Thomas M. Lillesand, Ph.D.
College of Forestry
University of Minnesota
St. Paul, MN 55108
Bov Bang Eav, Ph.D.
Lockheed Electronics Co., Inc.
Houston, TX 77058
Paul D. Manion, Ph.D.
College of Environmental Science and Forestry
State University of New York
Syracuse, NY 13210

Quantifying Urban Tree Stress through Microdensitometric Analysis of Aerial Photography*

Tests of the modeling process in Syracuse and Rochester, New York indicated that aerial predictions were as reliable as ground estimations, particularly under drought conditions.

Introduction

This article is a summary of a pilot project aimed at determining if and how optical density measurements made from color and color IR photography relate to on-the-ground observations of stress in urban shade trees. As used here, the definition of tree "stress" is adapted from that given by Agrios (1969). Stress is any disturbance of the normal growth cycle of a tree brought about by any living entity or environmental factor which interferes with the manufacture, translocation, or utilization of food, mineral nutrients, and water in such a way that the affected tree changes in appearance. In urban environments, many varied, complex, and interrelated factors cause tree stress. These factors include (but are not limited to) insect pests, disease agents, drought, air

Abstract: *Quantification of stress problems in urban shade tree populations is becoming increasingly important, complex, and expensive. This study investigated the technological potential for predicting stress levels in street-side maples on the basis of spectral densities measured on large-scale color and color infrared photography. Multidate imagery was acquired simultaneously with ground data for 1156 trees at four study sites in Syracuse, New York during the 1975 and 1976 growing seasons. Factor analysis was used to develop quantitative "stress indexes" based on the ground data. Multiple regression was used to develop a statistical model for predicting the stress indexes on the basis of image density measurements. Tests of the modeling process in Syracuse and Rochester, New York indicated that the aerial predictions were as reliable as ground estimations, particularly under drought conditions. The timing of aerial photography with respect to rainfall weighs heavily on the success of quantifying tree stress from density measurements.*

* Portions of this article were included in papers presented during the 1977 and 1978 Annual Meetings of the American Society of Photogrammetry.

pollution, temperature extremes, soil compaction, de-icing salt, and mechanical damage. The proper selection of locally adapted vegetation, old age deterioration, and changing environments are additional aspects of stress in urban trees. In short, even though shade trees are valued resources in urban and suburban areas, these areas often represent hostile growth environments.

Little is known regarding the amount of stress various external disturbances place on particular tree species in urban environments, and even less is known about the positive association of tree stress symptoms with any particular external disturbance(s). Consequently, urban tree stress, which has a profound effect on elements of the social and physical structure of entire communities, is simply not well understood. At the same time, tree maintenance in our ever-growing urban and suburban areas is becoming increasingly complex and costly. Any measure, therefore, that would aid in the basic understanding of tree stress mechanisms and help reduce the cost of maintaining urban trees would be of both scientific and practical value.

Many contributors to this journal (most recently, Heller, 1978, and Murtha, 1978a and 1978b) have aptly summarized the status of remote sensing and vegetation assessment. Suffice it to say here that, despite the long history of the use of remote sensing as a tool for detecting vegetation stress in rural forested settings, photographic remote sensing techniques have received little attention in the context of estimating the condition of urban tree cover. The few exceptions to this rule have been limited to *qualitative* determination of the presence or absence of a particular stress mechanism (e.g., Dutch elm disease). The purpose of the research reported here was to develop and evaluate a photographic remote sensing system for detecting and quantifying stress conditions in a test sample of maples in Syracuse, New York. Here, the concern was not whether stress was present or absent in the test trees. Rather, the test trees were plagued with a complex deterioration problem known as maple decline. With this type of multifaceted stress problem, all trees occupy some position along a continuum of vigor conditions. This condition is difficult to inventory and manage because of the large number of interacting factors involved and the long period of deterioration leading toward tree death.

The threefold objective of this research was

(1) To develop a means of quantifying stress levels on the basis of ground data alone,
(2) To develop a statistical model for predicting stress levels based on photo density measurement, and
(3) To test the validity of the photographic model by studying a random sample of test trees of known stress condition.

The following sections summarize how the above tasks were performed. A more detailed description of this research is given by Eav (1977) and Lillesand *et al.* (1978).

