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FINAL TECHNICAL REPORT TO
NASA - JOHNSON SPACE CENTER:
COVER PROJECT AND
EARTH RESOURCES RESEARCH TRANSITION

A Cooperative Agreement Between NASA-Johnson Space Center
and University of California, Santa Barbara

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FINAL REPORT: JOHNSON SPACE CENTER

COVER AND EARTH RESOURCES RESEARCH TRANSITION

1.0 INTRODUCTION

Funding for the work reported here was initially granted to continue ongoing research in the remote sensing of natural boreal forest vegetation (the COVER project). It was supplemented, upon the discontinuation of earth resources research at Johnson Space Center, to facilitate transfer of data bases and to maintain and transfer research programs from Johnson Space Center to other research centers following the termination of earth resources research at Johnson Space Center at the end of 1984. In particular, this effort was focussed on preserving and documenting the large and unique data base acquired by the COVER project in its research on remote sensing of boreal forests, and on maintaining continuity in the analysis of these data during transfer of the research to other centers. This required completion of ongoing data collection, preparation of research materials for transmission, and actual transmission of materials. Maintenance of value of materials required checking for error in entry, storage, and transferral of data, documentation of raw data sets, and documentation of an extensive package of software developed for data analysis.

The work was carried out by researchers from University of California, Santa Barbara (UCSB) and Johnson Space Center, all of whom had been involved in the development and performance of the COVER research program. Data and research programs were transferred, primarily, to UCSB and NASA-Goddard Space Flight Center.

The COVER project is described in detail in other documents (see initial proposal). In basic design, the project focussed on accurate ground measurements of important vegetation variables to be used in hierarchical calibration of spectral data from helicopter-borne spectrometers, aircraft-borne TMS, and satellite imagery. The overall goal of our research is to contribute to the measurement of the global biomass and net primary productivity in a program of assessing the continued habitability of the earth. Our intention is to demonstrate the validity of using remote sensing to monitor vegetation characteristics by measuring biomass, productivity, and leaf area for specific regions of boreal forest, with an error of less than 20%.

Since direct ground measures of biomass and production for large areas of the earth's surface is not feasible, we have worked to develop and test remote sensing techniques. Our approach includes the development and calibrating of models that relate vegetation characteristics to remote sensing data. In this work we use our understanding of physical relationships and appropriate statistical procedures to develop models relating (1) biomass and productivity to leaf area indices, and (2) leaf area indices to remotely-sensed spectral images. This requires (1) accurate ground measurement of vegetation characteristics, (2) acquisition of remotely-sensed data for measured sites, and (3) study and development of canopy reflectance models and statistical models. The vegetation selected for the initial research was boreal forest and our effort focused on testing our capacity to achieve these goals in important phases of boreal forest vegetation of an initial test site.

In the following sections we 1) summarize results of COVER research funded during 1983-1984 by Johnson Space Center (JSC) and 2) document the transfer, documentation, and distribution of materials from the research.

2.0 REVIEW OF 1983 RESEARCH TASKS AND RESULTS

We began research under an original proposal to NASA, Habitability of the Earth: Assessing Key Vegetation Characteristics in March, 1983. We chose to begin this research in the Superior National Forest (SNF) near the Boundary Waters Canoe Area, just outside of Ely, Minn. This site was chosen for a number of reasons. First of all, it is one of several areas where the boreal forest extends into the coterminous United States. We believed that our initial research should be done within the United States in order to minimize political and logistic problems. Second, because funds became available relatively close to the start of the vegetation growing season, we had to locate sites in an area where we could set up the research rapidly. One of us (D.B.Botkin) was familiar with the SNF, with research done in this area, and with some of the scientists who had done this research. We knew from personal contacts that we would have considerable assistance in locating sites near Ely. In particularly, Dr. M.L. Heinselman, an expert on the history of vegetation of this region, was extremely helpful, and assisted us in finding our initial sites. Moreover, we found that the U.S. Forest Service was very cooperative, and was well set up to support research of the kind we wished to do. Third, to minimize the complexities of the remote sensing measurements, we sought an area with relatively little topographic relief, and with comparatively clear weather. Fourth, we needed an area with a considerable variety of forest stands of different ages and composition, all within a distance that could be reached by the helicopter. The Superior National Forest near Ely met these requirements better than any other site we could locate in the United States.

Once funding was approved, an initial reconnaissance trip was made to Ely, Minn. where we met with Forest Service personnel, worked out the logistics for field in situ measurements and for the helicopter remote sensing. Sites were located, a field crew hired, and research started in the spring, with the first measurements made during May, 1983. During the summer new techniques and procedures were developed for many in situ tasks including the marking of sites so that they were clearly visible

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to the helicopter; procedures for recording data in the field; and methods for dimensional analysis. It is our belief that, in spite of an extremely short time to prepare the research (the time between when funds first became available and when the growing season required us to begin making measurements), we made considerable progress and obtained a very large amount of valuable data, some of which is unique. Below, we review data collection and analysis tasks for our first year's work (spring 1983 through spring 1984).

2.1 Establishment of a Baseline Forest Test Site.

Objective. The objectives of this task were the location of an initial study area in a boreal forest region with suitable characteristics of size, variability, species, and existing ancillary knowledge to support remote sensing research in forest ecosystems. Availability of necessary logistical support was also important. Within the test area, it was necessary to select vegetation types and particular sites for intensive measurement and study.

Scope. *In situ* field research in the primary study area has been conducted by UCSB Environmental Studies personnel.

Approach and Results. For this study, we have chosen the Superior National Forest (SNF) in Minnesota because it has a number of characteristics which make it particularly well suited to the estimation of forest biomass and productivity.

The SNF contains one of the largest areas of boreal forest in the contiguous United States (including the 200,000 hectares (ha) Boundary Waters Canoe Area wilderness). The SNF lies in a region of relatively little topographic relief compared to many evergreen forests of the world such as those of the Sierra Nevada and Rocky Mountains of North America, yet it also contains stands with a wide range of variation in leaf area, biomass, and productivity. In addition, the SNF is well suited as a study site because (1) tree species representative of much of the entire boreal forests (e.g., *Pinus banksiana*, *Picea mariana*, *Picea glauca*, *Abies balsamea*, and *Populus tremuloides*) are abundant within the region of the BWCA; (2) the area is strongly influenced by fire (Heinselman, 1973) which has produced a mosaic of forest stands exhibiting a range of age, biomass, productivity, and leaf area; (3) the area is well studied ecologically and valuable baseline information is available; and (4) excellent logistics are available, including jet fuel at the Ely, MN airport, assistance from U.S. Forest Service, and well-maintained road access to a wide range of vegetation.

Study plots were established in the SNF by a sequence of steps. First, the vegetation was stratified into 5-6 distinctive forest types, based on reports in Ohmann and Ream (1971) and Grigal and Ohmann (1975) and observations of the Principal Investigators (see Figure 1). These classifications are based on

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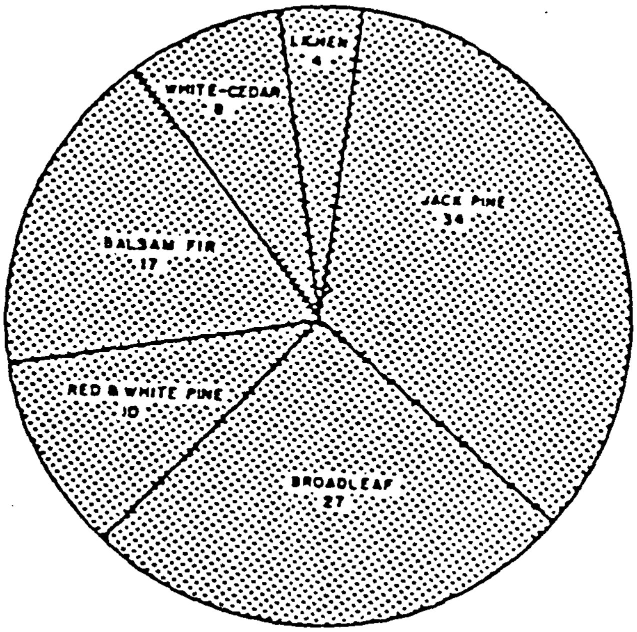

FIGURE 1[illegible]: Distribution (in percent) of forest-types in the Boundary Waters Canoe Area, Minnesota (from Chmann and Ream, 1971).

differences in species composition among stands and accurately reflect differing ecological conditions within the SNF. Heinselmann (1973) has established maps of all major fires there from the 17th century until the present. This and other information was used to select a set of forest stands representing a range of ages and a range of leaf area, biomass and productivity to establish likely sample areas.

The decision was made to concentrate initial efforts on stands of two species: black spruce (the primary dominant in wetland forests) and trembling aspen (the primary constituent in "broadleaf" forests in Figure 1). Black spruce and trembling aspen were chosen because these species have the broadest geographic ranges of North American boreal forest species and because, in every aspect, they represent opposite ends of a vegetation spectrum: black spruce is evergreen and characteristic of bogs and other wet sites, and of old growth forests; trembling aspen is deciduous and characteristic of dry, upland areas and of young forest stands. Some work was done in stands of other types, preliminary to more intensive study in future field seasons.

Stands of these species were chosen to cover the range of available biomass and leaf area for the two study species. An initial stratification on these characteristics was based on qualitative observations of the principal investigators. Specific sites were chosen within these stands as "hover-sites." These were the locations for which vegetation characteristics were measured and over which spectral data were taken from a hovering helicopter. Sites were 60 m in diameter and selected for homogeneity.

One of the unique contributions of our field-work in 1983 was the development of rapid site selection techniques using a coordinated team of helicopter and ground crews. In the past, site selection for ecological rsearch has been done by ground crews, but dense foliage and low visibility from the ground made selection of sites on the basis of biomass, productivity, and uniformity very slow and unreliable. We found that the principal investigators, working from the helicopter flown by NASA pilots, were able to choose sites quickly and direct ground crews, by radio, to sites by the most direct route. Ground crews marked sites and access routes for later use. The helicopter crew was able to locate sites and direct two ground crews simultaneously. We believe that this technique has broad potential for application to research related to the study of the biosphere and Global Habitability in many areas of the Earth.

During the summer of 1983, 31 hover-sites, or plots, were selected in black spruce stands and 31 in trembling aspen stands. 12 plots were selected in jack pine stands and 8 in mixed stands of jack pine and aspen.

2.2 Measurement of Biophysical Vegetation Characteristics

Objective. The objective of this task was accurate in situ measurements of leaf area index (LAI), biomass, net primary production, and other relevant vegetation characteristics for the intensive study-sites.

Scope. This task was conducted in the field in the SNF by UCSB Environmental Studies personnel.

Approach. Since measurement of important biophysical characteristics directly requires destructive sampling (cutting down and removing vegetation), and study sites needed to be left intact for repeated spectral measurement, values were estimated using a two-phase, indirect approach called dimension analysis. In this method sacrificed trees are carefully measured and weighed. Regression techniques are used to develop predictive relationships between over-all dimensions and parameters of interest. On the hover-sites, appropriate dimensions were measured non-destructively and used with fitted regressions to estimate biomass, LAI, etc. The dimensions of the trees included stem diameter, tree height, and height to the lowest and highest live branch.

Predictive equations derived from dimension analysis are species-specific and cannot be safely generalized between regions. Although dimension analyses has been done for most boreal forest species, it was necessary to perform our own analysis for black spruce and trembling aspen because (1) none has been done locally for black spruce; (2) available analyses do not provide predictors of leaf area; (3) available analyses have used non-mechanistic, correlative regression models and we felt that mechanistically-derived models would be superior, and (4) existing analyses do not provide sufficient statistical information to allow reliable estimates of the error associated with biophysical parameters.

We developed a series of potential regression models to be used in our dimension analysis (Figure 2). 31 spruce trees and 32 aspen trees were sacrificed. Components (bole wood, branch wood, new twigs, leaves, bark, and fruit) were separated (leaves, branches, and twigs were divided into three crown strata) and weighed and measured. Samples were taken for area measurement, dry biomass determination, and other detailed measurement.

