PHOTOGRAPHIC DETECTION AND QUANTIFICATION OF URBAN TREE STRESS

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ABSTRACT

This paper describes case studies aimed at detecting and quantifying urban tree stress of two fundamentally different types in two locations: 1) maple decline - in Syracuse, New York, and 2) Dutch Elm Disease - in St. Paul, Minnesota. In the maple decline study, factor analysis was used to develop numerical "stress indexes" based on ground data. Then, spectral density measurements from 1:6000 color infrared photography were related (through multiple regression) to these stress indexes. The resulting statistical model enabled prediction of stress conditions throughout the study area, based solely on spectral density measurements.

In the Dutch Elm Disease detection study, first a conventional interpretation of 1:6000 and 1:12,000 color infrared photography of multiple dates was performed. Second, scanning microdensitometer data were analyzed in various ways to explore digital approaches to detection of the disease. Described briefly are ongoing studies of the use of digitally enhanced images and discriminant function analyses to aid the disease detection process.

I. - - INTRODUCTION

Trees provide many tangible and intangible values in and around metropolitan areas. These values range from providing sanctuary for wildlife, to reducing temperatures, providing visual screening, and generally enhancing the setting for aesthetic enjoyment. While providing these values, however, trees in the urban environment are subject to inordinate sources and degrees of stress. Maintaining the delicate ecological balance between urban and suburban residents and their surrounding vegetative environment is becoming increasingly complex, important and costly. For example, in the last three years the city of St. Paul, Minnesota spent more than $21 million to remove trees killed by Dutch Elm Disease and plant replacements. In 1977 alone, some 47,000 elms were lost to the disease in this city.

With continued increase in land areas dedicated to urban use, the scope of the problem of urban tree cover maintenance is likely to be much larger. Hence, remote sensing will no doubt play an increasing role in monitoring tree stress problems. However, in contrast to their application in rural forested settings, remote sensing techniques have received relatively little attention in the urban context. This is particularly true for the application of quantitative techniques. The research reported herein was undertaken with this in mind. That is, the general intent of this work was to assess the utility of quantitative photographic analyses to urban tree stress detection.

"Stress" as used here refers to 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 pollution, temperature extremes, soil compaction, de-icing salt, and mechanical damage. The proper selection of locally adapted vegetation, old age deteriorization, and changing environments are additional aspects of stress in urban trees.

The case studies described in the remainder of this paper illustrate two quite different types of tree stress problems. The first study - conducted in Syracuse, New York - was aimed at quantifying a complex deterioration problem known as maple decline. This condition is difficult to inventory and manage because of the large number and diversity of interacting factors involved, and, the long period of deterioration leading toward tree death. With this type of multifaceted problem, the intent of monitoring activities is <u>not</u> to group trees into healthy vs unhealthy condition classes. Rather, all trees are known to occupy some position along a continuum of vigor condition. The object is to determine just where along this continuum any given tree resides. In the case study first described below, spot microdensitometer readings from color infrared film were used in a multiple regression model to predict quantitative indexes of maple decline. These indexes were based on the application of factor analysis techniques to various forms of ground reference data.

The second case study to be described in this paper is an ongoing evaluation of quantitative techniques for detecting Dutch Elm Disease. Contrary to the first case study the problem here is one of determining the healthy or unhealthy condition of any given tree. Digital image enhancement procedures and discriminant analysis techniques are being evaluated in this study. They are discussed very briefly in the latter part of this paper.

II. - - SYRACUSE MAPLE DECLINE STUDY

Study Objectives

The threefold objective of the Syracuse study was:

1) To develop a means of quantifying maple decline stress levels <u>on the basis of ground data alone</u>.

2) To develop a statistical model for predicting stress levels based on photo density measurement.

3) To test the validity of the photographic model by studying a random sample of test trees of known stress condition. Replicate tests were to be made during the 1975 and 1976 growing season.

The following sections summarize how the above tasks were performed. A more detailed description of this research is given by Eav (1977), Lillesand et al. (1978), and Lillesand et al. (1979).

