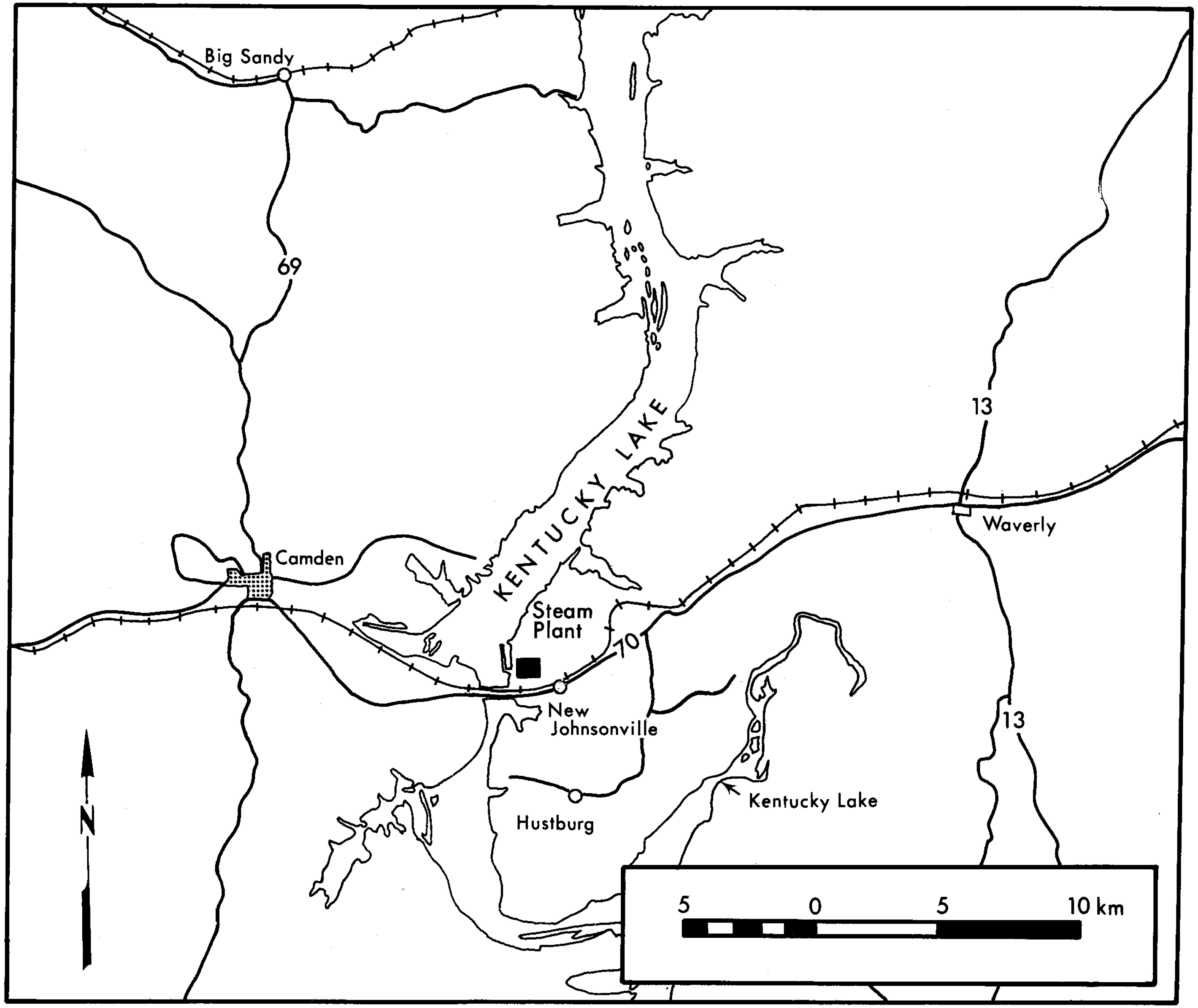


Figure 2. Johnsonville Steam Plant area in western Tennessee.

relatively constant temporally and can be used to subtract the effects of atmosphere and illumination. Reflectances of other objects can be measured to an accuracy of about 5 percent of their true values.[3] This performance is comparable with that expected from a field radiometer.

The image calibration procedure requires rigorous control of variables. A density step wedge was processed with the film so that film processing effects could be measured. This procedure used sensitometric curves (D-log E) that plot density against relative log exposure values (Appendix B). Tri-band (analytical) densities were then measured directly from the film and converted to changes in relative exposure.

Reflectances can be obtained from each of the three spectral bands comprising color film, whether the emulsion is true color or color-infrared. The spectral coverage of a particular band is determined by the sensitivity of that component of the film emulsion. For color-infrared film, the emulsions are sensitive to either green, red, or near-infrared wavelengths.[6] Both densitometers were equipped with selectable filters (nos. 92, 93, 94, and 106), enabling the operator to measure density in any one or all three emulsion layers.

Reflectance values from one band may be divided by reflectance values from other bands. The ratio thus obtained may be a sensitive indicator of stress. Three simple ratios were calculated in this study: infrared to red (IR/R); infrared to green (IR/G); and red to green (R/G). Figure 3 illustrates the relationship of the IR/R ratio to stress as shown by spectral curves of reflectance. The ratio approaches 1.0 as the curve flattens with stress from $SO_2$ or some other agent.

The spectral changes that occur in plants in response to stress have been described by Murtha.[1] We investigated the three single-band reflectances and the three reflectance ratios described above to determine whether they correlated with levels of foliar injury to soybeans.

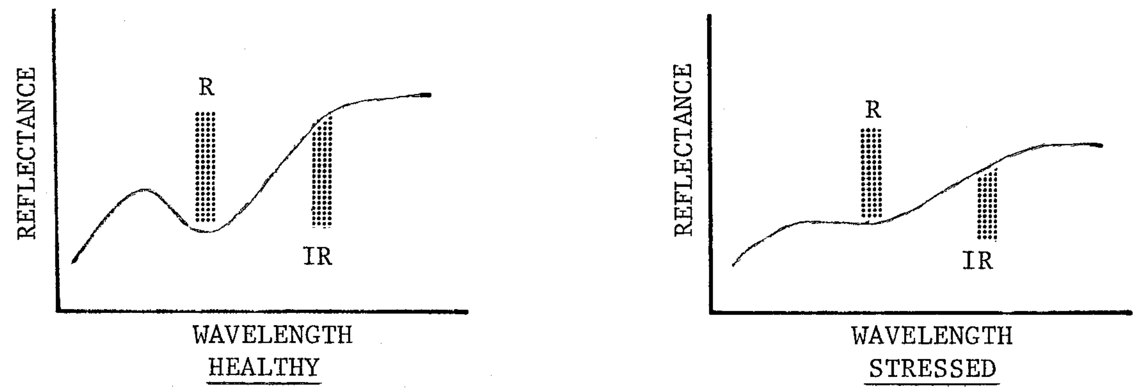


Figure 3. Generalized relationship of IR/R ratio to spectral curves of healthy and stressed vegetation. "R" indicates a reflectance measurement in the red region, and "IR" indicates a reflectance measurement in the near-infrared region.

# SECTION 4

# RESULTS AND DISCUSSION

An operational test of the photometric analysis technique was performed to determine whether it could be used to derive spectral reflectances at sample points within selected $SO_2$-affected soybean fields. The fields near Colbert exhibited foliar effects that were generally below 10 percent* and in the very light to light category. In contrast, Johnsonville had effects ranging from very light to severe. There were also coexisting foliar effects induced by herbicides or drought rather than $SO_2$. Fortunately, ground-truth data were available for the fields.

## COLBERT TEST

### General

Exposures to $SO_2$ caused visible foliar injury to soybeans in the project area on August 3 and August 26, 1977 (Figure 4). The Environmental Protection Agency (EPA) was asked to perform an overflight after the first exposure; but because of concurrent requests, the aircraft did not arrive until August 29. Drought-induced senescence and, in areas of adequate moisture, growth of the soybean canopy and weeds tended to dilute the $SO_2$ effects. Effects from the August 26 injury were still fresh. An attempt was made to distinguish and separate these types of stress through photometric analysis of the aerial photographs.