On study plots, three classes of field data were recorded: (1) environmental conditions of the study plot, (2) physical dimensions of trees, and (3) quantitative estimates of the cover of shrubby and herbaceous species. Environmental data are necessary for interpretation of vegetation patterns and as collateral data in the estimation of ecosystem biomass and net primary productivity. For each study plot, the following specific environmental data were recorded: geographic location,

BIOLOGICAL MODEL FOR DIMENSION ANALYSIS

To Predict Leaf Area (=k × Leaf Weight)

I. Simple Model

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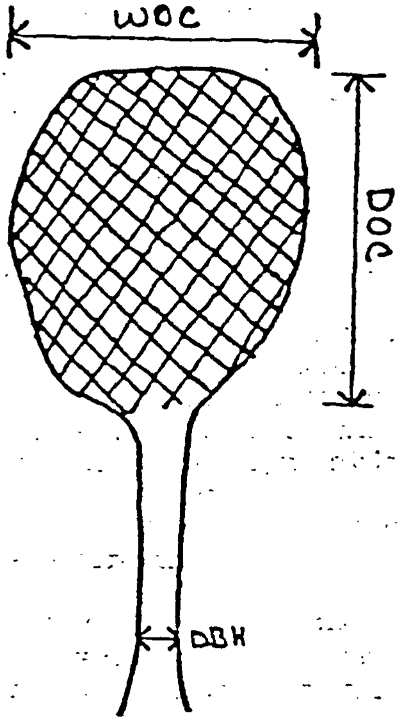
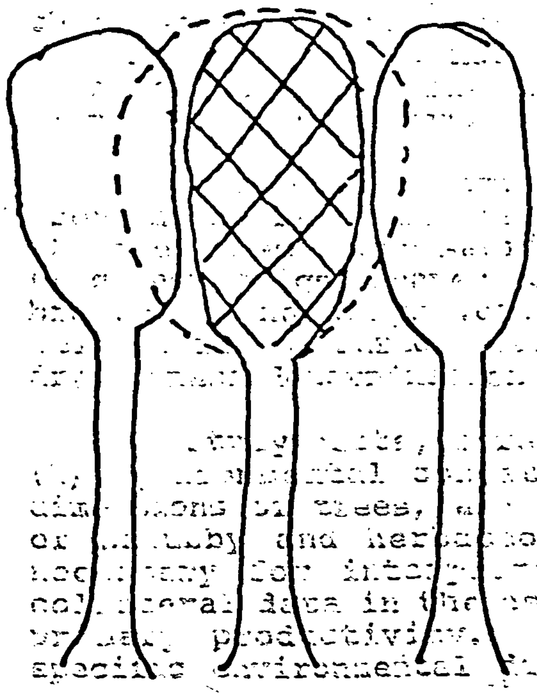


$$\text{Leaf Weight (LW)} = \rho \cdot c \cdot (WOC)^2 \cdot DOC$$

II. Competition Model



$$WOC = WOC_m \cdot f_1(\text{competition})$$

$$\rho = \rho_m \cdot f_2(\text{competition})$$

So

$$LW = \rho_m f_2 \cdot c \cdot (WOC_m f_1)^2 \cdot DOC$$

Figure 2[illegible]. Dimension analysis models were developed based on geometry of tree crowns and biological interactions between trees.

elevation, slope, aspect, and nature of soil.

At each site a circular plot of 60 m diameter was mapped, and within this larger plot five small plots were laid out (Figure 3). On each of these five plots standard measurements of all trees within a radius of 4-8 m (depending on density of stems) were made. These included diameter, height, height to the lowest and highest living branch, and diameter at first live branch. These were thought to be the best correlates with biomass, leaf area and productivity. Within 2 m of each subplot center, all shrubs were tallied and measured (height and diameter) and cover of herbaceous species estimated.

Although initial site selection was strictly qualitative, based on helicopter and ground observations, the available range of pertinent variables seems to have been well covered. 31 plots each of aspen and black spruce were sampled.

In addition to the spruce and aspen sites, data were also collected for twelve jack pine stands and eight plots with a mixture of two species (jack pine and aspen). (Jack pine measurements were taken to determine the accuracy with which two conifers could be differentiated by helicopter remote sensing and in anticipation of further work on this species in the future. The mixed stands were measured because large areas of forest are composed of stands of two to several species, and it was necessary to begin to consider the problem of mixed pixel responses for planning for the 1984 field season. These additional measurements, therefore, should facilitate design of further study involving stands of these types.)

Results. Initial analyses of data from sacrificed aspen and black spruce trees show strong relationships between tree dimensions and leaf area and biomass (Figures 4 and 5), allowing accurate estimates of total leaf area and biomass on hover-sites. We have also developed procedures for estimating statistical variance associated with each phase of the estimation process for leaf area and biomass (variance associated with within-tree sampling of leaves and branches, with number of trees sacrificed, and with geographical heterogeneity within plots). Aspen leaf areas are best estimated by a function of crown volume, biomass by a function of stem diameter. For black spruce, both biomass and leaf area are best estimated by functions of stem diameter. We have used these relationships to estimate LAI for 31 hover-site plots of each species. For aspen LAI ranges from about 1.0 to 3.5. Black spruce stand LAI's range from about 0.5 to 6.5. These ranges represent ranges to be expected for these stand types and densities and are, from an ecological stand-point, reasonable. Estimates of coefficients of variation are mostly less than 20%, although they range from 4% to 40%. Overall, the greatest uncertainty in our estimates is due to the number of sacrificed trees used in the development of dimension analysis relationships. However, several sites with particularly high C.V.s have large contributions due to geographic variation within the site. These statistical developments are a non-trivial

Figure 30. Sample plot design. Total diameter of plot is 60 m (radiometer pixel has diameter of approximately 30 m). All trees were measured in five sub-plots, each 16 m in diameter. Subcanopy and understory were measured in smaller sub plots within each 16 m sub-plot.

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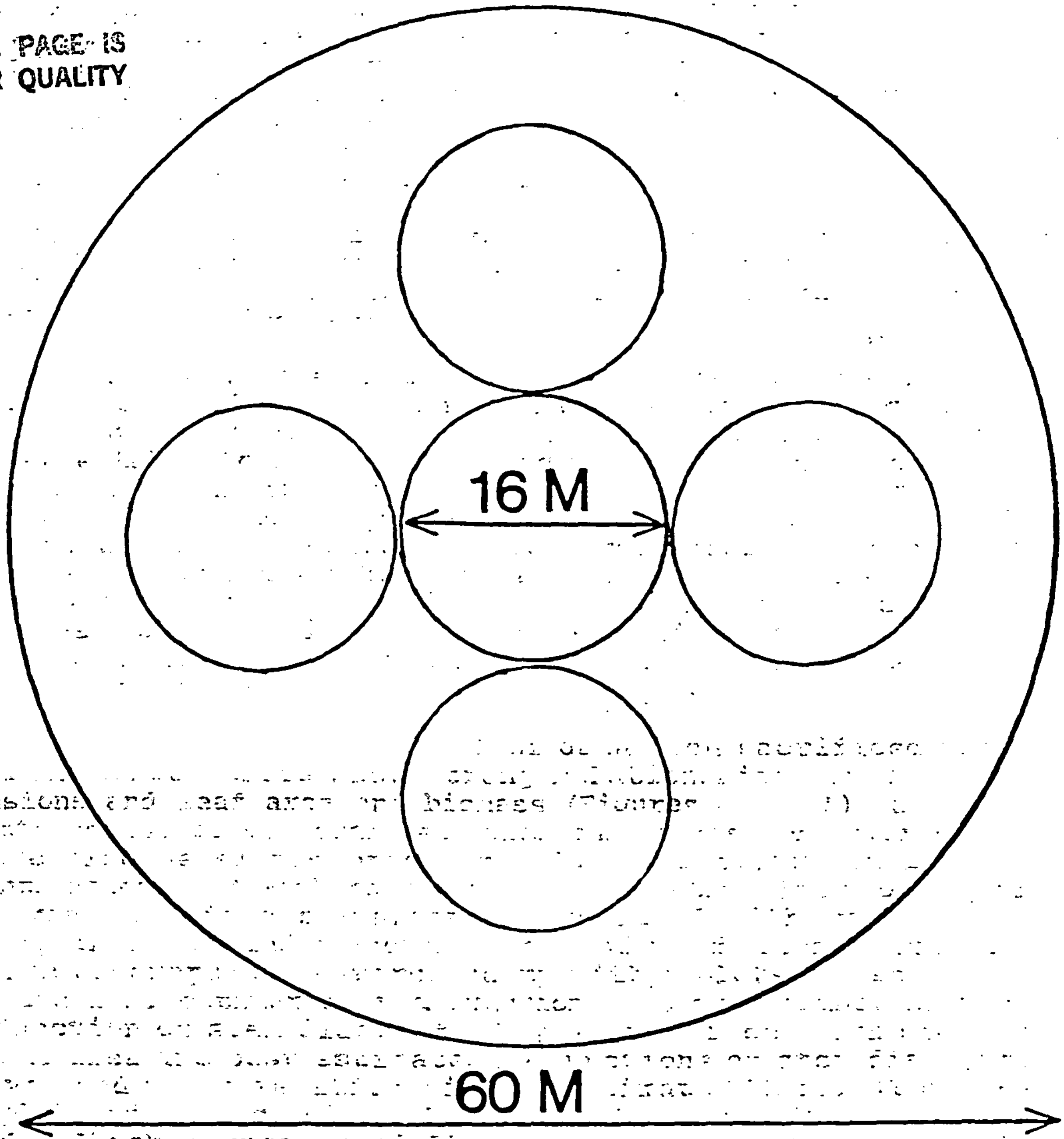

dimensions and leaf area and biomass (Figure [illegible]

[illegible] reasonable. Estimates of coefficients of variation are [illegible] although they range [illegible]. Overall the greatest uncertainty in our estimates is due to the number of [illegible] trees used in the development of dimension analysis relationships. However several sites with particularly high C.V.s have large contributions due to [illegible] variation within the site. These statistical developments are a non-trivial

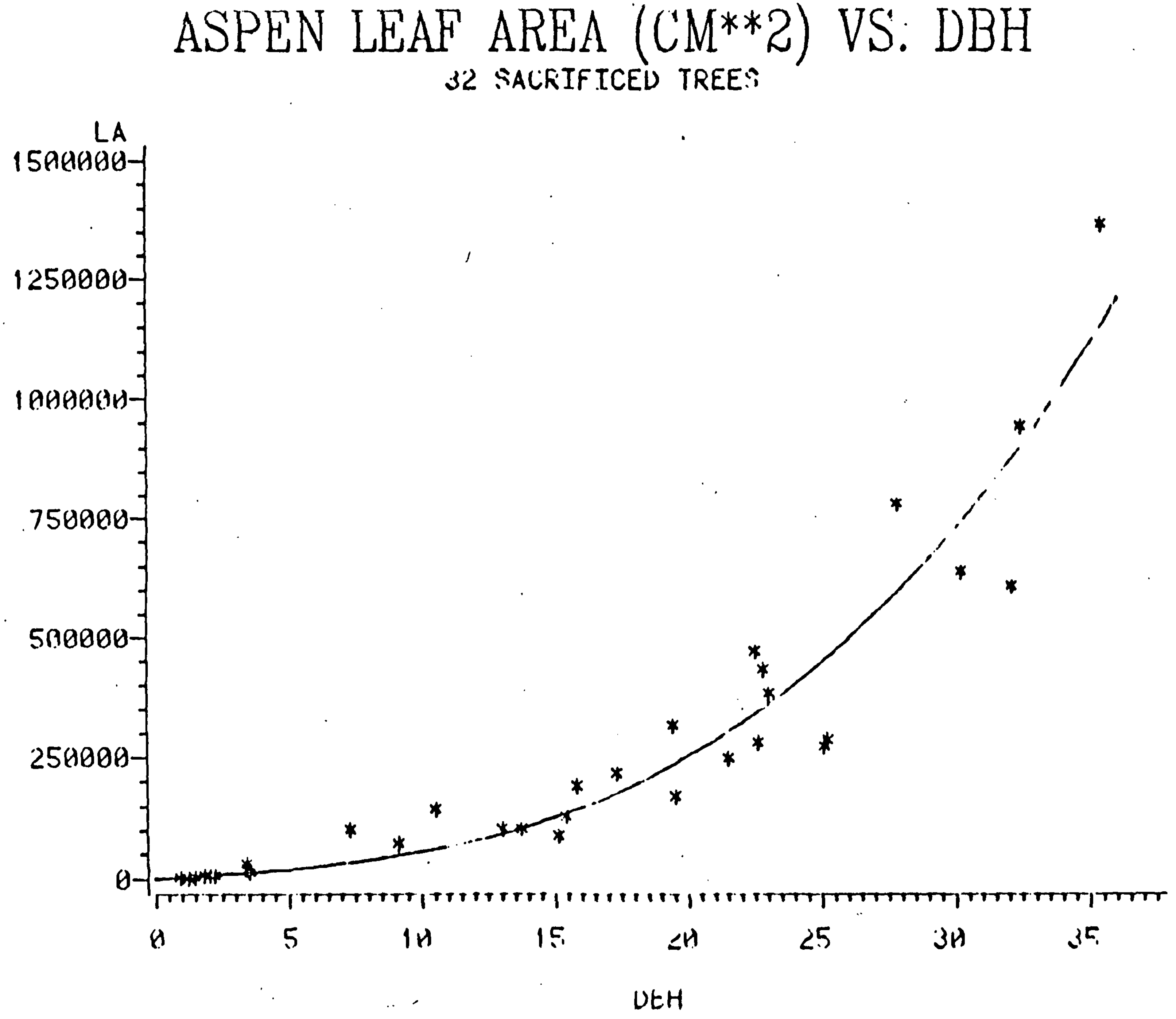

Figure 40. Relationship between tree diameter and leaf area. This dimension analysis relationship was used in estimation of plot LAI.