Data Acquisition

Four Syracuse sites were selected for intensive study. These typified residential, park-residential, Central Business District (CBD), and industrial land-use areas. For convenience, ground data within each study site were collected for street trees only. All maples having a diameter at breast height (DBH) of greater than 12 cm were included in the study population. This involved 696 Norway Maples, 312 Silver Maples, and 148 Sugar Maples, for a total of 1156 sample trees. (Maples made up 81 percent of all street trees in the study area.) During the 1975 growing season, the 1156 sample trees were visited on a monthly basis and stress problems were categorized and coded. Stress symptoms of the foliage, limbs, and stem were diagnosed and quantified. Site parameters such as utility wires, root surface covering, site disturbance, and turf condition were evaluated. Tree size parameters including DBH, height, crown width, and crown shape were measured. Electrical resistance of the cambium was determined with a Shigometer and increment cores were taken to evaluate growth on selected trees.

Of particular interest in the present article is the manner in which the trunk and limb, foliage, and overall health condition of each tree was measured. Each of these parameters was rated on a scale of 0 (excellent health) to 9 (dead). Estimates of the percentage of the trunk and limb and foliage affected by stress were also made and the type and cause of each stress problem were coded.

Aerial photographs of each study site were obtained concurrently with each ground survey. Thus, five photographic missions were completed over the study sites. The photographic coverage took the form of 1:6000, 70 mm format, vertical color (Kodak 2448, haze filter) and color infrared (Kodak 2443, Wratten 15 filter) positive transparencies. A pair of simultaneously triggered Hasselblad 500 EL (f = 80 mm) cameras was used to obtain the photography from a

Cessna 172 aircraft. Step wedges were exposed on each film leader prior to processing and all films used of each type were from the same emulsion batch.

Reduction of Ground Data

Various alternative strategies were considered for quantifying the stress conditions observed in the field. The seven field measurement parameters stemming from the field observations were

(1) Percentage of the live crown,
(2) Number of large dead limbs,
(3) Number of small dead limbs,
(4) Relative trunk and limb condition,
(5) Relative foliage condition,
(6) Percentage of foliage affected by a stress agent, and
(7) Relative general health of the tree.

One way to define a measure of the stress condition of the study population would have been to select the one parameter from the above list which correlated most strongly with the image densities measured from the photography. However, to select any single symptom as a stress index results in the loss of additional information expressed by the other variables. Hence, it was decided that the stress symptom data set would be reduced to a number of composite stress indexes. These indexes could then be compared with the calibrated image densities on a meaningful basis. For reasons which will be discussed later, the ground survey data collected during July were selected to develop the stress indexes.

The stress indexes were formulated with the aid of factor analysis—"a technique of multivariate analysis that attempts to account for the correlation pattern in a set of observable random variables in terms of a minimal number of unobservable or latent random variables called factors" (Press, 1972). The various computational approaches to factor analysis are discussed by Harman (1960), Morrison (1967), Comrey (1973), and others. The computer program used in the data analysis for this study was the BMD03M developed by the University of California and described by Dixon (1970a, 1970b).

The results of the factor analysis of the original seven variables are given in Table 1. A three factor solution was found to express adequately all of the original variables, with the factors representing

(1) A *trunk and limb* (TL) index composed of a proportion of the percent of live crown, the number of large dead limbs, the trunk and limb condition, and the general health condition;
(2) A *foliage* (FO) index which was a combination of the foliage condition, the percent of foliage affected, and a proportion of general health condition; and
(3) A *crown and branch* (CB) index formed by the percent of live crown and the number of small dead limbs.

The foliage index was observed on the ground to be most descriptive of the seasonal variation in stress symptoms. Longer-term effects of stress were observed in thin-crowned trees with numerous dead branches which were represented by the "trunk and limb" and "crown and branch" indexes.