Analysis of the Colbert photographs focused on five soybean fields that fell within a single frame (Figure 5). Four of the fields were affected by $SO_2$ and one was unaffected. The photographs also show a set of six test panels (arrow) for calibrating reflectance in the photometric analysis procedure. The soybeans were mature (generally 7 to 10 nodes) plants that had stopped showing new growth, but were not yet senescent. Some areas were infested with cockleburs [Xanthium strumarium (L.)]. The soybean canopies were generally continuous, with only a few areas of soil showing from overhead. The effects of $SO_2$ exposure consisted of light levels of chlorosis, but no necrosis.

### Measurement and Comparison of Reflectance

The sample points were selected systematically within each field (Figure 6), and the densitometer was used to measure the optical density of the photograph at each point. Exceptions to the uniform spacing of the sample points were made when required by the shape of a field. The

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*Calculations of injury used the LAP method (Appendix A). Foliar injury was classified as follows: light injury, up to 10 percent; moderate injury, 11 to 25 percent; severe injury, over 25 percent. Very light injury was the lower half of the light category.

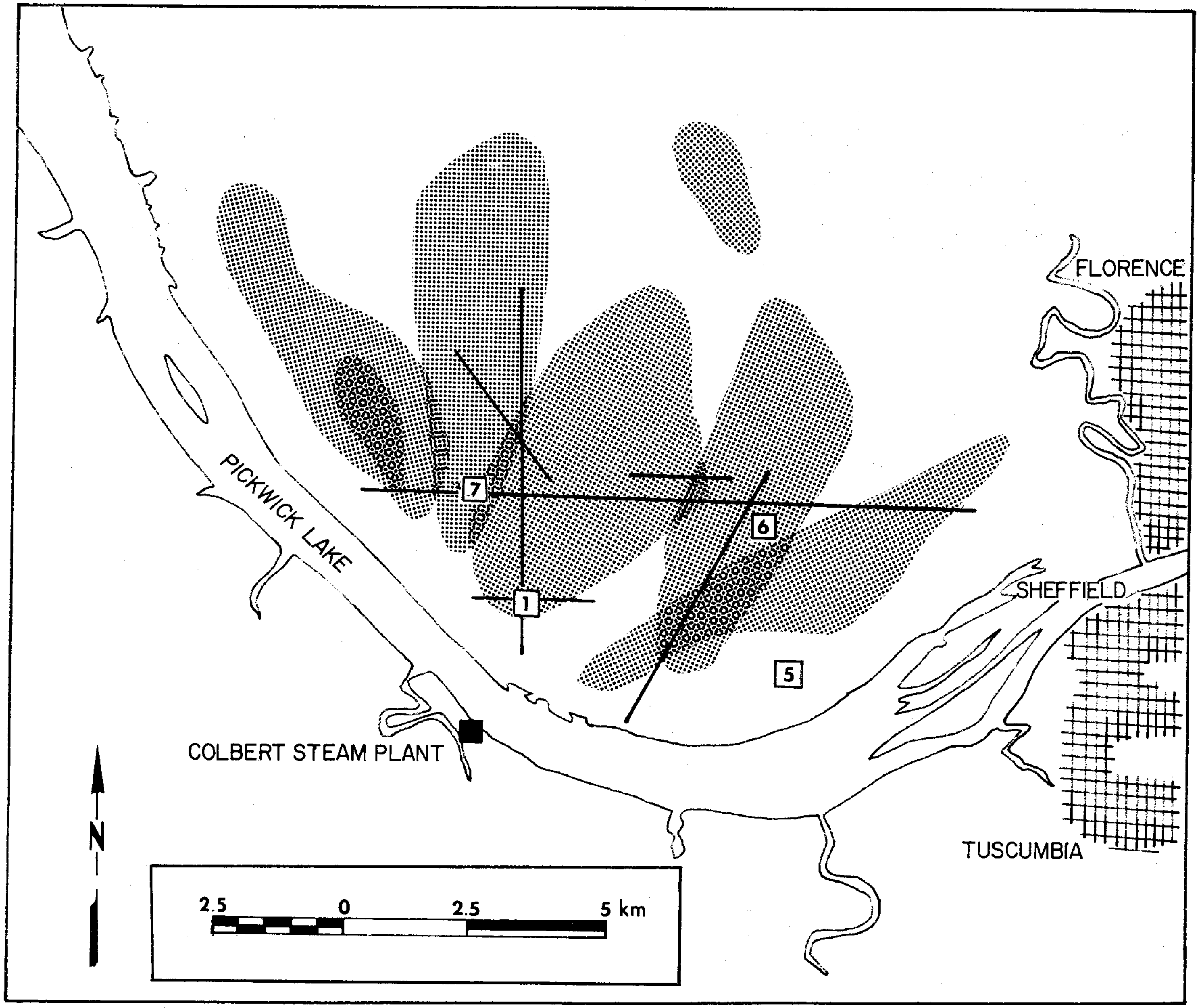


Figure 4. Flight lines and $SO_2$-affected areas near Colbert. (Boxed numbers locate fixed $SO_2$ monitoring stations.)


Figure 5. Aerial color-infrared photograph showing Colbert area. (Letters identify selected soybean fields discussed in report. Scale 1:12,000).