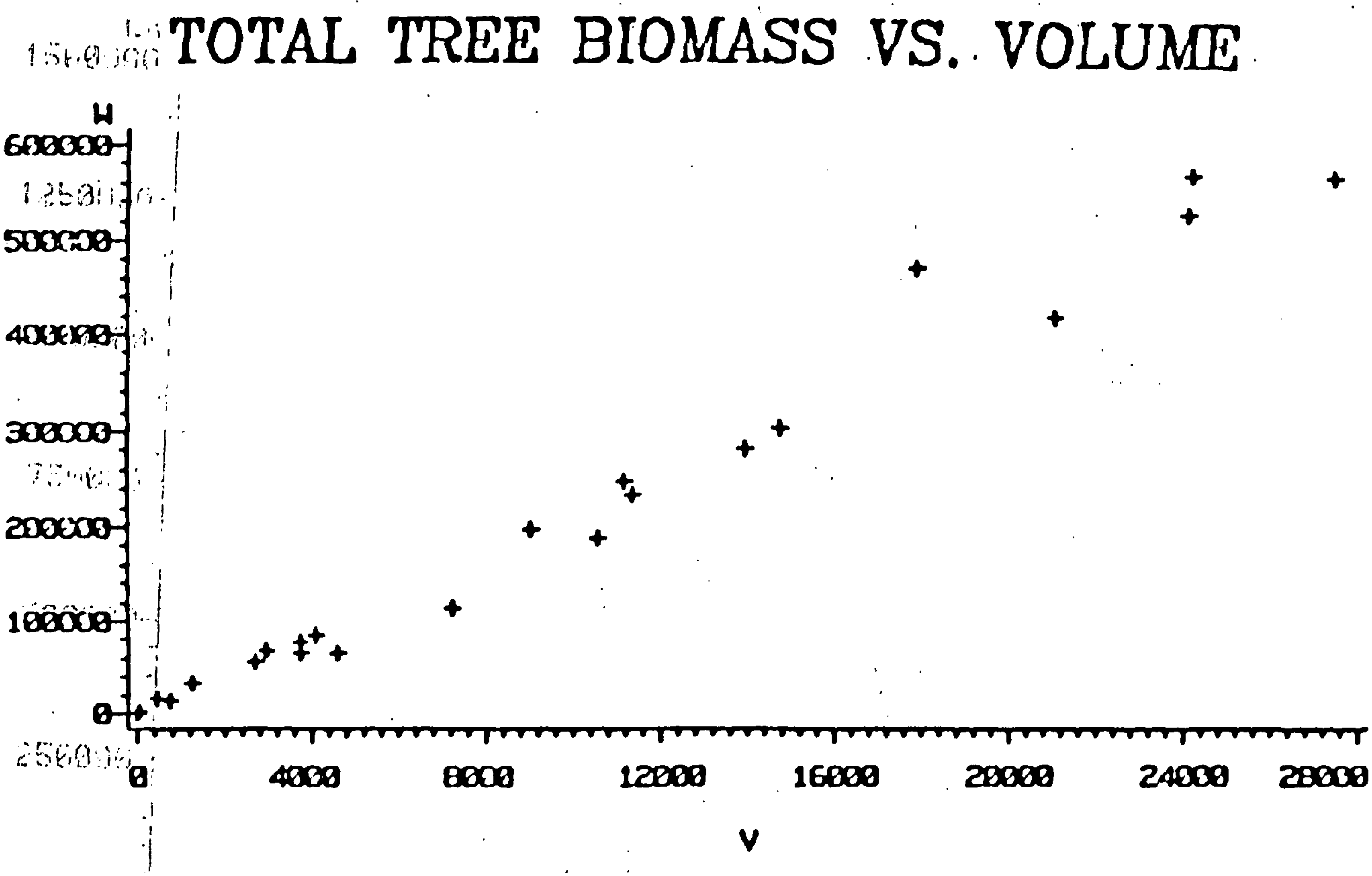

Figure 50. Relationship between diameter squared times height and tree biomass.

advance; appropriate estimates of variance associated with areal estimates of vegetation characteristics are complex and have never been made before.

Preliminary estimates of biomass show a range over sampled sites of at least ten-fold. We are still working to derive estimates of statistical moments comparable to those for LAI, but C.V.s will be considerably lower than for LAI.

We decided that further sampling of aspen trees was necessary in 1984 to achieve satisfactory understanding of relationships between measured dimensions and leaf area. This is because (1) variance is large for large trees, probably due to variation in shape of crown, (2) some sampled trees may have been atypical due to unusual weather (1983 had extreme summer drought), (3) larger samples in some size classes are required, and (4) it is important to characterize the year to year variation in leaf area of deciduous species.

Our estimates of LAI and biomass involve more statistical refinement than previous work. Published dimensional analyses have involved assumptions about variance and distribution of the measured and predicted variables, for convenience but without knowledge of true patterns. These lead to unreliable estimates of variance and, in some cases, to biased estimators of parameter values. We have developed models of variance structure based on empirical results and believe that these provide more reliable estimates of parameters and uncertainties. Statistical errors of estimation are being calculated for each step of the procedures described. Values have been derived for errors of regression estimators and variation within plots.

In our initial year of study we believe we have established field and analytical procedures and techniques superior to any previously available for producing the accurate ground measurements of biophysical parameters required for establishment and verification of relationships with remotely-sensed data. In such a brief period this alone is a major accomplishment. We have also acquired a very large vegetation data set -- over 2500 pages of raw data -- that is, to our knowledge, unparalleled in ecological research. Its importance is increased since we also have calibrated remotely-sensed data of several types. Since our estimates of vegetation characteristics are superior to any extant, predictive relationships with remotely-sensed data should be commensurately more reliable.

2.3 Transforms of MSS and TM Data for Forest Composition, Biomass, Leaf Area Index, and Net Primary Productivity

Objective. The objective of this task has two parts; first, to develop a capacity for determining forest composition using MSS and TM data and, second, to develop empirical transformations to be used with MSS and TM data from single dates for estimating biomass, leaf area index, and net primary productivity for forests.

Scope. Initial effort was confined primarily to intensive study sites in the SNF. Remotely-sensed data used were primarily from a helicopter-mounted, 8-band Barnes radiometer. TMS data from C-130 flight grids were also used. MSS data from Landsats 2 and 3, TM and MSS data from Landsat 4, TM-simulation data, and data from the NOAA AVHRR will eventually be used. Primary responsibilities for this task are taken by UCSB Geography personnel and facilities.

Approach. Although little work has been done toward the development of relationships between spectral response and biomass of forested regions, we have proceeded by building on the work discussed in the background section above. The initial approach has been to relate (1) remotely-sensed spectral values from the helicopter-mounted radiometer, acquired directly over SNF study plots and (2) *in situ* measures of biomass, net primary productivity, and canopy leaf area derived from field sampling on plots (discussed in Tasks 1 and 2).

Sample sites employed in this study for development of relationships between remotely-sensed data and LAI, biomass, and productivity were chosen to be homogeneous and dominated by single species of canopy trees at the scale of sensor resolution in order to permit valid correlation and extension of derived relationships.

We examined the relative success of the transforms discussed in earlier section (see Table 1) in revealing vegetation biomass, productivity, and leaf area. Raw and transformed radiance values from study sites were evaluated empirically to establish a relationship between these values and canopy leaf area index as sampled in the field for the aspen and black spruce stands. Relationships between transforms of spectral values and ecosystem variables derived for the various remote sensing images will be tested statistically using the field verification data set described above.

To examine the ability to determine species composition of stands, TMS data acquired from areas completely covered by C-130 flight grids were used. These data were submitted to various classification techniques and maps were constructed showing the distribution of classes of pixels. Maps were spot checked for accuracy by helicopter crews. In addition, spectral responses for pixels from stands of known composition (as determined by helicopter crews and from IR photographs) were examined and information analyses used to determine separability of pure stand types. These data were used to develop algorithms for assignment of pixels to stand composition classes on the basis of TMS data.

Results. The first year's work has shown that species and stand-types can be distinguished from MSS or TM. TMS data from C-130 overflights on a single date were registered to Forest

TABLE 1. SEVEN COMMONLY EMPLOYED BAND TRANSFORMS FOR THE DETERMINATION OF THE RELATIONSHIP BETWEEN A MULTISPECTRAL REFLECTED RAIDANCE RATIO AND VEGETATION AMOUNT

NAME	FORMULA	EXAMPLE
imple subtraction	IR-R	Pearson et al. (1976)
imple division	$\frac{IR}{R}$	Kanemasu (1974)
omplex division	$\frac{IR}{R + \text{other wavelengths}}$	Carter and Gardner (1977)
imple multiratio (vegetation index)	$\frac{IR - R}{IR + R}$	Ashley and Rea (1975)
omplex multiratio (transformed vegetation index)	$\sqrt{\frac{IR - R}{IR + R} + 0.5}$	Rouse et al. (1973)
erpendicular vegetation index (vegetation reflectance departure from soil background)	$\sqrt{(R_{soil} - R_{veg})^2 + (IR_{soil} - IR_{veg})^2}$	Richardson and Wiegland (1977)
reen vegetation index (for use with Landsat wavebands)	$-0.29(G) - 0.56(R) + 0.60(IR) + 0.49(IR)$	Kauth and Thomas (1976)

Service stand-type maps (checked by helicopter) for one portion of our study area. Five major single-species stand-types were studied. Algorithms were developed which, in the test data set, correctly identified pixels belonging to these five types. 84% of pixels were correctly assigned to species. Deciduous and coniferous canopies were almost perfectly distinguished (Figure 6, Table 2). This accuracy should become even greater with multi-temporal data since species differ in temporal patterns of optical properties.

Calibration of radiometric data from the helicopter-mounted radiometer with ground measurements showed some meaningful patterns and suggests interesting and important questions. Initial comparisons of spectral data from black spruce stands with first estimates of leaf area index show definite relationships (Figure 7). These preliminary results, though, do not permit evaluation of the predictive power of these relationships. Patterns observed are not those expected if response were totally a result of chlorophyll absorption and reflection in the spruce canopy; understory apparently plays an important role. Phenological change -- the development and expansion of leaves during the growing season at a particular site -- is apparent in the radiometric data for both aspen and black spruce (Figure 8 shows such sensitivity in aspen stands). This indicates that changes in the leaf area index over time can be observed by remote sensing. Although we have radiometer data from only a few aspen sites for the period before and during leaf-out in the spring, these data suggest a possible response to leaf area as measured in the summer. TMS data, acquired from the C-130 aircraft, cover more sites during this period and show more clearly a similar response (Figure 9) (When TMS data are corrected for atmospheric path properties, they very closely match corresponding Barnes radiometer data; so, with more data, any trends should be detectable using the helicopter-mounted instrument).