Equations to compute the stress indexes were derived by a method suggested by Comrey (1973, p. 233). For each factor, the original variables which had loadings above 0.40 (underlined in Table 1) were singled out. The original variables (standardized to

Table 1. Factor Analysis Results For 1975 Ground Data

	Factor 1	Factor 2	Factor 3	h^2
Tree Stress Symptoms:				
Percent live crown	0.486	0.032	0.710	0.741
No. large dead limbs	0.834	0.108	0.030	0.708
No. small dead limbs	0.090	0.130	0.924	0.878
Trunk & limb condition	0.802	0.159	0.397	0.825
Foliage condition	0.312	0.839	0.169	0.830
Percent foliage affected	0.063	0.931	0.022	0.872
General health condition	0.733	0.403	0.334	0.811
Percent of total variance	51%	18%	12%	

h^2: communality
underscored loadings are above the cutoff point (0.40)

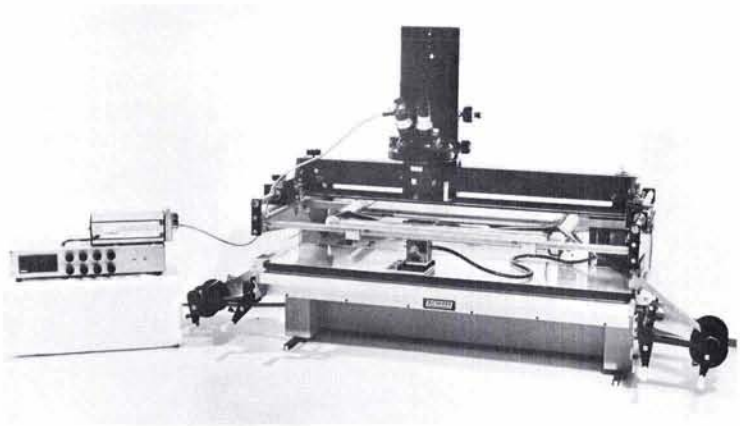

FIG. 1. Microdensitometer system.

the same mean and standard deviation) and the factor loadings were used to compute the three factor scores, stress index values, as follows:

$$\text{TL} = 0.486S_1 + 0.834S_2 + 0.802S_4 + 0.733S_7 \quad (1)$$

$$\text{FO} = 0.839S_5 + 0.913S_6 + 0.403S_7 \quad (2)$$

$$\text{CB} = 0.710S_1 + 0.924S_3 \quad (3)$$

where TL = "Trunk and Limb" index;
FO = "Foliage" index;
CB = "Crown and Branch" index; and
S_1 $S_2, \ldots, S_7$ = standardized values for the original variables.

The advantage of this method of computing factor scores is that it allows those variables with the highest loadings on a factor (i.e., the most important variables) to have the greatest effect in estimating the factor scores. All three indexes increased in value along a scale from -2 to $+8$, as tree health declined from a healthy to a dying stage.

REDUCTION OF AERIAL DATA

Spot density readings were made on selected subsets of the aerial photography through the use of the microdensitometer system shown in Figure 1. This system consists of a Bausch and Lomb Zoom 240 Stereoscope/Richards Light Table combination to which a densitometer assembly has been added. Fabricated by Calspan Corporation, this system enables the image analyst to view positive transparencies in three dimensions in a conventional manner and obtain digital density readings simultaneously. Figure 2 illustrates the operating principles of the system. The system is calibrated during each use to yield readings on a calibration step tablet identical to those obtained with a Macbeth TD-504 densitometer equipped with American National Standards Institute (ANSI) Status A filters. The optical system of the stereoscope controls the size of the measurement spot in the plane of the image. In this study, tree crown densities were read using a 200 μm spot size. Three such readings were taken on each crown along a line perpendicular to the azimuthal direction of the sunlight at the time of imaging. The average of these three readings formed the "raw" density reading on each tree crown. Measurements were taken solely on crowns lying near the principal points of each photograph to minimize vignetting effects.

Each density measurement consisted of three spectral readings through Wratten filters number 94, 93, and 92 for the blue, green, and red-forming color film layers. All raw density readings were converted to their corresponding exposure values by employing the characteristic curve for each film layer. This amounted to finding polynomials of the form

$$\text{Log E} = b_0 + b_1D + b_2D^2 = \ldots + b_kD^i \quad (4)$$

which permit accurate computation of log E values from measured D values. In the above equation, $b_0, b_1, \ldots, b_k$ are constants for a given layer of a given roll of film. Sequential F-tests indicated that third degree polynomials adequately fit the step wedge data. Thus, all densities were converted to relative exposure values using such equations.