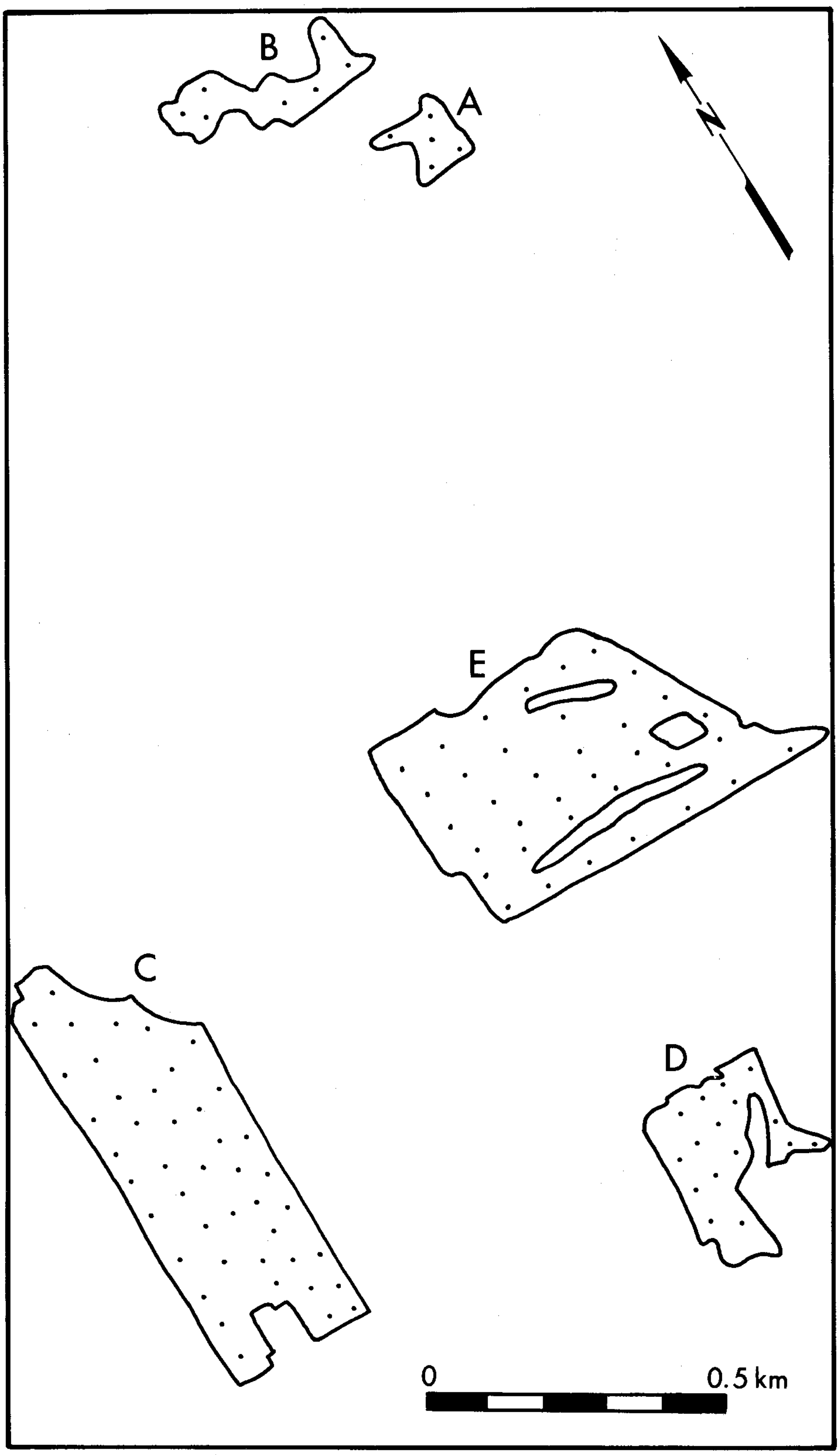


Figure 6. Location of densitometer sampling points within soybean fields near Colbert Steam Plant.

mean and standard deviations of the reflectance values from each spectral band with foliar injury levels obtained from ground-truth indicated poor correlations. The next step was to ratio the near-infrared (IR), the

red (R), and the green (G) reflectances (Table 1). The IR/R ratio provided the best separation of affected and unaffected soybeans. The $SO_2$-affected soybeans had lower IR reflectance and higher R reflectance. This finding is in accordance with published theories on the behavior of stressed plants.[1]

Comparison of the foliar injury data with the IR/R reflectance ratios for the five fields (Table 2) showed that the field with the highest mean reflectance (A) was unaffected by $SO_2$; field B, with 2 percent injury, had the next highest mean; and field C, with the highest injury level, had the lowest mean reflectance. Therefore, it appears that the smaller the IR/R ratio, the greater the $SO_2$ effects. Figure 7 further illustrates the relationship between injury and each reflectance ratio. Field D was infested with weeds and had a discontinuous canopy; this heterogeneity is reflected in the high standard deviation (1.11) for reflectance for the field. A low standard deviation for the reflectance values from a field indicates a homogeneous canopy and few weeds.

## JOHNSONVILLE TEST

### General

Two incidents of $SO_2$ injury to vegetation occurred in the photographed Johnsonville area during July 1977. The effects were classified generally as light to moderate. The earliest incident occurred on July 3 in an area northwest of the plant (Figure 8). The effects persisted and were photographed by EPA on July 21. TVA acquired ground truth and obtained a duplicate copy of the film from the EPA Vint Hill Farms Station. Another $SO_2$ incident occurred on July 23 in the same general area. Injury to soybeans was still visible in the field on August 2, the date of the TVA overflight.

The photometric analysis focused first on 15 soybean fields in the Johnsonville area where the $SO_2$ plume contacted the crop. The number was later reduced to 9 because of differing stages of growth. One aerial color-infrared photograph (Figure 9) shows some of the fields.

As with the Colbert data analysis, the field-to-field variations in reflectance ratios were studied. Next, the relationship between the ratios and the $SO_2$ injury levels was investigated. Finally, the relationships among reflectance, $SO_2$ injury levels, and yield were explored.

### Measurement and Comparison of Reflectance

Reflectance values from soybean fields located northwest of the Johnsonville Steam Plant were compared to determine whether they were related to foliar injury levels. The $SO_2$ effects ranged from very light to severe, providing a full scale for study. The affected area contained no-till fields, tilled (plowed) fields, and barren (unplanted but recently plowed) fields. Some fields contained mature soybeans, whereas others

TABLE 1. SPECTRAL REFLECTANCE RATIOS FOR SELECTED SOYBEAN FIELDS NEAR COLBERT

| Field no.[a] | IR/R[b] | | IR/G[b] | | R/G[b] | |
|---|---|---|---|---|---|---|
| | Mean | S.D. | Mean | S.D. | Mean | S.D. |
| A | 5.77 | 0.338 | 5.75 | 0.128 | 0.99 | 0.052 |
| B | 5.34 | 0.676 | 4.99 | 0.407 | 0.94 | 0.062 |
| C | 3.01 | 0.486 | 3.67 | 0.399 | 1.12 | 0.199 |
| D | 4.55 | 1.109 | 4.47 | 0.763 | 1.01 | 0.112 |
| E | 4.91 | 0.569 | 4.96 | 0.444 | 1.02 | 0.052 |

[a]Keyed to Figure 6.
[b]Abbreviations: IR--infrared reflectance; R--red; and G--green.

TABLE 2. COMPARISON OF GROUND TRUTH WITH IR/R RATIO STATISTICS FOR SELECTED SOYBEAN FIELDS NEAR COLBERT

| Field no.[a] | Observed level of injury[b] (%) | IR/R | |
|---|---|---|---|
| | | Mean | S.D. |
| A | 0 | 5.7 | 0.34 |
| B | 2 | 5.3 | 0.68 |
| C | 4 | 3.0 | 0.49 |
| D | 2[c] | 4.6 | 1.11 |
| E | 2 | 4.9 | 0.57 |

[a]Keyed to Figure 6.
[b]Field estimate based on degree and extent of injury to foliage in affected parts of field (L x A method--see Appendix A).
[c]Estimated because of conflicting data.

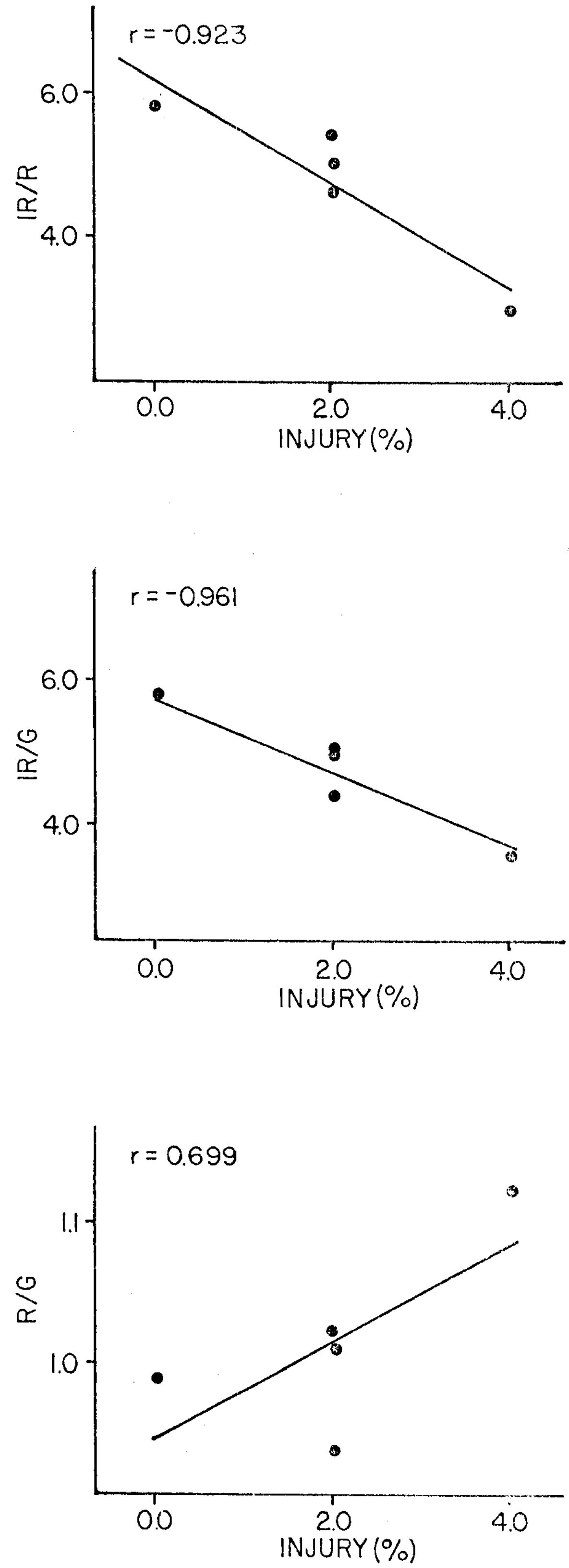


Figure 7. Regression of reflectance ratios and foliar injury levels for Colbert soybean fields.