However, it is significant and interesting that when radiometer data from mid-summer -- <u>one</u> time of year -- for aspen plots are plotted against LAI, no response is apparent, even for our wide range of LAI's (Figure 10). The inability to detect changes in LAI over space, even though they are detectable over time and over space at other seasons, presents intriguing questions. Potential explanations for this seeming paradox involve (1) background reflectance, (2) effects of view angle, (3) seasonal changes in the relative reflectance of different canopy components, and (4) internal shadowing of limbs. We intend, this summer, to evaluate these hypotheses by appropriate field measurements and experiments and by modification of canopy reflectance models (see proposed research). These results make obvious the importance of multitemporal data. A primary effort this summer will be devoted to collecting data during what we now believe to be "sensitive" times of the year -- particularly just before and during leaf expansion in the spring and collection of appropriate ground-data to quantify background shadowing and phenological patterns. We also hope to collect radiometric data with snow-cover in the fall 1984. Our discovery of the

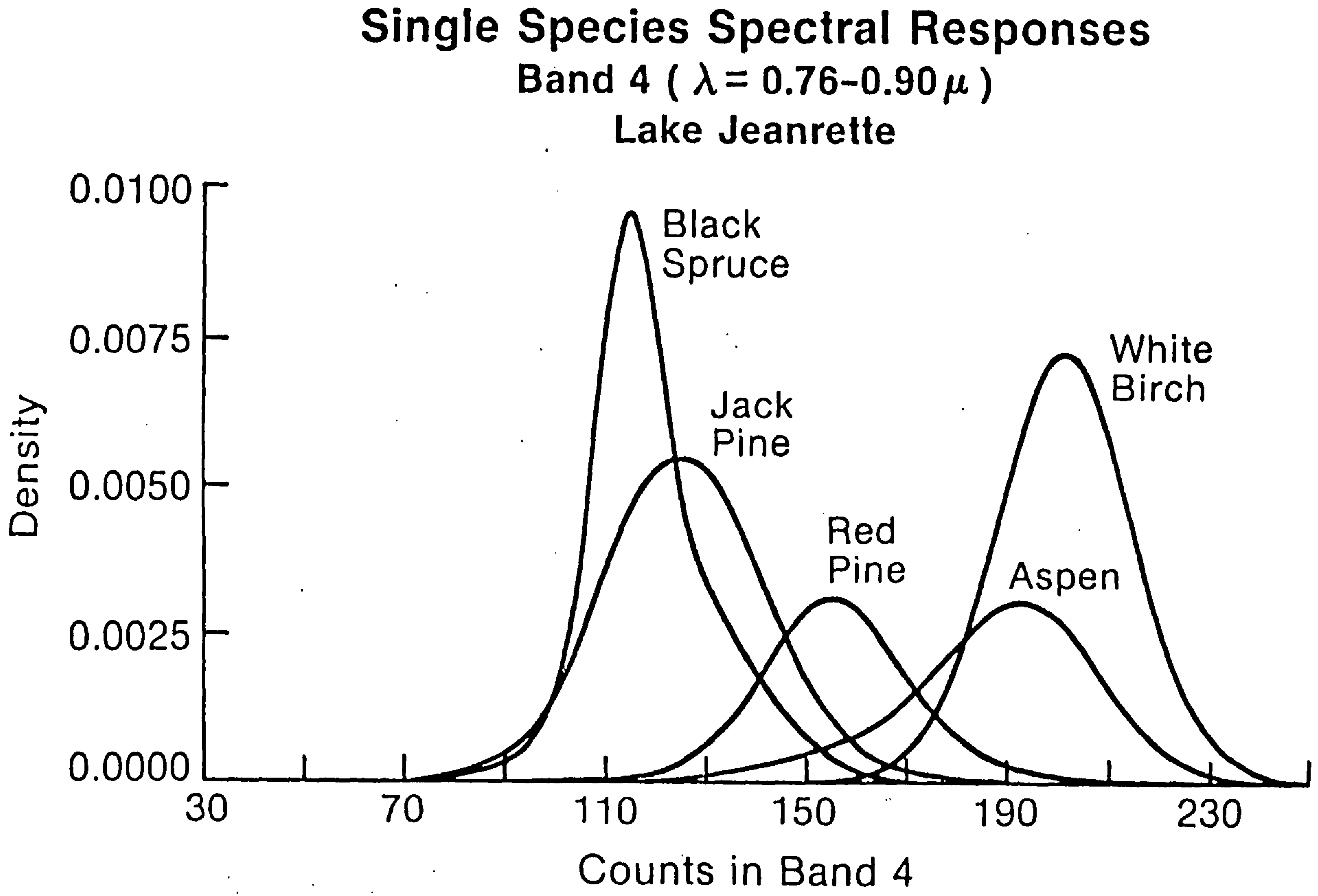

Figure 60. Response in TMS band 4 of 5 major species in pure stands, Lake Jeannette area.

TABLE 2 LINEAR DISCRIMINANT ANALYSIS WITH ALL 7 TMS BANDS

- CLASSIFICATION OF PURE STANDS OF 5 SPECIES

ASSIGNED CLASS

ACTUAL CLASS	BS	RP	JP	BIR	ASP	TOTAL
BS	104	0	12	0	0	116
RP	0	32	5	0	0	37
JP	26	6	149	2	3	186
BIR	0	0	0	97	3	100
ASP	0	4	1	17	39	61

OVERALL % CORRECT CLASSIFICATION = 84.2

KEY:

BS = BLACK SPRUCE
RP = RED PINE
JP = JACK PINE
BIR = BIRCH
ASP = ASPEN

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- CLASSIFICATION BETWEEN CONIFEROUS AND DECIDUOUS

ASSIGNED CLASS

ACTUAL CLASS	C	D	TOTAL
C	330	9	339
D	7	154	161

OVERALL % CORRECT CLASSIFICATION = 96.8

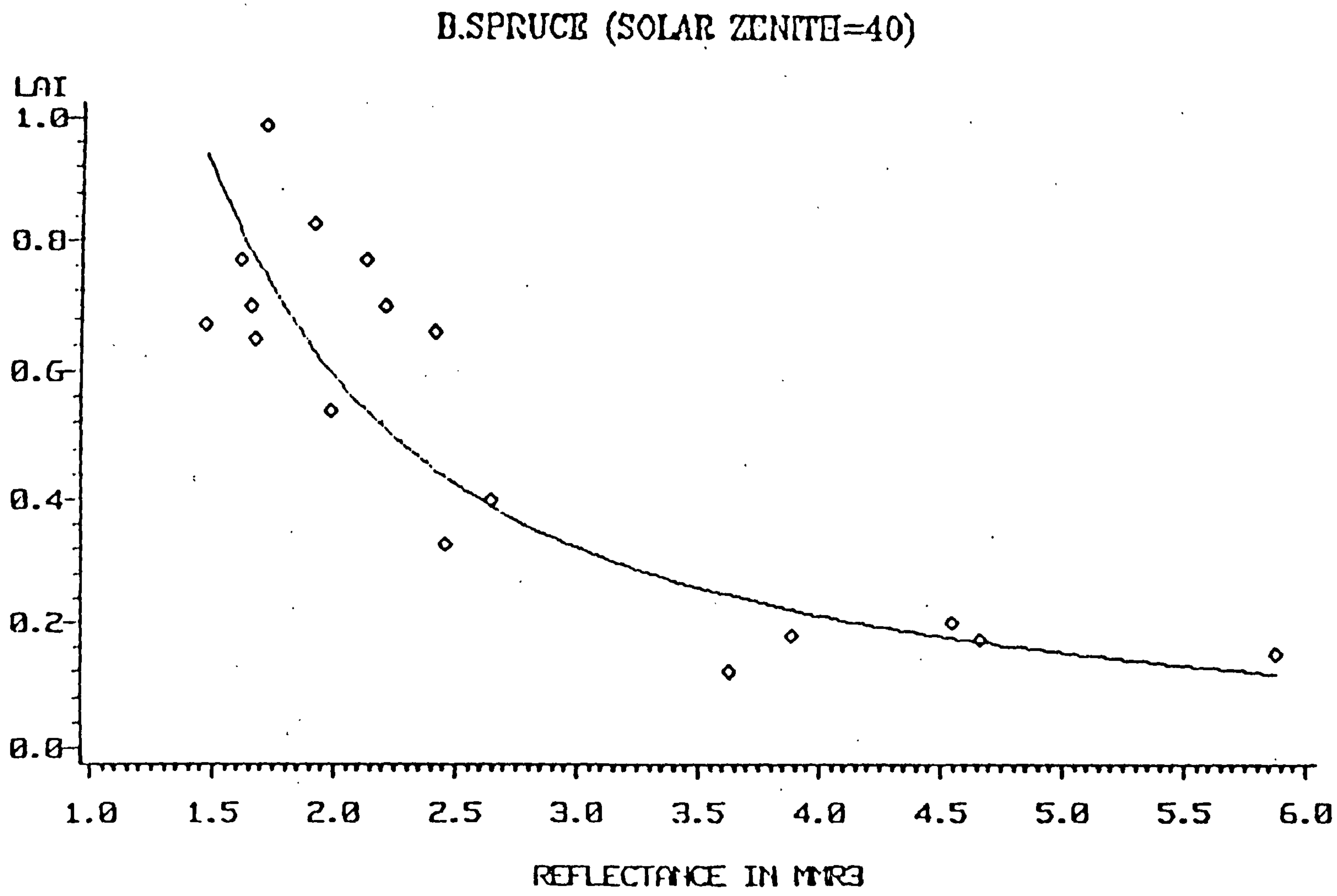


Figure 7[illegible]. Relationship between black spruce plot LAI and reflectance in Band 3.
Data are from summer 1983.

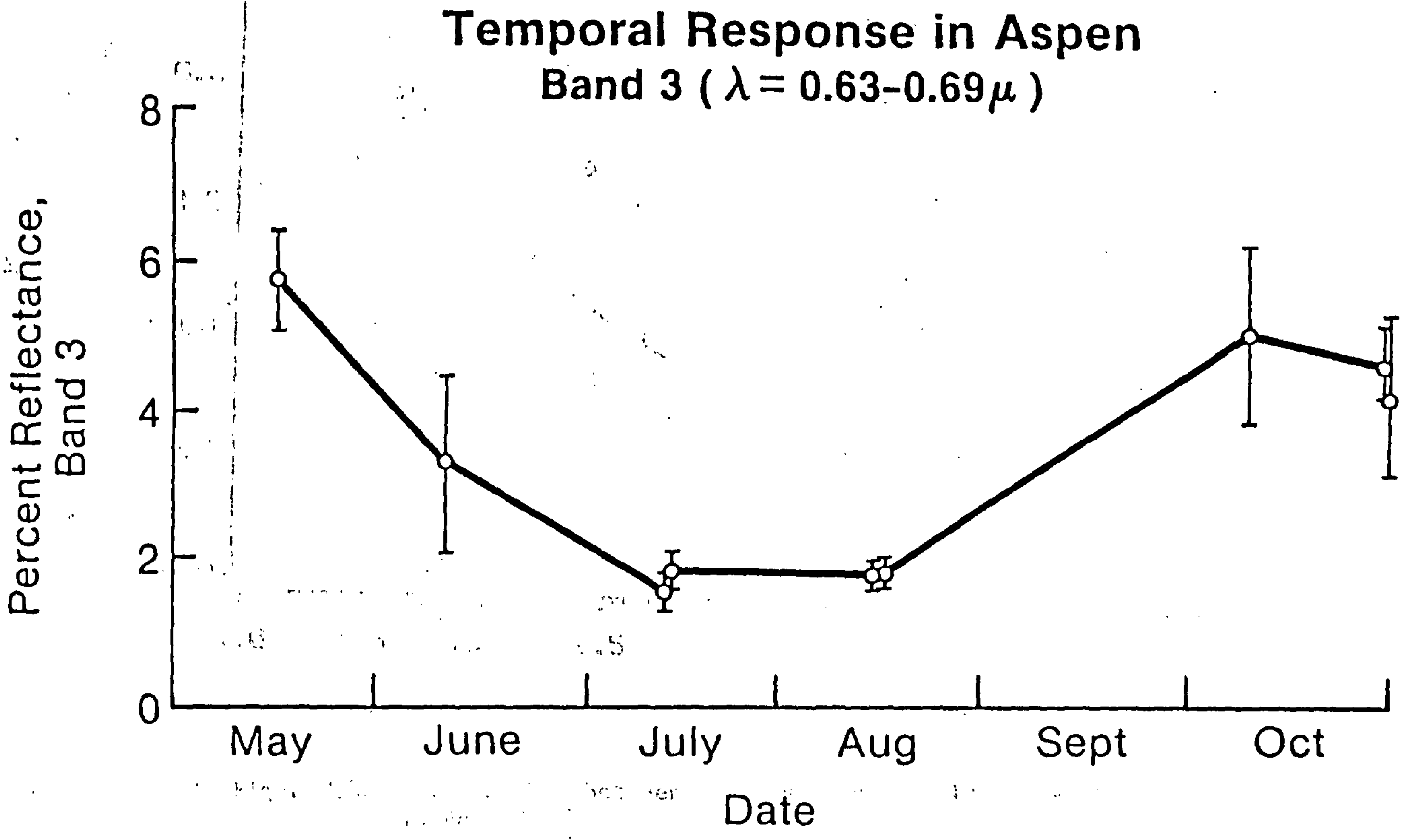
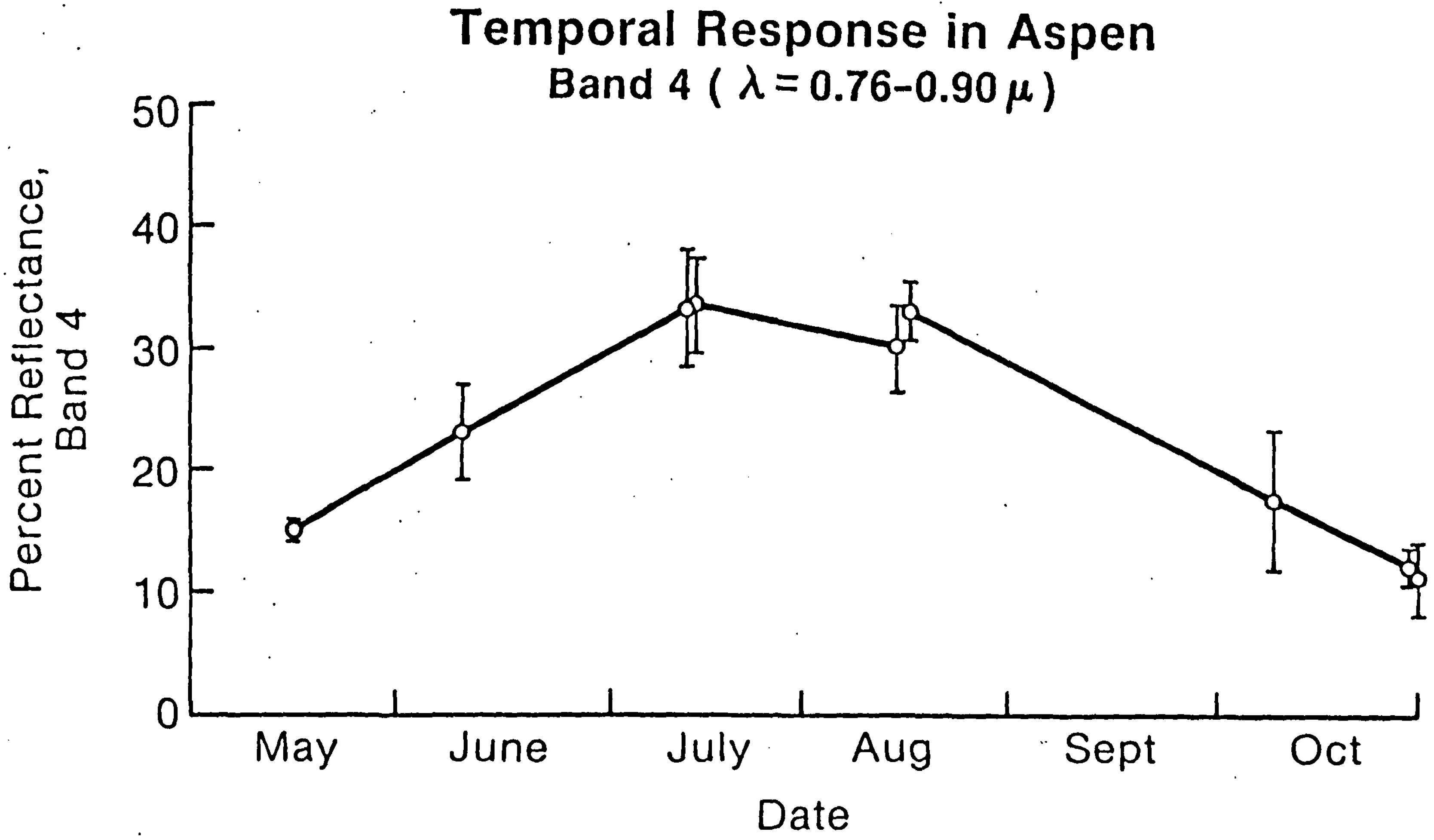