Among the five dates of both color and color infrared photography available for densitometric analysis, one date and film type was selected as the optimal combination for subsequent development of the stress pre-

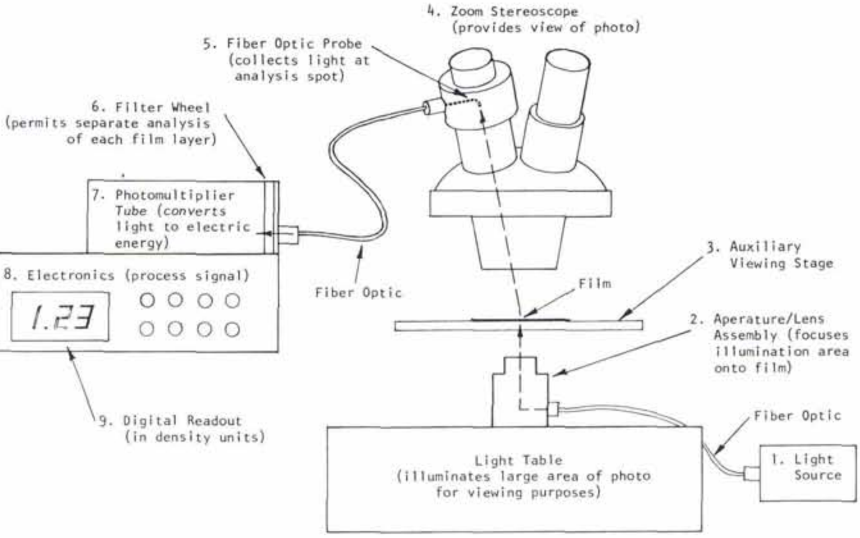

FIG. 2. Microdensitometer schematic.

diction model. The statistical criterion used to select both the film type and the analysis date was that of canonical correlation (Morrison, 1967). Based on a preliminary visual analysis, it appeared that the July photography provided the most interpretable variation in tree stress symptoms. Hence, a random sample of 70 trees was selected on the July photography and density measurements were taken in each of the three layers of both the color and color IR film. The density measurements were converted to relative exposure values, and canonical correlations were performed between the photographic data sets and the five dates of ground data sets. Average correlation coefficients of 0.884 for the color data and 0.906 for the color IR data were obtained and the color IR data were more highly correlated with the ground data on all dates.

As mentioned, the preliminary visual examination of the photography indicated that the July date provided the most interpretable variation in tree stress symptoms. To evaluate this hypothesis, densities of the 70 sample tree crowns were measured on the infrared photography for all five dates. Once again, canonical correlations were computed between the photographic data sets (consisting of exposure values from the three layers plus six interband ratios) and the ground data set (consisting of the seven stress symptom variables). The results of this analysis are given in Table 2. As anticipated in the visual analysis, the highest overall correlation was found for the July date of observation. The average canonical correlation coefficient increased from 0.842 for the June flight to 0.865 for July and then decreased in the months of August, September, and October. Because of its high canonical correlation overall and its high correlation during the period when stress symptoms were most evident on the ground (July), the July photography was selected for the development of the 1975 stress prediction model. Note also that the June photography appeared to be a very good indicator of the stress condi-

TABLE 2. CANONICAL CORRELATION COEFFICIENTS FOR VARIOUS DATES OF PHOTOGRAPHY AND GROUND DATA ACQUISITION

Date of Photography	Date of Ground Data					
(1975)	June	July	Aug.	Sept.	Oct.	Average
June	0.863	0.884	0.833	0.824	0.808	0.842
July	0.902	0.906	0.848	0.838	0.763	0.865
August	0.787	0.830	0.786	0.781	0.763	0.789
September	0.802	0.842	0.793	0.767	0.719	0.785
October	0.797	0.780	0.783	0.775	0.765	0.780

tions to be manifested in subsequent months. In fact, as will be discussed later in this article, we believe that the photography taken in June was recording predisposition to drought stress previsually.

Development of Stress Prediction Model

The photographic and ground data were related using three statistical models (one for each stress index). These models formed the basis for estimating the stress indexes for any tree whose photographic density values were known. The stress prediction equations were determined from a stepwise regression of each stress index on the photographic data for 63 trees selected at random from the park-residential study site. The photographic variables used in the models consisted of (1) the exposure values in each of the three spectral sensitivity bands and (2) the ratios of exposures in the red and green over infrared, red over green, and each band over the sum of the exposures in the three bands.