Data Acquisition

Four study areas containing substantial numbers of maples were selected for the study. They typified residential, park-residential, Central Business District (CBD) and industrial land use areas, respectively. The study population included 696 Norway Maples, 312 Silver Maples, and 148 Sugar Maples. During the 1975 growing season, the 1156 sample trees were inspected on the ground on a monthly basis and stress problems were both categorized and coded numerically. Stress symptoms of the foliage, trunk and limbs, and overall health condition were diagnosed and 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 of five ground surveys. The photographic coverage took the form of 1:6000, 70mm format, vertical color (Kodak 2448, haze filter) and color infrared (Kodak 2443, Wratten 15 filter) positive transparencies. Hasselblad 500 EL (f=80mm) cameras were used to obtain the photography from a fixed wing Cessna 172 aircraft. Step wedges were exposed on each film leader prior to processing for sensitometric calibration.

Reduction of Ground Data

Various alternative strategies were considered for quantifying the stress conditions observed in the field. The seven field measurement parameters 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 should be reduced to a number of composite stress indexes. These indexes could then be compared with the calibrated image densities on a meaningful basis. The stress indexes were formulated with the aid of factor analysis -- a technique of multivariate analysis that attempts to account for the essence of the correlation pattern in a set of observable random variables through computation of a minimal number of unobserved latent random variables called factors. For reasons which will be discussed later, the ground survey data collected during July were selected to develop the stress indexes.

The results of the factor analysis of the original seven variables are given in Table 1. For each factor the original variable having loadings greater than 0.40 (underlined in Table 1) were included. A three factor solution was found to adequately express 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.

3) A crown and branch (CB) index formed by the percent of live crown and the number of small dead limbs.

Table 1. Factor Analysis Results For 1975 Ground Data

	Factor			
	1	2	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%	

notes: h^2: communality

underscored loadings are above the cutoff point (0.40)

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. The original variables (standardized to the same mean and standard deviation) and the factor loadings were used to compute the three stress index values as follows:

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

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

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

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

Thus, those variables with the highest loadings on a factor (i.e., the most important variables) have the greatest effect in estimating each index. 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 a specially fabricated microdensitometer system. This system consists of a Bausch and Lomb Zoom 240 Stereoscope/Richards Light Table combination, to which a densitometer assembly has been added. This setup enables the image analyst to view positive transparencies in a conventional manner and obtain digital density readings simultaneously. Tree crown densities were read using a 200μm 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 blue, green and red-forming color film layers. All raw density readings were converted to their corresponding exposure values via a cubic polynomial approximating each characteristic curve.

Among the five dates of both color and color infrared photography available for densitometric analysis, one date and film type was selected - on the basis of canonical correlation - as the optimal combination for subsequent development of the stress prediction model. Densities of 70 randomly selected sample tree crowns were measured on the photography for all five dates. 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). As anticipated through visual analysis, the highest overall correlation was found for the July date of observation and the color IR film type (0.865).

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 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 included 11 parameters whose identities and values are given in Table 2.

Included in the table are the estimates of the regression coefficients, B's, 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 2 indicates that the equations for all three indexes were statistically significant.

	Tree Stress Index		
	TL	FO	CB
R	0.785	0.891	0.732
s	1.546	0.850	1.586
F	12.591* (7,55)	27.87* (8,54)	13.20* (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 $p \leq 0.001$

Table 2. Results of Multiple Regression Relating Tree Stress Indexes to Photographic Data (1975)

Model Testing

Testing of the stress prediction models took on two 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).

Testing the Foliage Index Model

Because of its observed importance as a sensitive indicator of the tree stress problems encountered in the study, the foliage index became the initial focus for model testing. A random sample of 189 trees drawn from all four test sites was used to test the model. This involved making density observation 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. A paired t-test was performed to determine if there was a significant difference between the stress 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

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 with color IR film in an attempt to bracket the time during which stress conditions were most evident. 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 compared to 1975.

As was the case with the 1975 ground data, the 1976 data were subjected to a factor analysis to formulate stress indexes. 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. The August photography correlated best with the ground observations for all dates. 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 manifestation of stress. The rainfall in 1976 was above normal for May, June, July, and August. Every flight in 1976 was preceded by rainfall and there was no drought period. Under these conditions, trees were never water stressed so 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. Accordingly, the modeling results for 1976 were generally weaker than those obtained in 1975 and the unique condition of no water stress in 1976 reduced the reliability of the foliage index as a predictor.