Figure 18a. Phenological change in reflectance (TMS bands 3 and 4) of aspen stands, mean and one standard deviation shown.



Temporal Response in Aspen

Band 4 ($\lambda = 0.76\text{-}0.90\,\mu$)

Figure 81b.

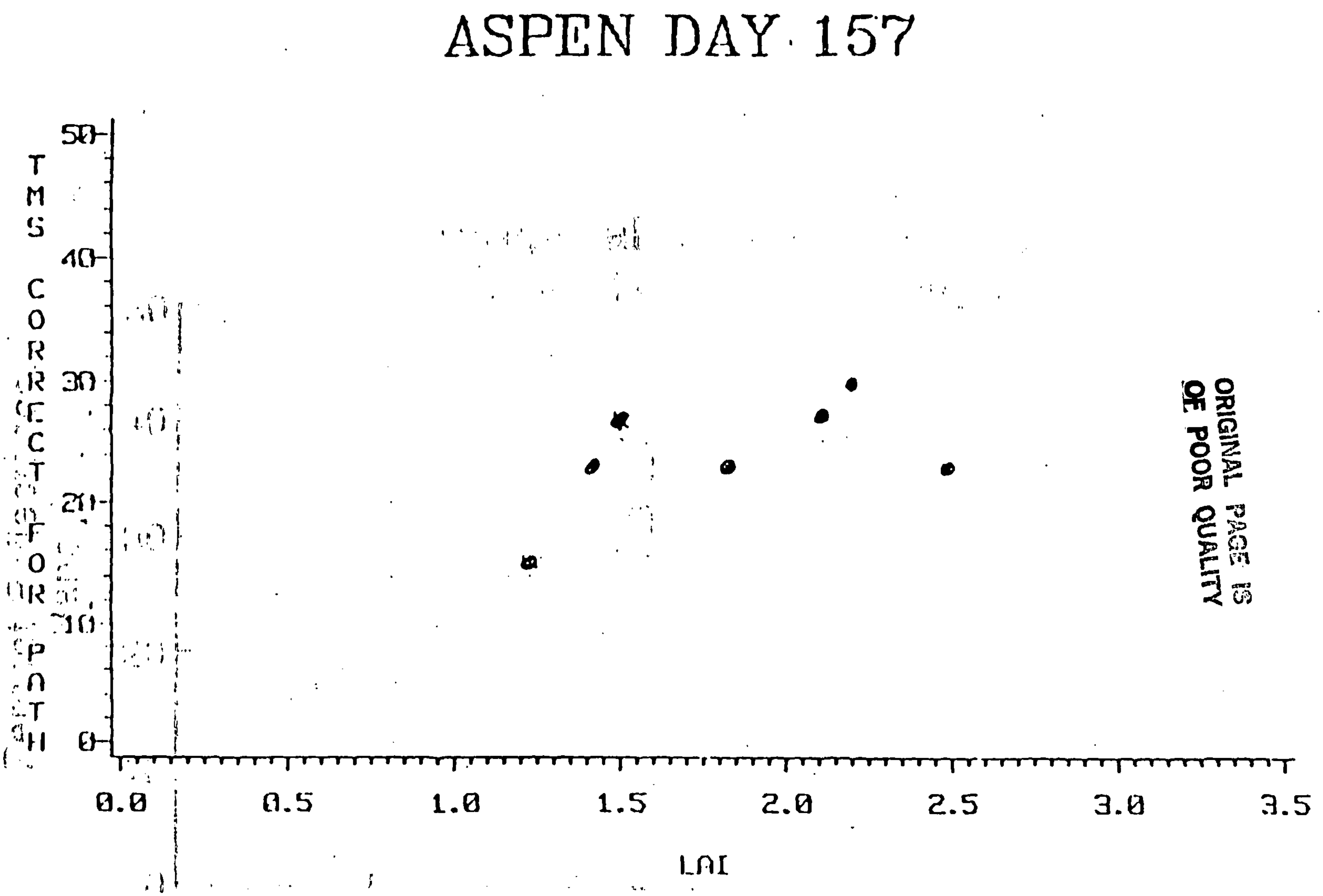


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Figure 90. Relationship between TMS Band 4 reflectance and aspen stand LAI in early June.

Aspen Reflectance Data
Band 3 ($\lambda = 0.63\text{-}0.69\mu$)

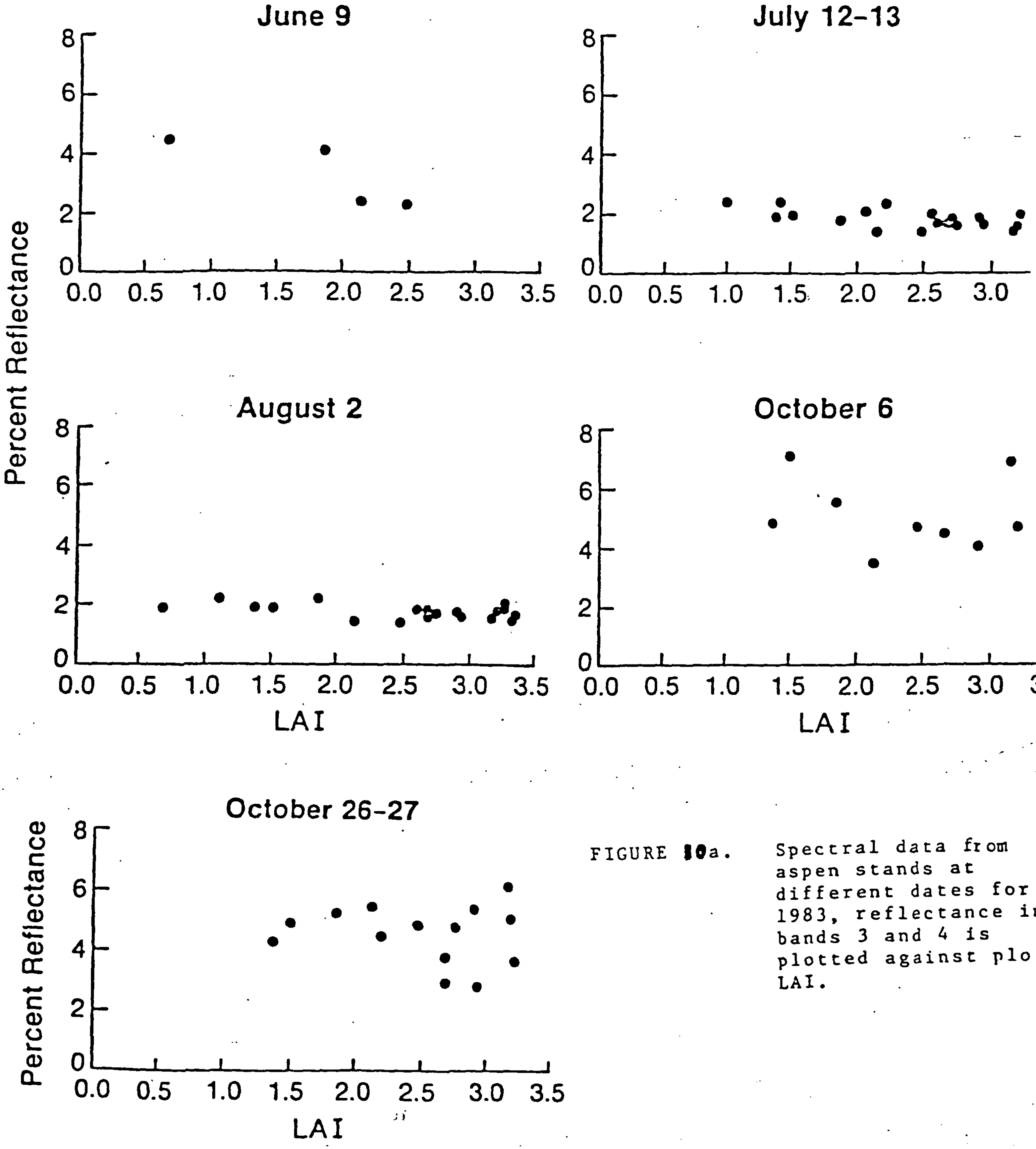

FIGURE 10a. Spectral data from aspen stands at different dates for 1983, reflectance i bands 3 and 4 is plotted against plo LAI.