The regression functions obtained from the stepwise technique were used to compute the predicted stress indexes for each of the 63 trees used in the model development. A plot of the predicted versus the observed values of the stress indexes indicated that second or third order terms might be needed to better fit the ground data. An F-test indicated that inclusion of such terms was warranted. Thus, the final form of the regression equations included 11 parameters whose identities and values are given in Table 3. Included in the table are the estimates of the regression coefficients; the multiple correlation coefficients, R; the standard errors of estimate, s; and the F-statistics for testing the significance of the overall regression equations. All three prediction equations yielded standard errors of estimate which were considered acceptable, particularly given the difficulties inherent in quantifying the ground data.

Inspection of Table 3 indicates that the equations for all three indexes were statistically significant. As expected, the "foliage index" appeared to be most accurately predicted from the photographic data. As we shall see in the next section of this article, under certain circumstances a trunk and limb index or a crown index might be best predicted. The important point is to recognize that the expression of stress by the foliage, the trunk and limbs, and the crown are three distinct expressions of stress, probably different stresses.

Table 3. Results of Multiple Regression Relating Tree Stress Indexes to Photographic Data (1975)

	Tree Stress Index		
	TL	FO	CB
R	0.785	0.891	0.732
s	1.546	0.850	1.586
F	12.591*	27.87*	13.20*
	(7,55)	(8,54)	(5,57)
	Independent Variables		
Constant	105.470	37.2376	−74.8707
IR	0.1655	−0.0585	0.0430
R	−1.9649	−0.2127	—
G	1.6298	0.6930	—
R/IR	−57.1114	−25.4726	−125.3182
G/IR	—	—	58.3690
R/G	−50.1050	11.4869	—
R/S	348.1216	—	408.3616
G/S	—	200.6139	—
G/R	−110.2579	—	—
IR/(R+G)	—	−9.1591	9.2436
$(R/IR)^3$	—	68.3735	—

where G = Exposure in green-sensitive layer
R = Exposure in red-sensitive layer
IR = Exposure in infrared-sensitive layer
S = Sum of exposures in three layers
* significant at $p \leq 0.001$

Model Testing

Testing of the stress prediction models took on three distinct forms, as follows:

(1) The reliability of the foliage prediction model, as developed for trees from one study site, was tested by using it to predict the foliage indexes of a random sample of trees drawn from all four study sites;
(2) The entire modeling scheme was repeated over the test sites during the subsequent growing season (1976); and
(3) The modeling procedure was applied to data collected in another metropolitan area in Rochester, New York.

Testing the Foliage Index Model

Again, because of its observed importance as a sensitive indicator of the tre stress problems encountered in the study, the foliage index became the initial focus for model testing. A random sample of 189 trees drawn form all four test sites was used to test the model. This involved making density observations on these trees and using the results to estimate each tree's foliage stress index. The actual stress index values were computed from the ground data. Figure 3 illustrates the correlation between the predicted and observed values. A paired t-test was performed to determine if there was a significant difference between the stress

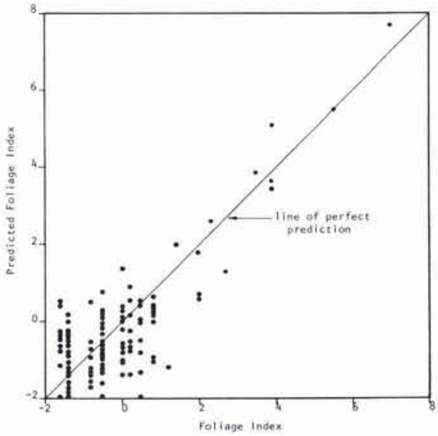

FIG. 3. Reliability analysis of Foliage Index Model (Syracuse, 1975).

index values determined from the aerial and ground data. The resulting t-statistic (0.20) was not significant and was well below the critical value ($t_{0.05,188} = 1.96$). In other words, the foliage prediction model was found to predict the stress index values as reliably as they could be generated from the ground data.

REPETITION OF EXPERIMENT IN 1976

In order to evaluate the repeatability of the results obtained in 1975, the entire model development process was repeated for data collected during the 1976 growing season. Two July flight missions and one August mission were flown in an attempt to bracket the time during which stress conditions peaked. Based on the experience with the 1975 photography, only color infrared film was used in 1976. To enlarge upon and refine the ground data set obtained in 1975, the 1976 field surveys included measurements of the following variables:

- Crown shape
- Crown density
- Number of large dead limbs
- Percentage of small dead limbs
- Relative trunk and limb condition
- Relative foliage condition
- Percentage of foliage affected by primary foliage problem
- Percentage of foliage affected by secondary foliage problem
- Relative seed production

Ground observations during the season indicated that stress problems became observable later in the season than was the case in 1975. This delay in symptom development was apparently due to excessive rainfall in 1976 as compared to 1975.