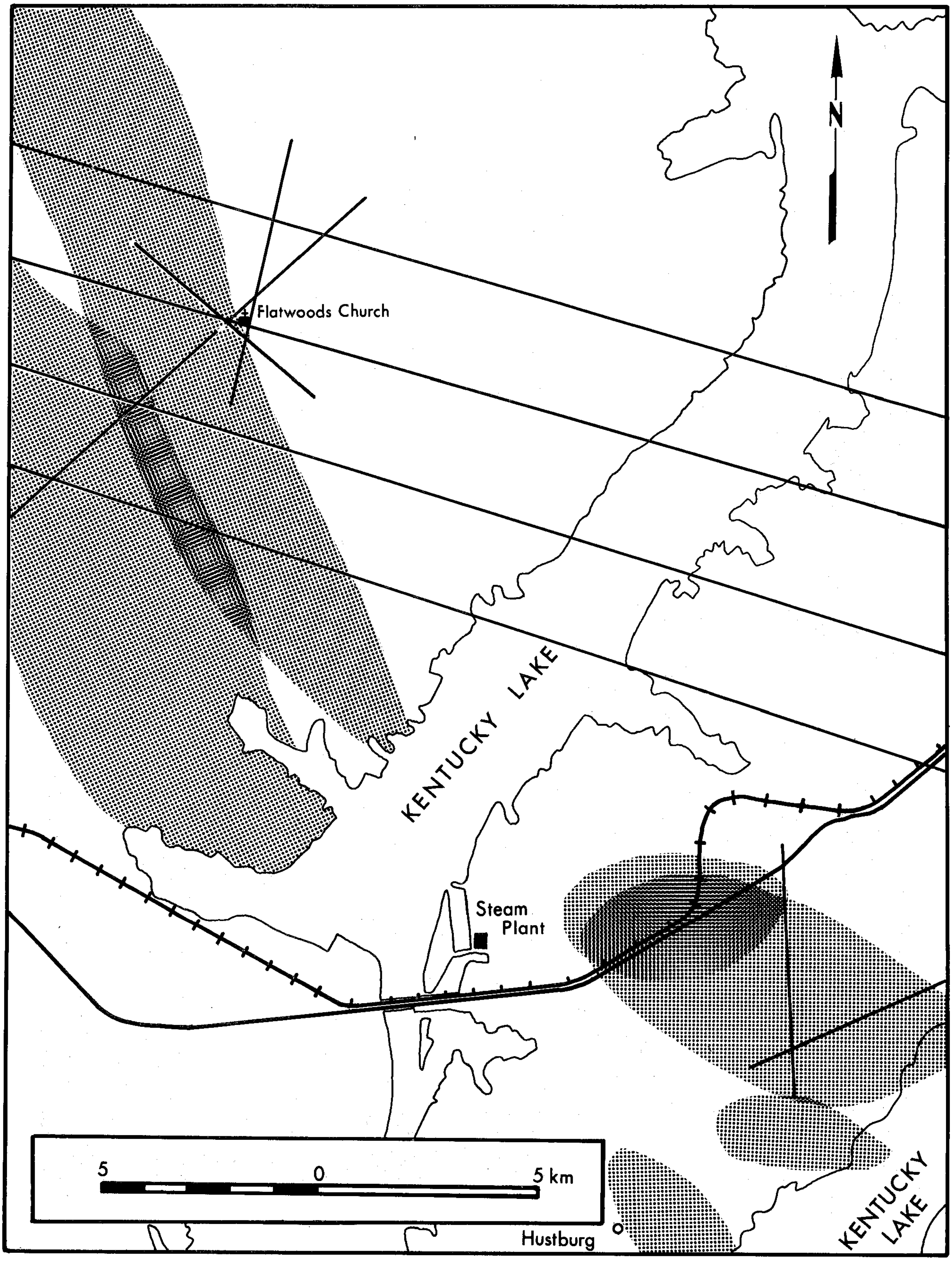


Figure 8. Flight lines and $SO_2$-affected areas in Johnsonville area.


Figure 9. Aerial color-infrared photograph showing selected soybean fields near Johnsonville Steam Plant (scale 1:12,000). Acquired by EPA on July 21, 1977, from 1800 m above ground level.

had young plants. Some fields had been planted twice. Weeds, mainly cockleburs, were prevalent in some of the no-till fields. Some no-till fields contained wheat stubble between the bean plants.

The image densities were measured, and the values were converted to percentage reflectance. Means, standard deviations, and ratios were computed (Table 3 and Appendix B). Because previous analyses indicated the relative superiority of the IR/R ratio, this ratio was used instead of the R/G and IR/G ratios in the search for a relationship between reflectance and injury levels.

Correlation coefficients were generated for reflectance, $SO_2$ injury, and yield (Table 4). The IR/R increased with the level of injury, the opposite of what was expected (Figure 10a). The IR component of the ratio increased and the R component decreased with injury (Figures 10b and c). The G reflectance also decreased with increasing injury (Figure 10d). None of the three single-band reflectance correlations were significant ($\alpha = 0.05$), but the IR/R ratio was significant. The correlation coefficients are shown on the illustration.

The best indicator of yield was the G reflectance (Figure 10e). The R and IR reflectances (Figures 10f and 10g) were also good, and all three correlations of yield and reflectance were significant ($\alpha = 0.05$). The IR/R ratio results (Figure 10h) were not significant. Yield increased with injury (Figure 10i). This last correlation, which may appear surprising at first, is explained by the association of yield with canopy density. The density variable, as measured from overhead photographs, is associated with stage of growth, availability of soil moisture, soil fertility, and many other factors that affect plant conditions before, during, and after an incident of exposure to $SO_2$. Certainly, the more dense canopy is associated with higher yield. Injury level was apparently not a sufficiently powerful factor to override the density (and therefore yield) factor. More study is needed to define the relationship between foliar injury levels and yield before reflectance can be used as a surrogate for yield.

The relationship between the effects of power plant emissions and productivity of crops is not well known. In general, crop yields are not affected by $SO_2$ exposure unless visible foliar effects occur. Evidently, over 5 percent of the leaf area must be affected to measurably reduce yield.[7] Common practice for estimating yield reduction involved (1) field sampling to determine the percentage of leaf area destroyed and (2) applying an empirically or theoretically derived factor to calculate loss. The difficulty is that many uncontrollable cultural, edaphic, and climatic factors also affect yield. Certainly, the stage of growth at the time of exposure to $SO_2$ is one of the more important factors. Significant reductions in yield caused by $SO_2$ exposures during the pod-filling stage of growth in soybeans has been documented and related to the amount of foliar chlorosis.[8] However, other exposures to soybeans during the prebloom stage did not reduce yield significantly.[9]