III. - - St. Paul Dutch Elm Disease Study

Most U.S. programs aimed at Dutch Elm Disease Detection from color infrared photography have yielded generally unacceptable results -- due to high errors of interpreter omission and commission. In addition, few studies have employed quantitative disease detection through image density measurement. Most notable are those reported by Stevens (1972), and Hammerschlag and Sopstyle (1975). In the former effort, laboratory spectroradiometer readings varied markedly as a function of the point in the growing season of disease symptom development, and no single spectral region yielded definitive information at all times. In the latter study, ratioing of multiband images proved inconclusive in enhancing disease detection. However, the investigators suggested that "there should be further use of the scanning microdensitometer as an analytical tool to compare reflectance values from healthy and variously stressed vegetation." This is precisely what is being investigated in the ongoing St. Paul study described briefly below.

Data Acquisition

Two test sites were selected which contain a representative range of conditions under which an operational disease detection system might be implemented. Ground data about the health of the 2000 elms in the study areas were acquired as photographs of the areas were obtained on May 3, May 15, June 25, July 25 and September 6, 1979. The photographs were 70mm color infrared transparencies taken at scales of 1:6000 and 1:12,000. The May photographs showed all elms in a "leaf-off" condition, in contrast to the other four image sets.

Preliminary Visual Analysis

To provide a baseline against which to evaluate subsequent microdensitometer analyses, a preliminary "manual" interpretation of all imagery was undertaken. Using the May leaf-off photography, elms could be identified very readily from other species by their distinctive crown shadow and black trunk color. Several elms known to have Dutch Elm Disease were both field checked and located on the July leaf-on imagery to develop a set of identifying characteristics on the photographs for trees having the disease. Then, the 1:12,000 and 1:6000 images for each of the five dates were interpreted sequentially. Apparent disease symptoms were rated into high, medium and low levels of interpreter confidence. After the image interpretation process was completed, ground data from each area were made available on the precise location, date of detection, and approximate date of removal for diseased elms. In general, the preliminary results of comparing the aerial and ground data have been disappointing in that some 30% of elms known to be diseased were not identified as being so (on either scale of imagery on any date) by two trained interpreters. At the same time substantial numbers of commission errors were made by both interpreters. While disappointing, these results were not unanticipated based on similar previous research, such as that reported by Nash et al. (1977).

Digital Analysis

Selected frames covering the entire study population have been digitized using a P-1700 Optronics drum scanner. In this process, density readings in the 0-3D range are recorded using a 50µm spot size and a 0-255 integer recording range. Separation filters are used to scan the film to isolate the approximate image structure on the blue, green, and red layers, respectively. The resulting digital data are being used in two ways: 1) to prepare enhanced image products for subsequent manual interpretation, and 2) to develop discriminant functions to "automatically" separate healthy and diseased trees numerically.

The enhanced images are made in a D-47 Dicomed Color Image Recorder. Prior to recording, the digital data from each band of the original film are contrast enhanced using analyst-supplied values for the lightest and darkest densities for elm crowns. Also, two-band ratio images of all combinations of the original data have been prepared. As illustrated in the oral presentation of this paper, the digital recording techniques appear to improve the information content of the original image and facilitate disease detection.

The discriminant analysis techniques under investigation involve the use of training data for healthy and diseased trees to develop a linear function for classifying arbitrary pixels into either of the classes based on the densities observed. Space precludes detailed description of this procedure, but the oral presentation of this paper described the methods being used and the results being obtained with this method.

IV. - - CONCLUSIONS

Based on the results of these case studies, the following general conclusions have been reached:

1) The full potential for studying decline-type tree stress from aerial photography can be 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 symptoms observable on the ground to a workable and meaningful set of stress indexes. In the Syracuse study, factor analysis was found to provide an effective, rational means for doing this.

2) Color infrared film has been shown statistically to be generally superior to color film in the stress quantification process (due primarily to the influence stress has on infrared and red reflectance of stressed trees).

3) Exposures and ratios of exposures, extracted from sensitometrically calibrated film and used in multiple regression models, can predict selected stress indexes as reliably as they can be estimated through ground observation in decline studies.

4) The success of any aerial photographic stress prediction effort is highly dependent upon the rainfall conditions prior to the acquisition of the photography. While under the "drought" conditions of the 1975 study in Syracuse, 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.

5) Individual crown delineation and species recognition is often done most easily in urban tree stress studies using "leaf-off" photography for this purpose.

6) Efforts aimed at detecting Dutch Elm Disease using conventional interpretation were only moderately successful. Digital image contrast enhancement, ratioing, and discriminant analysis improved upon disease detection. Additional research is continuing in this vein.

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