As was the case with the 1975 ground date, the 1976 data were subjected to a factor analysis to formulate stress indexes. Table 4 shows the results of the analysis. Using the revised ground data variables, a four factor solution was employed and factor loadings which exceeded a cutoff value of 0.4 (underlined in Table 4) were used to formulate the appropriate stress index equations. ie.,

$$\text{TL} = 0.776S_2 + 0.604S_3 + 0.829S_4 + 0.677S_5 \quad (5)$$

$$\text{FO} = 0.866S_6 + 0.818S_7 + 0.722S_8 \quad (6)$$

$$\text{CS} = S_1 \quad (7)$$

$$\text{SP} = S_9 \quad (8)$$

TABLE 4. FACTOR ANALYSIS RESULTS FOR 1976 GROUND DATA

	Factor				
	1	2	3	4	h²
Tree Stress Symptoms:					
Crown shape	0.064	0.064	<u>0.941</u>	−0.024	0.893
Crown density	<u>0.776</u>	0.130	−0.091	−0.065	0.632
No. of large dead limbs	<u>0.604</u>	0.063	0.172	−0.215	0.445
% small dead limbs	<u>0.829</u>	0.155	−0.067	0.076	0.722
Trunk & limb condition	<u>0.677</u>	0.046	0.395	0.147	0.637
Foliage condition	0.255	<u>0.866</u>	0.020	0.105	0.827
Degree 1st fol. problem	0.161	<u>0.818</u>	−0.036	0.042	0.698
Degree 2nd fol. problem	−0.031	<u>0.722</u>	0.102	−0.016	0.532
Seed production	−0.055	0.086	0.001	<u>0.970</u>	0.952
% of total variance	31%	17%	12%	10%	

h^2: communality
underscored loadings are the cutoff point (0.40)

where TL = *Trunk and Limb* index (first factor);
FO = *Foliage* index (second factor);
CS = *Crown Shape* index (third factor);
SP = *Seed Production* index (fourth factor); and
$S_1, S_2, \ldots, S_9$ = standard scores of the nine stress symptoms.

Canonical correlation was again used as the basis for selecting the optimum date of photography for the 1976 analysis. In contrast to 1975, in which July photography proved to be the best selection for stress prediction, the August photography was superior in 1976. This is shown in Figure 4, which depicts the canonical correlation for each set of photographs as a function of ground observation date. Note from this figure that the August photography correlated best with the ground observations for all dates. Note also that the June and September ground observation dates had higher average values than July and August. This represents a quite different result than was obtained in 1975, when July photographic data correlated best with July stress symptoms. The correlation coefficients were also generally lower than those realized in the 1975 analysis. Evidently, these differences were caused by the relatively cool and wet conditions of the 1976 growing season. It is hypothesized that a continuous flushing of young foliage tended to mask the stress symptoms, both from the air and on the ground.

The relationship between the aerial/ground canonical correlation and health conditions was a significant finding in this study. Comparatively little stress information was extractable from any aerial photography taken shortly after a period of rainfall and moderate temperature. Under the condition of early drought in 1975, the June photography correlated with the July stress symptoms nearly as reliably as the July photography. That is, the photographs appeared to indicate drought-induced stress conditions previsually. In fact, the June photography indicated predisposition to drought stress which was not predictable from the June ground data. Rainfall after July in 1975 tended to weaken subsequent photographic manifestations of stress. The rainfall in 1976 was 4.39, 4.33, 2.16, and 3.23 inches above normal for May, June, July, and August, respectively. Every flight in 1976 was preceeded by rainfall and there was no drought period. Under these conditions, trees were never water stressed so that whatever stress manifestations were recorded on the photographs or observed by the ground crews were caused by agents other than water stress. The reduced correlation between photographic and ground data during 1976 are in part due to this absence of one of the major stress factors of urban trees.