TABLE 3. REFLECTANCE, FOLIAR INJURY LEVELS, AND YIELD FOR JOHNSONVILLE SOYBEAN FIELDS AND BARE SOIL

| Field designation | IR | | R | | G | | IR/R | | Observed level of injury[a] (%) | Yield | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Mean | S.D. | Mean | S.D. | Mean | S.D. | Mean | S.D. | | bu/acre | $m^3/ha$ | kg/ha |
| F | 21.1 | 3.7 | 6.4 | 1.0 | 7.2 | 0.8 | 3.3 | 0.66 | 34.8 | 22.5 | 0.300 | 3676[b] |
| G | 23.2 | 4.5 | 6.5 | 0.9 | 7.5 | 1.3 | 3.6 | 0.73 | 44.6 | 23.4 | 0.312 | 3823[b] |
| H | 24.8 | 2.8 | 7.3 | 0.8 | 7.9 | 0.6 | 3.4 | 0.55 | 20.2 | 28.0 | 0.373 | 4574 |
| I | 24.0 | 4.3 | 6.8 | 0.7 | 7.8 | 0.6 | 3.5 | 0.65 | 30.8 | 28.5 | 0.380 | 4656 |
| J | 17.9 | 1.7 | 6.6 | 0.6 | 7.0 | 0.7 | 2.7 | 0.35 | 20.0 | 22.4 | 0.299 | 3659 |
| K | 22.6 | 1.8 | 6.7 | 0.6 | 7.8 | 0.5 | 3.4 | 0.46 | 22.0 | 24.9 | 0.332 | 4068 |
| L | 25.7 | 1.0 | 4.6 | 0.8 | 4.7 | 0.6 | 5.6 | 0.95 | 14.5 | 31.0 | 0.413 | 5064[c] |
| Bare soil | 20.6 | 1.9 | 17.1 | 2.0 | 13.7 | 1.0 | 1.2 | 0.10 | - | - | 0.000 | 0 |

[a] L x A method (see Appendix A.)
[b] Yield = 1/2 actual reported value due to double planting.
[c] Tilled field; all others are no-till.

TABLE 4. CORRELATION COEFFICIENTS FOR REFLECTANCE, $SO_2$ INJURY, AND YIELD OF SOYBEANS[a]

| | G[b] | R[b] | IR[b] | IR/R[b] | Injury[b] |
|---|---|---|---|---|---|
| Injury | (-0.125) | (-0.574) | (0.209) | (0.565) | - |
| Yield | 0.860 | 0.806 | 0.784 | 0.480 | 0.265 |

[a] $\alpha = 0.05$, except as noted by coefficients in parentheses, which are not significant at this level.

[b] Abbreviations: G = green band reflectance; R = red; IR = infrared; IR/R = ratio of infrared to red reflectance.

[c] Injury is the percentage for fields calculated by the L x A x P method (Appendix A). Yield data were collected in field at harvest.

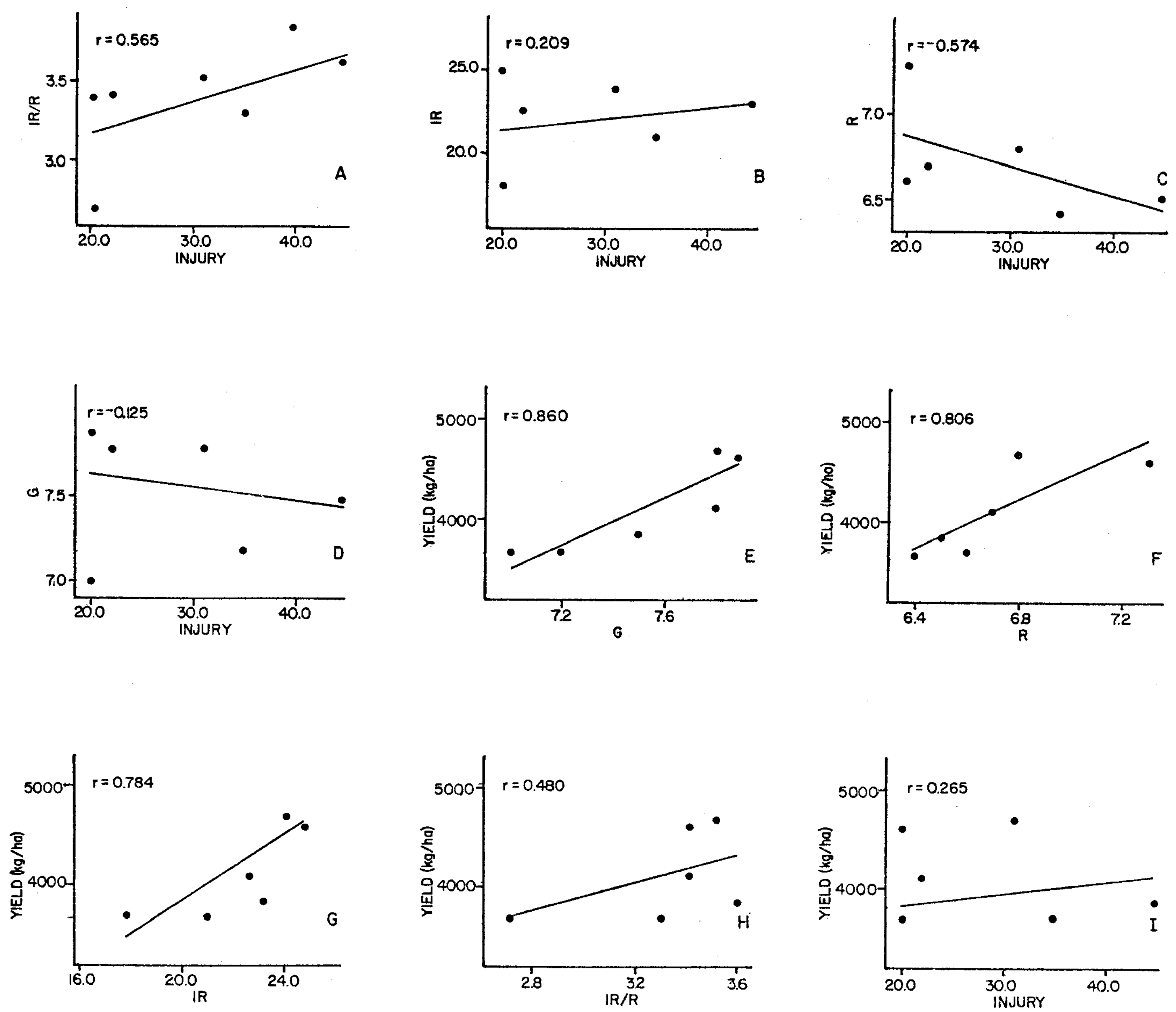


Figure 10. Statistical regressions of reflectance, injury levels, and yield for Johnsonville soybean fields.

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# APPENDIX A

## EXPLANATION OF PROCEDURE FOR ESTIMATING FOLIAR EFFECTS OF $SO_2$ ON CROP SPECIES

L = Percentage of leaves affected on an average affected plant

A = Percentage of leaf area affected on an average affected leaf

P = Percentage of plants affected in field

L x A = Percentage of total leaf area affected on an average affected plant

L x A x P = T = Average of total leaf area affected in a given field

# APPENDIX B

## PHOTOMETRIC CALIBRATION

The atmospheric and illumination contributions to the total exposure of an image on film are, by definition,[1]

(1) a multiplicative attenuation of the energy for every object in the scene ($\alpha$) and

(2) an additive contribution of energy from the optical path between the objects and the sensor ($\beta$).

To measure these two parameters ($\alpha$ and $\beta$), one must first derive the relationship between image density (D), which is measured from the images, and the exposing energy (E) that caused the image density. This is accomplished by using a step wedge (series of known exposures) that has been imaged on the film before it is processed. TVA furnished one set of EPA aerial photographs with a step wedge (Colbert) and two sets of TVA photographs without wedges (Johnsonville). The densities of the steps in the Colbert wedge were measured and plotted against their known relative log exposure values. The resultant curves are shown in Figures B-1, B-2, and B-3 for the infrared energy (red filter), red energy (green filter), and green energy (blue filter). The Eastman Kodak Handbook curve for CIR film was also plotted. The comparison of these curves showed a significant difference in the low-exposure end, with severe density compression present in the EPA film. Examination of both the wedge and scenes under 30X magnification revealed a microscopic pattern generally related to processing to correct for underexposure during data collection. This processing problem could manifest itself in several ways in photometric analyses if the analyst were not aware of its presence.