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Aspen Reflectance Data
Band 4 ($\lambda = 0.76\text{-}0.90\mu$)

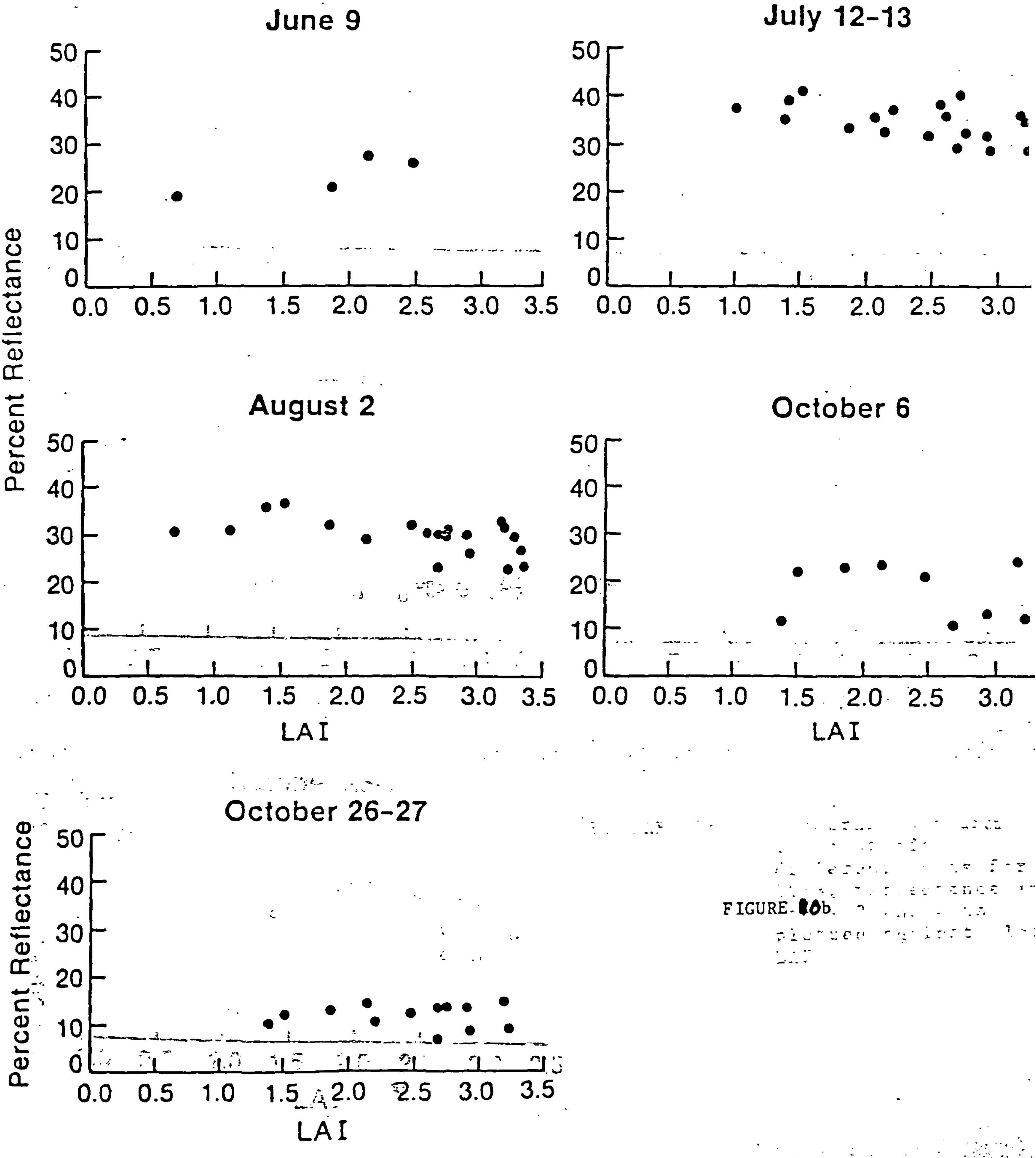

FIGURE 10b. [illegible] reflectance [illegible] plotted against [illegible]

insensitivity of TM-type spectral sensors to wide variations in LAI at certain times places obvious constraints on the interpretation of single-date data. Multi-temporal approaches will be emphasized in this study.

2.4 Inversion of Models to Obtain Biomass, Leaf Area Index, and Net Primary Productivity

Objectives. The objective of this task was to use existing radiative transfer models, such as the Suits and SAIL models, (i) to develop relationships between LAI/biomass and spectral variables that can be inverted to obtain LAI/biomass from spectral data, and (ii) conduct sensitivity studies to determine the effects of forest composition and structure, view and sun angles, atmospheric conditions, etc., on the relationship between spectral data and LAI. This task will allow a mechanistic understanding of spectral data taken.

Scope. This work was done by JSC personnel, N. Goel of SUNY, Binghamton, using data obtained by UCSB and JSC.

Approach. The new Suits model as well as that of Verhoef and Bunnik (1981) are being implemented and verified using field plot data. Having verified the model, it would be used to provide: (i) a relationship between LAI/biomass and spectral reflectance (see Figure 11 for an example using crops), and (ii) sensitivity of these relationships to canopy parameters (such as leaf angle distribution, etc.), sensing procedures, etc.

Results. To date, canopy reflectance models have had primary use in aiding experimental design and generating hypotheses explaining observed patterns. As field data are processed, accurate values for LAI and biomass obtained, and model parameters measured or fitted, progress may be made in developing predictive power and testing sensitivity. These procedures have begun in the last few months.

An important conclusion from early experimentation with models is that accurate prediction of LAI (or bark area) requires knowledge of leaf reflectance/absorption characteristics for each species (otherwise, the number of unknowns is too great). This implies a requirement for ability to recognize species from remotely-sensed data.

Another important general conclusion from use of models is that multiple, non-nadir view-angles are needed. Multiple angles allow estimation of LAI when leaf angle distribution is unknown or variable. Optimal view-angles and sun-angles have been calculated. Experimental and equipment design for 1984 have been greatly affected by these findings.

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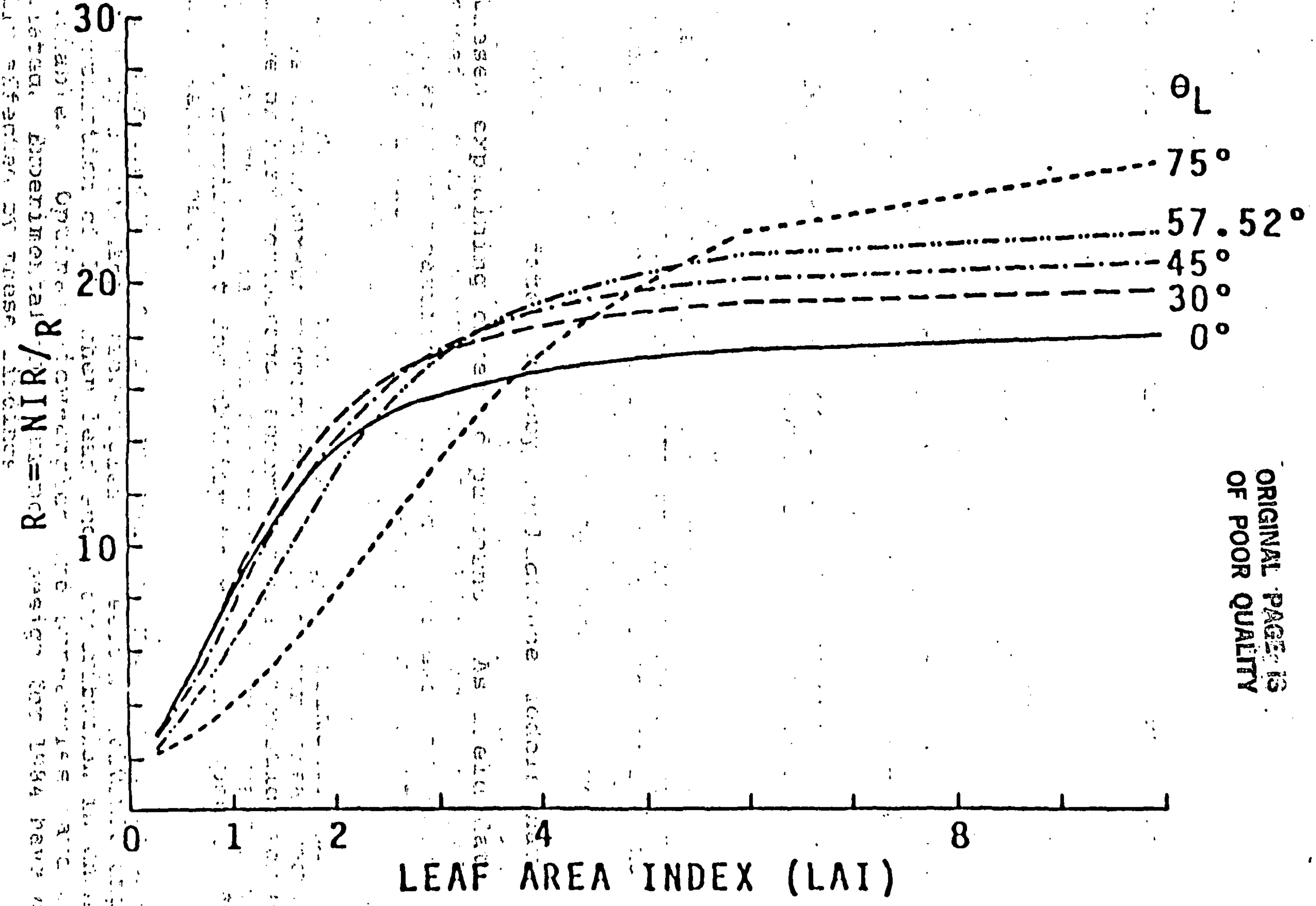


FIGURE 11: The calculated ratio of near infrared and red canopy reflectance as a function of leaf area for wheat grown in dry sandy loam soil. TO_L is the leaf angle and sun is 30° zenith angle and canopy is observed at nadir view.

2.5 Summary of Advances During 1983

We began the field season in 1983 with untested field procedures and a priori assumptions about important variables and relationships. Some of the most important progress of the 1983 field season was the testing and streamlining of procedures, clarification of important questions and relationships, and discovery of previously unsuspected, but important, problems and needs. Plot sampling time has been roughly halved; a four person crew can now sample, on average, one plot per day. Initially the full crew (8-10 workers) was able to destructively sample one to two trees per day, but this rate increased to three trees per day by summer's end. At the same time as rates of data collection increased, accuracy and replicability was improved.

At the same time, various problems arose to which we are currently addressing our efforts. It became apparent early in the summer that transfer of data from the field to Houston, its entry into the computer data base and proof-reading was a major bottleneck. For the 1984 field season, we are developing procedures for entering data on magnetic media in Ely, with immediate proof-reading. Data may then be sent to Houston for direct entry. By this means the interval between data collection and beginning of analysis should be decreased by several months.

The background and first-year results presented above show that reliable in situ measurements of vegetation characteristics are necessary for development of techniques for measurement of biophysical paramters by remote sensing. Further field work during the 1984 field season and plans for the next 12 months of the project are detailed below. These tasks and needs are essential for acquisition of suitable ground verification for remotely-sensed data, for providing necessary inputs to and using canopy reflectance models, for expanding initial results to cover additional species and areas, for support of aircraft activities, and establishment of future research plans.

3.0 RESULTS OF 1984 FIELDWORK

1984 fieldwork was designed to address three separate groups of research questions. These concern: (1) testing hypotheses to explain the observed spectral responses in aspen; (2) acquiring data needed for canopy models; and (3) expanding our efforts to new species and mixtures of species (and, in a preliminary way, to new areas). The first two elaborate on work done during the first field season; the 3rd is necessary so that we can begin to expand our approach to the entire boreal forest of North America.

The following sections present rationale underlying our 1984 field design and summarize field procedures developed and used and data collected. Analysis of these data was not completed due to interruption of funding; as we have completed transfer and cataloguing of data and programs at other study centeres than JSC, data analysis has continued and results are being generated.

3.1 Hypotheses Regarding Observed Spectral Responses to Changes in LAI in Aspen

Several hypotheses might account for the patterns of spectral response seen in aspen stands in 1983 (observed changes in spectral response over the year but a lack of response to LAI among different plots during the same time in mid-summer): (1) there is no change in total LAI (LAI contributed by all vegetation including understory, herbs, and shrubs) with changes in tree biomass, and observed differences are due to (A) seasonal patterns in the understory vegetation; (B) effects of leave emergence on reflectance from bark surfaces; (2) there is a change in LAI, but it is obscured by artifacts of the view angle; (3) there is a change in LAI, but internal differential shadowing by tree limbs obscures differences among leaf reflectance in different stands.

The last hypothesis assumes that larger trees have more complex shapes and larger limbs and that these limbs shade the internal structure of the trees and the leaves of the lower strata. As the biomass increases, the LAI increases, but internal shadowing also increases, and compensates for the changes in LAI. The net change in reflectance is therefore nearly zero.

The second hypothesis, invoking the effects of view angle, recognizes that, when the sun is not directly overhead, individual tree crowns will have a lighted side and a shaded side. From a nadir view both sides will be visible, and the spectral response of bright and dark sides will be averaged. This averaging might obscure the effects of differences in LAI. View angles could be chosen so that only the bright sides of tree crowns are seen (if view is from sunward), or only the dark sides are seen (if view is toward sun)

To elaborate on the hypotheses concerning phenology, one conjecture is that differences in understory vegetation between plots of high, medium, and low LAI obscure the changes in the tree LAI. More specifically, a stand with low LAI in the canopy trees would be more open to light at the ground and have a denser ground vegetation than a mature forest stand with a high LAI. In this case, the changes in LAI of the canopy trees would be compensated for by opposing changes in the ground vegetation. To put this another way, interdependence of canopy and understory/sub-canopy LAI may lead to relatively constant total LAI during the summer, but differences in phenology between canopy and understory strata could produce distinguishable response to canopy LAI in spring or fall. For instance, if leaf expansion in understory strata were later than that for the canopy strata, differences in canopy LAI would be visible during the period between leaf-out of the two strata.