Table 5 indicates the results of the regression analysis performed on the 1976 data. Note that only three of the four stress indexes are shown; the "seed production" index model (as anticipated) was not significant. Note also that the modeling results for 1976 were generally weaker than those obtained

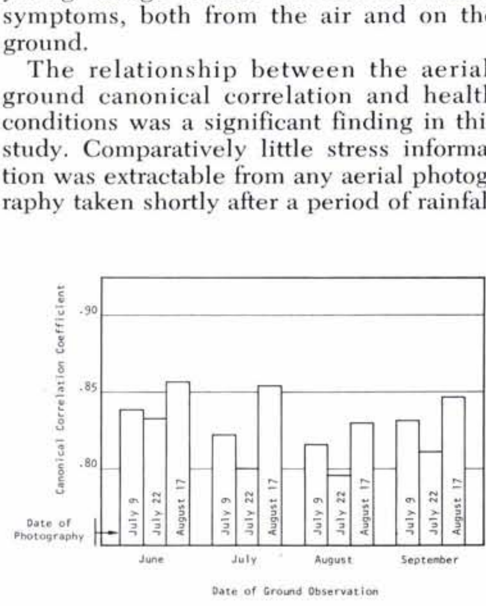

FIG. 4. Canonical correlation between ground and aerial data for 1976 dates of observation in Syracuse.

TABLE 5. RESULTS OF THE MULTIPLE REGRESSION ANALYSIS OF THE 1976 SYRACUSE DATA

	Tree Stress Index		
	TL	FO	CS
R	0.595	0.631	0.680
s	1.584	1.782	0.588
F	4.75* (6,52)	4.83* (7,51)	7.45* (6,52)
	Independent Variables		
Constant	−79.045	−16.109	−171.169
IR	−1.221	—	—
R	—	−3.761	—
(IR^2)	0.0115	0.00423	—
$(R)^2$	—	0.0614	—
G/IR	—	263.367	—
IR/S	—	—	327.539
G/R	138.636	—	−45.463
$(G/IR)^2$	—	—	−306.589
$(R/S)^2$	484.773	—	—
$(R/IR)^3$	−86.736	−97.481	183.829
$(G/S)^3$	—	−2880.309	7002.652
$(G/R)^3$	−47.026	−12.083	—
$(IR/(IR+G))^3$	—	—	2.763

where: G = Exposure in green-sensitive layer
R = Exposure in red-sensitive layer
IR = Exposure in infrared-sensitive layer
S = Sum of exposures in three layers
* significant at $p \leq 0.001$

in 1975 and the "crown shape" index was most reliably predicted by the photographic data. The unique condition of no water stress in 1976 reduced the reliability of the foliage index as a predictor. It would be expected that the foliage index is the most responsive to current moisture condition. This was seen in the 1975 model. The stress observed in Syracuse in 1976 is a more long-term stress expressed through deterioration of the crown.

ROCHESTER TEST

In order to assess the applicability of the modeling scheme in another metropolitan area, an aerial and ground survey was completed for two study sites located in Rochester, New York (approximately 120 km from Syracuse). A total of 683 maples were observed for this purpose during August, 1976. The same procedure as employed in Syracuse was used to collect the aerial and ground data. The modeling approach was applied to 81 maples located on seven streets whose names were selected at random. The results of the factor analysis of the ground data were essentially the same as those obtained in the Syracuse data analysis. For purposes of comparison, the stress index formulas for both the Syracuse 1976 and Rochester 1976 data are listed below:

$$\text{TL (Syracuse)} = 0.776S_2 + 0.604S_3 + 0.829S_4 + 0.677S_5 \quad (5)$$

$$\text{TL (Rochester)} = 0.743S_2 + 0.529S_3 + 0.839S_4 + 0.706S_5 \quad (10)$$

$$\text{FO (Syracuse)} = 0.866S_6 + 0.818S_7 + 0.722S_8 \quad (6)$$

$$\text{FO (Rochester)} = 0.704S_6 + 0.738S_7 + 0.838S_8 \quad (11)$$

$$\text{CS (Syracuse)} = S_1 \quad (7)$$

$$\text{CS (Rochester)} = 0.818S_1 + 0.664S_3 \quad (12)$$

$$\text{SP (Syracuse)} = S_9 \quad (8)$$

$$\text{SP (Rochester)} = S_9 \quad (13)$$

where TL = *Trunk and Limb* index;
FO = *Foliage* index;
CS = *Crown Shape* index;
SP = *Seed Production* index; and
$S_1, S_2, \ldots, S_9$ = standard scores of the nine stress symptoms.