The first manifestation could be in the photometric calibration process to derive the additive contribution to image exposure ($\beta$). This task is accomplished by performing a regression analysis of the exposures of dark and light objects in the scene illuminated by skylight (shadow) and also by sunlight plus skylight. Because of density compression due to processing, the exposure range between objects illuminated by skylight and those illuminated by skylight plus sunlight is reduced. Thus, the plotting scale used in the computerized regression program to derive $\beta$ must be expanded to obtain meaningful values for $\beta$. This actually occurred in the first attempt to derive $\beta$ for the Colbert data, with negative $\beta$'s being output by the regression program. Expanding the plotting scale, however, did allow the derivation of meaningful $\beta$'s. The expanded scale and plot allowed the operator to recognize erroneous data points and eliminate them from the analysis, an important interactive step in calibration.

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1. Piech, R., and J. R. Schott. Atmospheric Corrections for Satellite Water Quality Studies. Proceedings of the SPIE, 51:84-89, 1974.

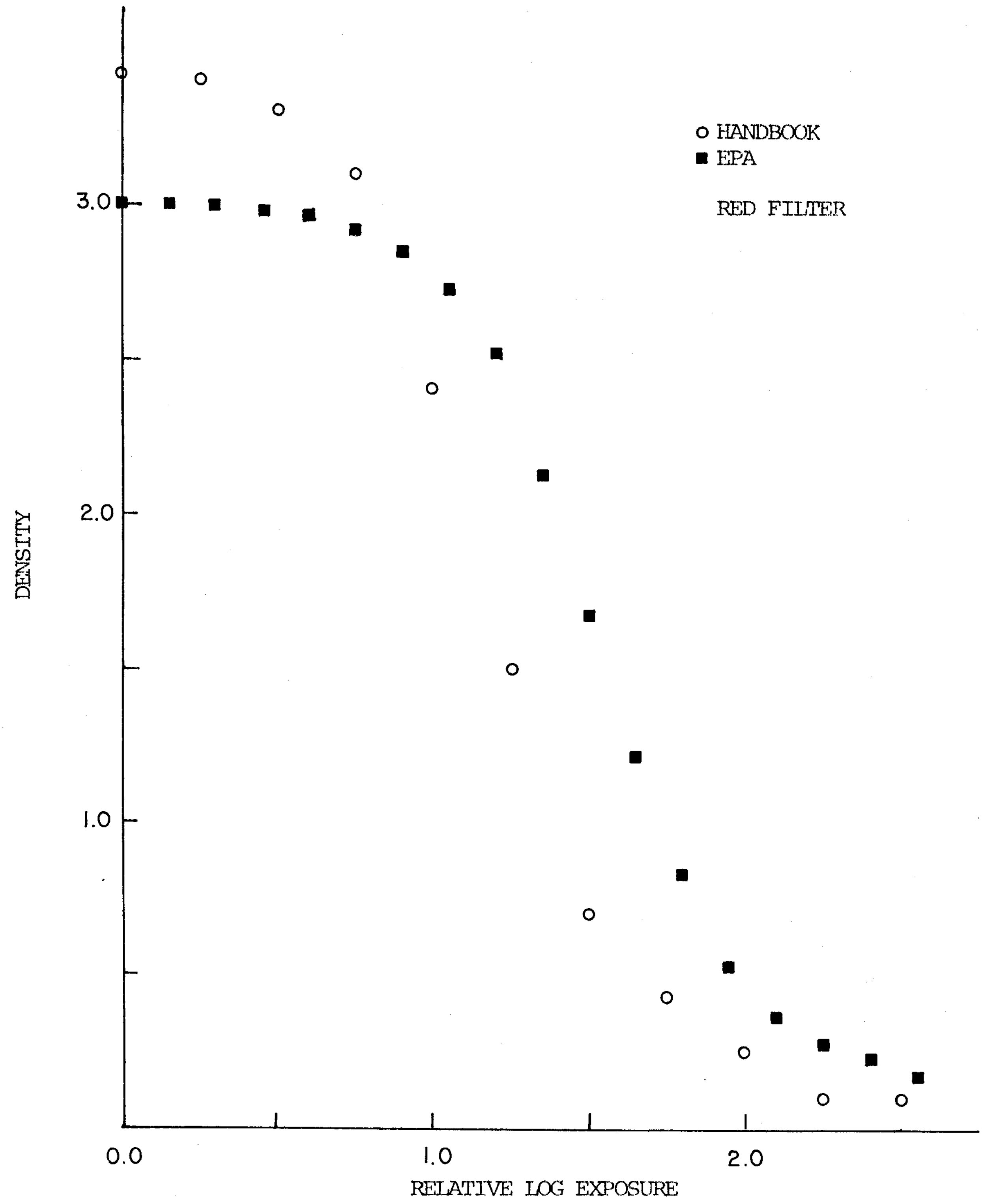


Figure B-1. Comparison of D-log E curves--red filter.

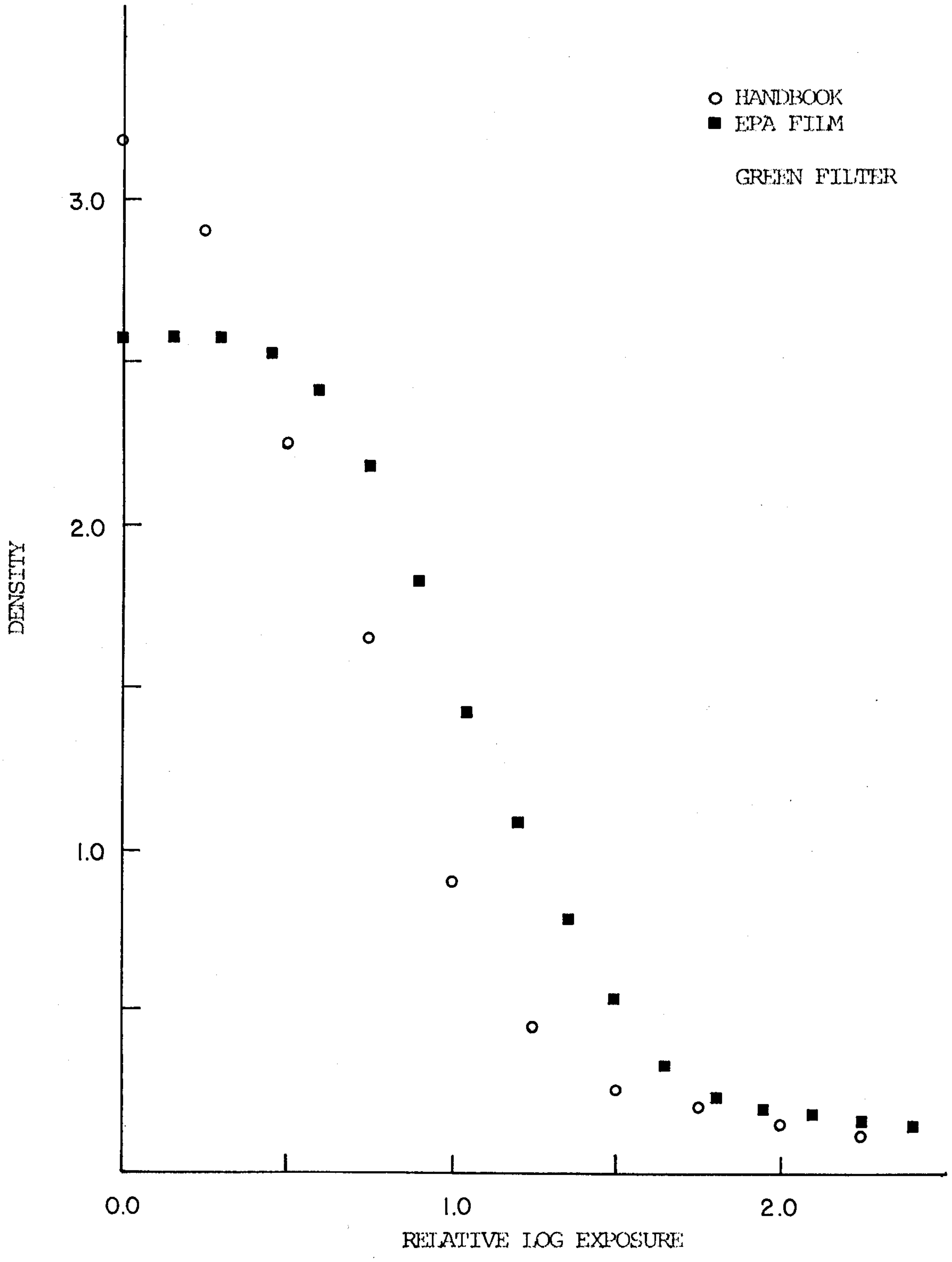


Figure B-2. Comparison of D-log E curves--green filter.