The second hypothesis involving phenology suggests that differential shading of bark and background by expanding leaves may be important. This is based on the assumption that the reflectances of bark and background are different. Leaves will tend to obscure the bark more than the ground surface. Prior to leaf-out, the reflective components seen from above will be, primarily, bark and ground surface. Under these conditions, differences in spectral response among stands could be observed due to differences in the bark surface area (Stands with higher biomass have greater bark surface area as well as greater leaf area).

Later in the year, fully expanded leaves on canopy trees will obscure larger proportions of bark than of ground surface since they are clustered on trees, directly above most of the bark. Thus, if total stand LAI is relatively constant (as proposed in the previous hypothesis) during summer, there may be no difference between stands in spectral response because the important reflecting surfaces are leaves, while bark surfaces are largely obscured by the leaves. The effect on spectral response should be especially strong for nadir view when leafy crowns are directly superimposed over boles and branches of trees.

To test these hypotheses, data on phenological patterns, bark area index, and tree canopy structure for important species are required, along with spectral data from a variety of view angles. These needs, in addition to needs for canopy modelling and expansion of project coverage, are addressed by the following tasks.

3.2 Specific Field Tasks Performed During 1984

Task 1. Description of Phenology of Major Species.

Objectives. This task was intended to provide data on the temporal pattern of bud-break and leaf expansion in major canopy and understory species as needed to test hypothesis one above.

Approach and Results. Rates of leaf expansion and changes in LAI for aspen and black spruce and major understory species were measured. Two approaches were used. First, randomly selected twigs on several stems of each species at three sites were marked prior to the beginning of leaf expansion. As leaves expanded, major dimensions for each leaf on sampled twigs werer measured repeatedly. These data allow calculation of leaf area relative to its final value, which is known through our dimension analysis work. Second, photographs of canopy and sampled twigs were taken concurrently with each measurement. A point grid superimposed on the photograph and sampled for presence or absence of bark, leaf, or other surfaces allows estimatioin of relative crown closure. Observations on general phenological patterns were made throughout the year. This work began in April, 1984 and continued through the summer and fall. At intervals throughout the season, samples of leaves were sent to JSC for measurement of spectral properties in order to detect phenological changes in these characteristics.

Scope and Results. Field measurements of phenology were carried out by UCSB field crew. A Cary-14 spectrometer at JSC was used to measure foliage spectral characteristics. Analysis of field data produced curves shown in Figure 12. Results indicate that 1) subcanopy shrubs leaf out later than the canopy aspen trees, and 2) there is variability among sites in actual dates of initial and full leaf expansion. The first result is consistent with hypothesis above. The second result may be a consequence of variability in physical parameters of sites, or in genetic control of phenology among aspen clones. Cary-14 data exist on computer tapes.

Task 2: Characterization of leaf area of major understory species.

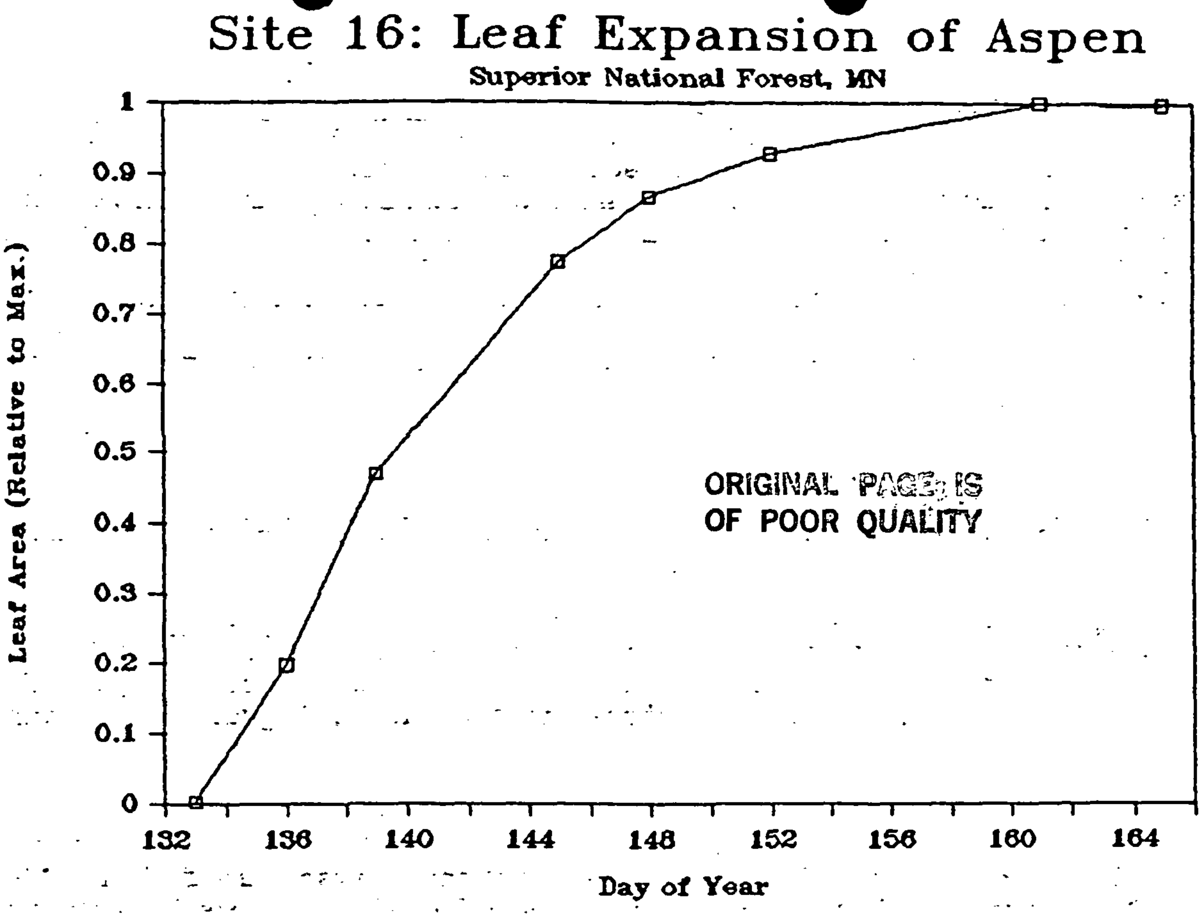
Objectives. In connection with evaluating hypotheses involving significant roles of understory reflectance (see above), it is essential to devise means of estimating understory and sub-canopy LAI on our intensive study plots.

Approach. Dimension analyses of understory and sub-canopy species have been done for most of the important species in the SNF, but these have produced estimates of biomass only. Most past studies have not developed predictors of leaf area. In many cases regressions are available for leaf weight. For some species, we may be able to use these regressions by measuring leaf area and weight of a sufficient number of leaves to calculate a conversion ratio of weight to area. For other species, for which studies are not available or are statistically insufficient, a more complete form of dimension analysis may be necessary. Because individual plants of these species are small, this procedure will be simpler and faster than for trees.

During 1984 we sampled 35 stems each of the two major sub-canopy species (*Corylus cornuta* and *Acer spicatum*) Smaller numbers of stems were sampled for several minor species. for each stem we separated leaves and wood and measured area of leaves. Both components were weighed wet and dry.

Predictive equations from dimension analysis were used in conjunction with dimension measurements made on sub-canopy and understory plants in sub-plots within our intensive ground-truth plots (see Task 7 for discussion of plot sampling for understory and sub-canopy species). This allows estimates, with estimates of variance, of plot LAI for understory and sub-canopy.

Scope and Status. Field work was done by UCSB field personnel. Preliminary dimension analyses have permitted first-order estimates of shrub-layer LAI in sample plots Figure 13.



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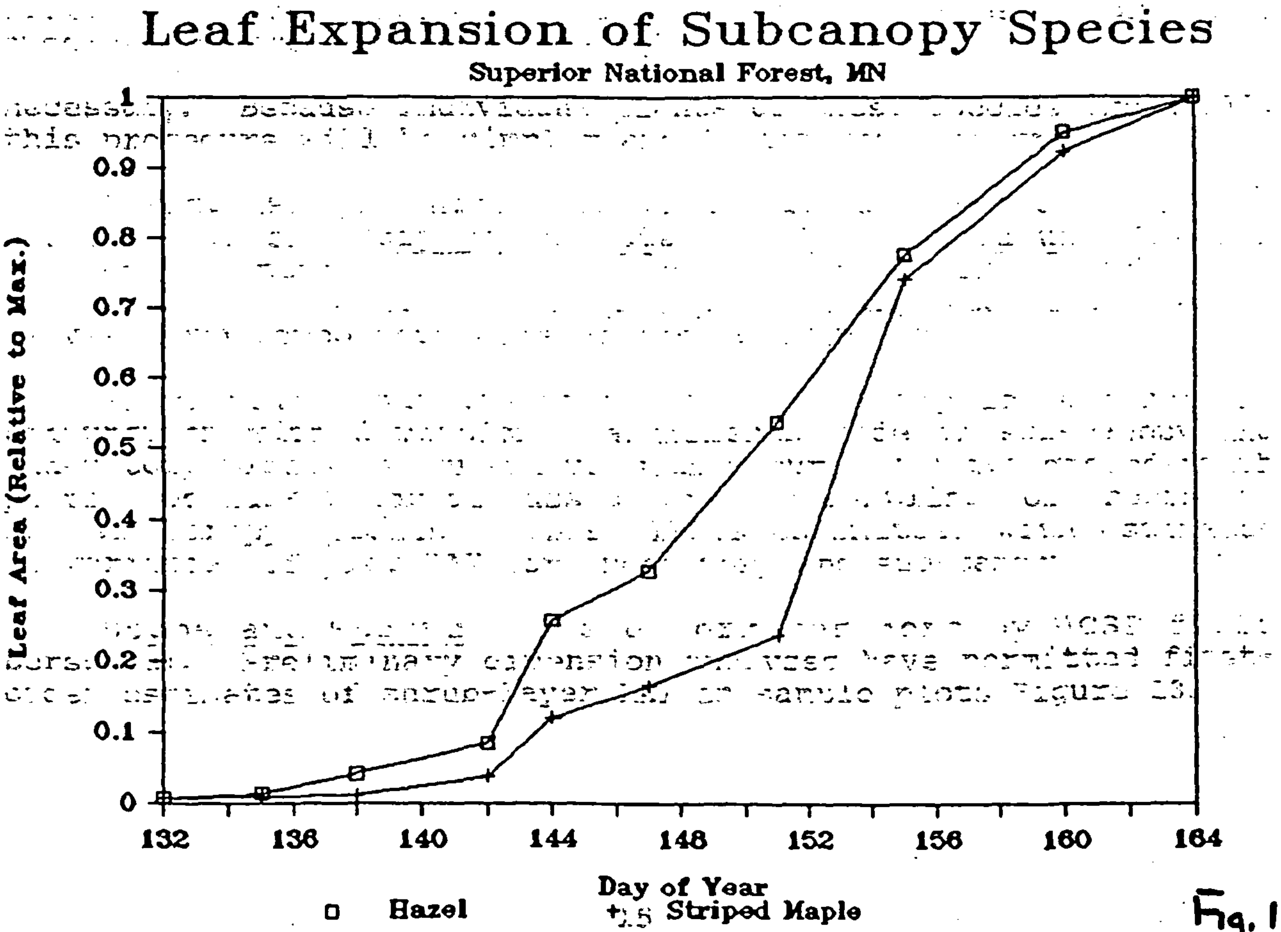
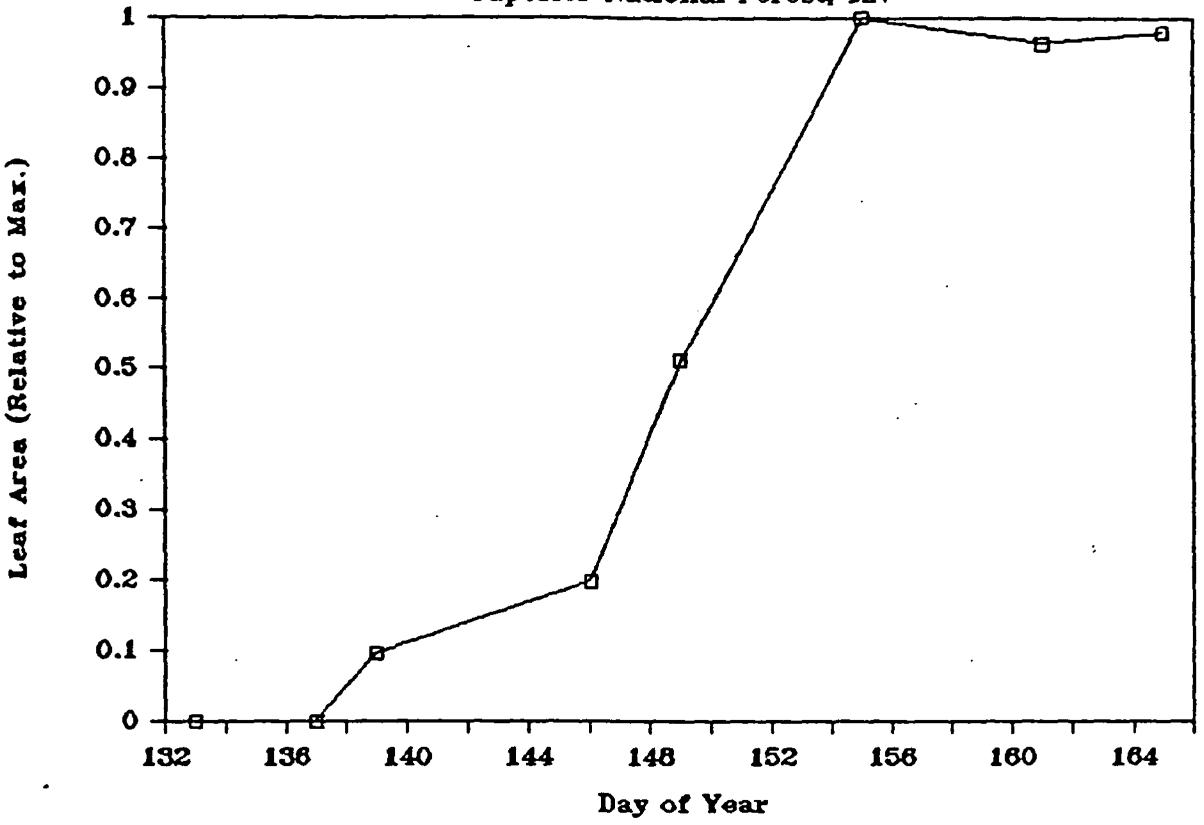