The fact that the factor loadings for both the Syracuse and Rochester data were so similar suggests that this approach to stress index development has some degree of goegraphic universality.

Because the stress index results had been nearly identical, the equations developed previously (Equations 5, 8) were applied to the Rochester ground data. Again, stepwise regression was used to develop predictive models. The results of the regression analysis are indicated in Table 6. Only the "Trunk and Limb" and "Foliage" index equations were significant, but the standard errors of estimate and multiple correlation coefficients were even better than those obtained with the Syracuse 1976 data.

TABLE 6. RESULTS OF THE MULTIPLE REGRESSION ANALYSIS OF THE 1976 ROCHESTER DATA

	Tree Stress Index	
	TL	FO
R	0.821	0.672
s	1.554	1.498
F	21.50*	15.65*
	(7,73)	(4,76)
	Independent Variables	
Constant	−118.078	−59.065
IR	0.280	—
G	−0.891	—
(R/IR) (G/IR)	153.425	—
(R/IR) (R/G)	257.733	136.558
$(R/IR)^3$	−727.379	−323.084
$(IR/R)^3$	0.160	—
$(IR/G)^3$	—	0.0697
$(G/R)^3$	40.394	25.215

where: G = Exposure in green-sensitive layer
R = Exposure in red-sensitive layer
IR = Exposure in infrared-sensitive layer
* significant at $p \leq 0.001$

The significance of the "trunk and limb" and "foliage" indexes but not the "crown shape" index for Rochester is presumed to result from differences in tree management between the two cities. Crown disruption from utility wires in Rochester is much less prevalent than is the case in Syracuse. A relationship between crown disruption and death of branches was found for Syracuse but not for Rochester. The absence of a crown disruption stress in Rochester thereby greatly reduces the significance of a "crown shape" stress symptom index. The higher level of significance of the "trunk and limb" than the "foliage" index continues to reflect the absence of water stress on the Rochester tree population and emphasizes the role of other stress agents.

CONCLUSIONS

Based on the results and experiences of this study, the following general conclusions have been reached:

(1) The full potential for detecting urban tree stress from aerial photography can be thoroughly evaluated only when the stress conditions are expressed quantitatively. Given the complexity of stress

manifestations in urban environments, some means must be provided for reducing the large set of observable symptoms to a workable and meaningful set of stress indexes. In this study, factor analysis was found to provide an effective, rational means for doing this.

(2) Exposures and ratios of exposures, extracted from sensitometrically calibrated film and used in multiple regression models, predicted selected stress indexes as reliably as they could be estimated through ground observation.

(3) The success of any aerial photographic stress prediction effort is highly dependent upon the rainfall conditions prior to the acquisition of the photography. Under the "drought" conditions of 1975 in this study, foliage stress was previsually detected from the photography. Attempts at quantifying stress from photography taken shortly after periods of excessive rainfall were far less successful.

(4) Color infrared film is generally superior to color film in the stress quantification process, due primarily to the influence stress had on the infrared to red reflectance ratio.

(5) Of the stress indexes developed for this study, the "foliage" index was the best predictor of water stress. The increase in importance of the "trunk and limb" and the "crown shape" indexes during periods of water abundance shows the utility of the method for assessing more long-term stress symptoms.

The above conclusions should be construed as working hypotheses only. The authors suggest that further research is necessary to confirm the validity of these hypotheses over a range of alternative conditions. These conditions include, but are not limited to, changes in study location, species, stress index parameters, image processing hardware, sensor system (e.g., airborne multispectral scanning), statistical characterization of stress conditions, and sampling procedures. Our major point is that urban tree stress can be quantified only when meaningful combinations of on-the-ground observations can be developed statistically to arrive at a series of stress indexes. Related to this is the fact that no single spectral density measurement or combination of measurements will tell an analyst about the overall picture of the vigor condition of a tree under all conditions. Multiple spectral observations are required; how they can be combined effectively to estimate stress levels will vary with every situation. One must recognize the need for a multivariate definition of tree stress, be it measured on the ground and/or from the air. The authors hope that the approach taken in this study will encourage other investigators to take a second look at the urban tree stress detection process in this light.

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