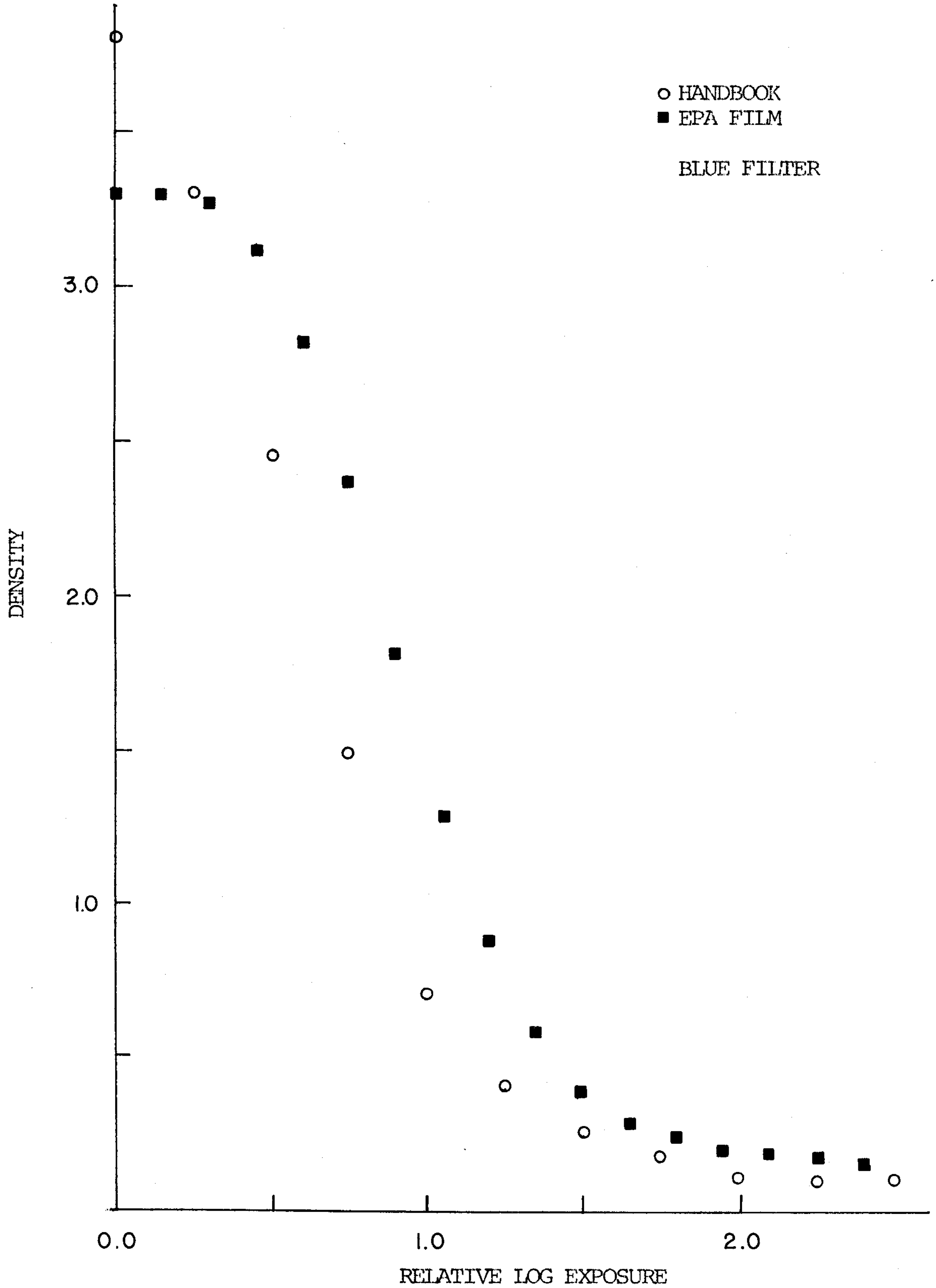


Figure B-3. Comparison of D-log E curves--blue filter.

Another manifestation that could occur is that the density of healthy soybean fields located in the extreme corners of the film format, especially in the red information band (green filter-chlorophyll absorption band), could reach the maximum density limit imposed by the processing problem; even with correction for lens fall off, an incorrect value of red reflectance could result. This did not occur in the case of Colbert data, but the analyst should be aware that processing problems can result in maximum density compression.

A third manifestation to be aware of, because of this type of processing problem, is the effect of the microscopic pattern on densitometry. If a large-aperture (1 mm) densitometer is used, it integrates the variations in density within the microscopic pattern anomaly with little or no effect on the densitometry. However, if a densitometer with a small sample aperture (50 μm) is used, the placement of the aperture is critical. The processing pattern consists of circular areas, about 100 μm in diameter, over the entire film format. In the center of each circular area of normal dye concentration is an abnormal "snowflake" pattern that is generally of higher density than the normal dye concentration surrounding the "snowflake." Therefore, the analyst must be sure he places the small aperture in the normal dye area and not on a "snowflake" when making an image density measurement.

Fortunately, the Colbert photographs were acquired in late August, when most soybean crops had reached full cover condition. Therefore, it was possible to use the 1-mm aperture and have the effect of the processing problem averaged into the noise of the overall measurement process.

The $\alpha$'s and $\beta$'s derived for the Colbert photographs are shown in Table B-1.

TABLE B-1. $\alpha$'S AND $\beta$'S FOR COLBERT PHOTOGRAPHS OF AUGUST 29, 1977

| | Infrared band | Red band | Green band |
|---|---|---|---|
| $\alpha$ | 206.92 | 157.14 | 174.70 |
| $\beta$ | 6.72 | 3.45 | 10.37 |

For the Johnsonville photographs it was necessary to assume characteristic curves to obtain $\alpha$'s and $\beta$'s. The Johnsonville films were examined under 30X magnification to determine whether the microscopic pattern present in the Colbert wedge and scenes was still present. The pattern was not present in either the July 13, 1977, films furnished by EPA to TVA or in the August 2, 1977, TVA films. The maximum densities of these films were checked (i.e., zero exposure in borders), with the expectation that they would be significantly higher. However, because the maximum densities were not found to be significantly higher, we decided to use the original wedge data for the Colbert scene to derive α's and β's for Johnsonville. The α's and β's for the two sets of Johnsonville films are given in Table B-2.

TABLE B-2. α'S AND β'S FOR JOHNSONVILLE PHOTOGRAPHS

| | Infrared band | Red band | Green band |
|---|---|---|---|
| | July 13, 1977 | | |
| α | 322.588 | 130.486 | 138.611 |
| β | 13.39 | 3.21 | 4.27 |
| | August 2, 1977 | | |
| α | 329.139 | 214.169 | 219.411 |
| β | 7.15 | 3.28 | 3.45 |

The assumptions necessary to obtain a photometric calibration of these films were pointed out to the TVA representative. The necessity for the exposure of a 21-step wedge on the original aerial films and a duplicate of this wedge for subsequent duplicates of scenes to be analyzed in any future field experiment was also emphasized. This requirement was the first experimental design criterion resulting from this effort.

Because of the problems of sensitometric and densitometric control for the aerial photographs, absolute spectral reflectances and reflectance ratios could not be obtained from photometric interpretation; however, important relative reflectance information within any one scene could still be obtained, depending on the level of reflectance. The film covering the Colbert site (frames 5353 through 5355, August 29, 1977) was selected for analysis because it did have a wedge. Thus, these reflectances would be closest to absolute values.

The TVA representative measured the spectral reflectance and reflectance ratio properties of soybean plants in five fields at the Colbert site (fields A through E). The number of measurements per field was limited by the field of view of the densitometer used. This was a 1-mm-diam aperture, representing a 12-m-diam area on the ground. A 0.6-m-diam area could have been used, but this was not considered necessary for these fields because they were mature fields with very full cover. The 12-m-diam area still allowed about 50 samples to be measured per field in less than 15 min.

This is considered a very important point relative to the comparison of any potential aerial photometric method of soybean stress measurement to a ground survey method. It would be very difficult to obtain a sample rate of 200 samples/h per field when using a ground survey method, whether they are spectral reflectances from a ground-based TSR or L x A x P (see Appendix A) estimates. This is a very practical advantage of an aerial photographic approach. Furthermore, the photograph would provide a valuable permanent record of the crop condition.

The TVA representative compared the mean IR/R reflectance ratios for these fields and found the most injured (4 percent by the L x A x P method) plants had a ratio of 3.0±0.49, whereas the least injured (0 percent) plants had a ratio of 5.7±0.34. In previous photometric interpretation analyses of vegetation stress (chlorosis-necrosis) by Calspan, the mean IR/R reflectance ratio has always been high when stress was low and low when stress was high. Thus, even with known processing problems, the reflectance and ratio results obtained were consistent with previous studies.

However, one inconsistency was noted. The standard deviation in the red (chlorophyll absorption) band is usually extremely large in comparison with that in the infrared band. These data showed the infrared band to have the larger standard deviation. The presence of a sunspot image in the Colbert scene could have caused these inconsistencies.

Field B, having 2 percent injury by the L x A x P method, appeared on three frames (nos. 5353, 5354, and 5355) at different format positions relative to the sunspot and center of the format. Spectral reflectance gradient functions from the center of the sunspot image through the center of each format to the edge of the film away from the sunspot were derived from regressions of soybean reflectances against distance from the center format. Deciduous tree reflectance was also regressed relative to distance with almost identical results. This result would be expected since both canopies are highly textured and contain multiple reflectances.

A second-order regression resulted in a functional relation with high correlation coefficients ($r^2$):

$$R_\lambda = B_2X^2 + B_1X + B_0,$$

where X = the distance of an image from the center of the film format (0) to (+) the sunspot and away from (-) the sunspot, in inches along the sunspot, center format line.

The constants $B_0$, $B_1$, and $B_2$ are shown in Table B-3, with the correlation coefficients for each spectral band.

TABLE B-3. SPECTRAL REFLECTANCE GRADIENT CONSTANTS

| | $R_{IR}$ | $R_R$ | $R_G$ |
|---|---|---|---|
| $B_0$ | 0.0248 | 0.0575 | 0.0539 |
| $B_1$ | 0.0139961 | 0.008437 | 0.0076 |
| $B_2$ | 0.001159 | 0.0007353 | 0.0008 |
| $r^2$ | 0.728 | 0.879 | 0.865 |

Eight to nine spectral reflectance measurements were made in field B on each of the three frames on which the field was imaged. The results of the measurements are shown in Table B-4.

TABLE B-4. MEASUREMENTS OF REFLECTANCE--FIELD B

| Frame no. | $R_{IR}$ | $\sigma(\%)$[a] | $R_R$ | $\sigma(\%)$[a] | $R_G$ | $\sigma(\%)$[a] | $R_{IR}/R_R$ | $\sigma(\%)$[a] |
|---|---|---|---|---|---|---|---|---|
| 5353 | 29.26 | ±7.5 | 05.65 | ±3.4 | 06.14 | ±4.1 | 5.2 | ±8 |
| 5354 | 28.89 | ±3.0 | 05.76 | ±6.0 | 05.83 | ±7.0 | 5.4 | ±4 |
| 5355 | 24.88 | ±5.0 | 04.51 | ±4.0 | 04.38 | ±5.0 | 5.5 | ±2 |
| All data | 27.5 | ±9 | 05.14 | ±5.3 | 05.38 | ±15.8 | 5.4 | ±6 |

[a]Standard deviation, as percentage of mean reflectance.

Next, a preliminary gradient correction method under development at Calspan was applied to the spectral measurements. The corrected reflectance data for the field are shown in Table B-5.

TABLE B-5. REFLECTANCES CORRECTED FOR ILLUMINATION GRADIENT

| Frame no. | $R_R$ | $\sigma(\%)$[a] | $R_R$ | $\sigma(\%)$[a] | $R_G$ | $\sigma(\%)$[a] | $R_{IR}/R_R$ | $\sigma(\%)$[a] |
|---|---|---|---|---|---|---|---|---|
| 5353 | 31.96 | ±7.6 | 07.01 | ±3.3 | 07.39 | ±4.1 | 4.5 | ±8 |
| 5354 | 32.60 | ±3.3 | 07.10 | ±6.0 | 07.44 | ±7.4 | 4.6 | ±4 |
| 5355 | 31.67 | ±4.7 | 08.04 | ±4.1 | 06.94 | ±5.2 | 3.0 | ±2 |
| All data | 32.06 | ±5.2 | 07.37 | ±7.9 | 07.24 | ±6.4 | 4.3 | ±9 |

[a]Standard deviation, as percentage of mean reflectance.

The preliminary correction for illumination gradient normalizes all reflectances to a common point in the scene--in this case, the sunspot location. Theoretically, the mean values of reflectance for field B should be identical on all three frames. Therefore, we can compare the difference of the mean reflectance values for any single frame with the mean reflectance for all frames, as a measure of the accuracy of the photometric interpretation method with and without the correction for illumination gradient. The results of such a comparison are shown in Table B-6. There can be no doubt from these results that a correction provides a major improvement.

TABLE B-6. COMPARISON OF PHOTOMETRIC INTERPRETATION ACCURACY WITH AND WITHOUT PRELIMINARY ILLUMINATION GRADIENT CORRECTION

| Frame no. | $R_{IR}$(%) | | $R_R$(%) | | $R_G$(%) | |
|---|---|---|---|---|---|---|
| | With | Without | With | Without | With | Without |
| 5353 | 0.3 | 6 | 5 | 10 | 2 | 12 |
| 5354 | 2 | 5 | 4 | 12 | 3 | 8 |
| 5355 | 1 | 10 | 9 | 12 | 4 | 18 |

$$\text{Accuracy in \%} = \frac{\bar{R}\lambda \text{ (all data)} - \bar{R}\lambda \text{ (field)}}{\bar{R}\lambda \text{ (all data)}} \times 100$$

## TECHNICAL REPORT DATA
*(Please read Instructions on the reverse before completing)*

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16. ABSTRACT


Spectral reflectances were measured by tri-band densitometry of aerial color-infrared photographs of soybean [Glycine max (L.) Merr.] fields that had been affected by sulfur dioxide ($SO_2$) emissions from large, coal-fired power plants in northwestern Alabama and western Tennessee. The photographs were photometrically calibrated.

Results indicate that, at very light levels of foliar injury, the infrared-to-red reflectance ratio decreased with increasing injury. This behavior was in accordance with theory. However, at moderate and severe levels of injury, the ratio increased with injury. The infrared component increased, and the red component decreased as injury level rose. Two other ratios of reflectance (infrared-to-green and red-to-green) did not correlate significantly ($\alpha = 0.05$) with injury. The best indicator of crop yield was green band reflectance, but the red and infrared bands were nearly as good. Ratios produced no significant correlations with yield. The yield variable actually increased with the level of injury, apparently because of field-to-field variations in canopy density.


17. (Circle One or More) KEY WORDS AND DOCUMENT ANALYSIS

| a. DESCRIPTORS | b. IDENTIFIERS/OPEN ENDED TERMS | c. COSATI Field/Group |
|---|---|---|
| Environments<br>Geography<br>Other: | Transport Processes<br>Charac. Meas. & Monit. | 6F 8A 8F<br>8H 10A 10B<br>7B 7C 13B |

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