Fig. 12a

Site 93: Leaf Expansion of Aspen

Superior National Forest, MN



Leaf Expansion of Subcanopy Species

Superior National Forest, MN

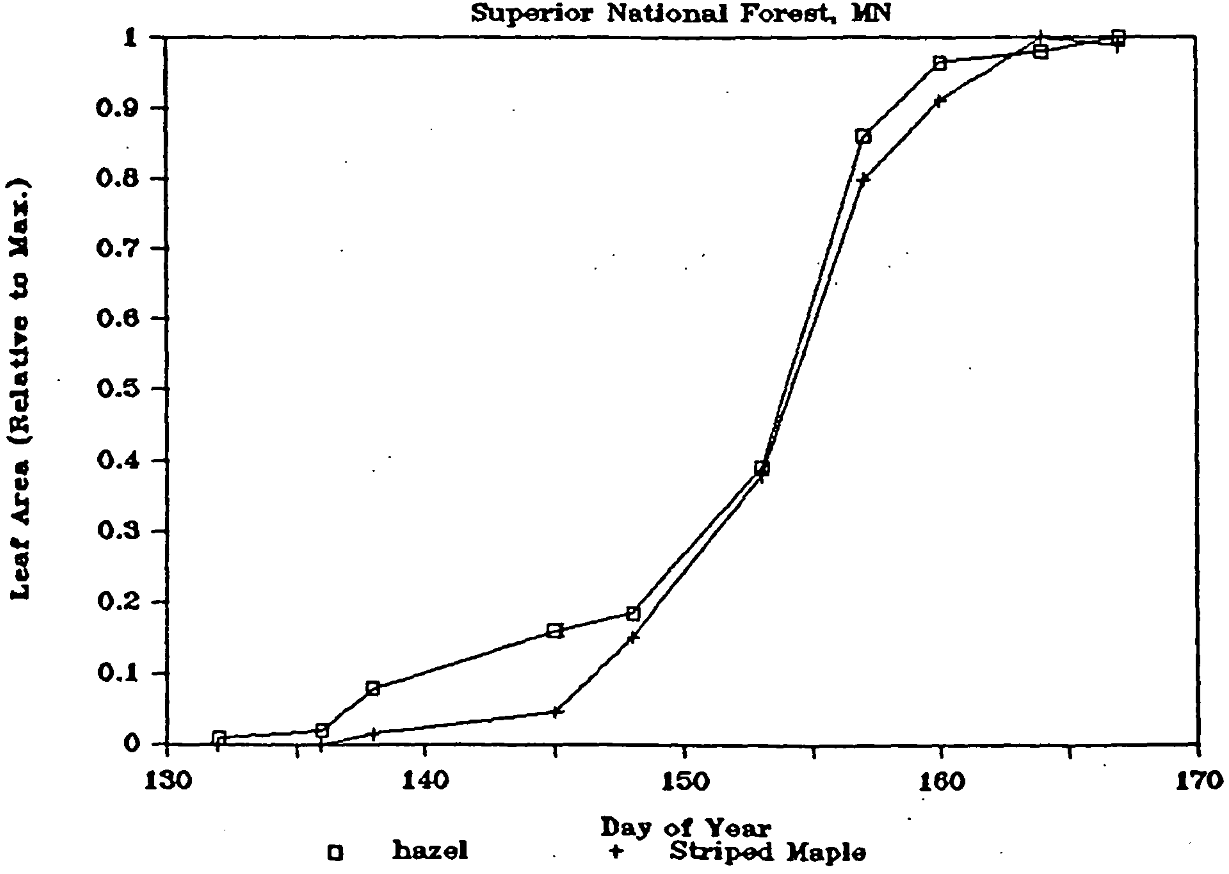


Fig.12b

ASPEN: Proportion shrub LAI vs. Total

Superior National Forest, MN

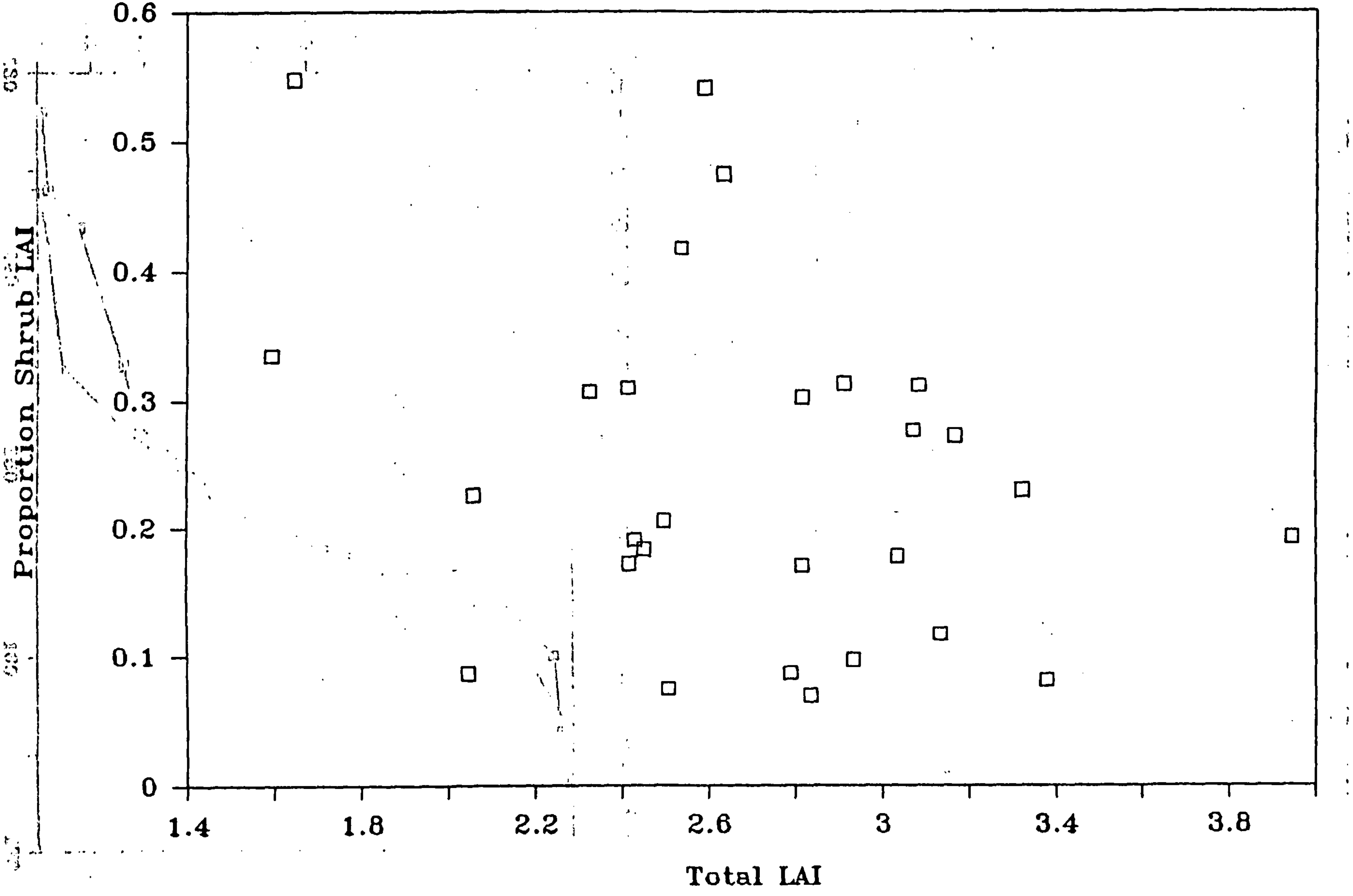


Fig. 13

Task 3 Further dimension analysis of aspen.

Objectives. As pointed out in the previous section, sufficiently reliable ground-truth, with some indication of year-to-year variation, for aspen required sacrifice and analysis of additional trees in several size classes in 1984. This is important to improve the statistical power and reliability of our estimators. Additional understanding of canopy structure is also needed for canopy modelling (see Task 4), and to test hypotheses (above) concerning canopy structure and shadowing effects.

Approach. Dimension analysis procedures were as described for 1983 field season, with the addition of measurements required for Task 4 (branch angles, bark area measurements, leaf angle distribution) and a more thorough and appropriately distributed sample of branches taken within each tree. Selection of trees was by a stratified sampling design to obtain statistically desirable sizes of trees. Twenty-four trees were sacrificed, covering a size distribution weighted for small and large trees. This represents about three weeks work for the full field crew.

Scope and Status. This task was carried out by UCSB field personnel. Data are entered on computer files and proof-read and preliminary analyses completed. Total leaf area for the sacrificed trees has been estimated and related to tree dimensions by the same procedure and models used for 1983 sacrificed trees. It appears that parameters of the function relating leaf area to tree dimension show small but significant changes from year to year.

Task 4. Characterization of Canopy Structure and Leaf Angle Distribution of Important Species.

Objectives. This task was required for testing hypotheses explaining observed patterns of canopy reflectance (see previous section) and to provide data for the application of canopy reflectance models (to obtain the values of parameters needed for predictive inversions of models). In particular, it is important to have some idea of the angular distribution of reflecting surfaces. It is also desirable to have estimates of total bark surface area and a better understanding of the vertical distribution of all reflecting surfaces (bark and leaf) and of biomass.

Approach. Data for this task were collected in the sacrifice of aspen trees described for Task 3 and by sacrifice of six additional spruce trees. Necessary additional characteristics were measured on sacrificed aspen trees; branch angles were measured for all branches, and three branches from each tree were sampled for measurement of bark surface and leaf angle distribution. Six branches were sampled for each sacrificed spruce tree and measurements were made of bark area, needle angle distribution, needle age distribution, and size and angular distribution of needles as a function of age.

Scope and Status. Field work was done by UCSB field personnel. Data have been entered on computer and preliminary analyses for aspen completed to allow first-order estimates of bark area index for aspen plots. These estimates are shown, in Figure 14 to be closely correlated with biomass density. Spruce data have not been analyzed.

Task 5. Measurement of Microwave and Optical Properties of Vegetative Materials.

Objectives. This is necessary to interpret and evaluate results from both optical instruments and C-band scatterometer. Early work with canopy reflectance models has indicated that vegetation characteristics such as LAI cannot be estimated from remotely-sensed data without knowledge of reflectance and absorption characteristics of vegetative matter. It is necessary, then, to obtain measurements of these for important species in the SNF study area.

Approach. Samples of leaf, twig, and bark material were collected periodically throughout the year, packaged appropriately, and shipped to JSC (for analysis of optical properties) and Univ. of Kansas (for analysis of microwave properties). Experiments done last year indicate that optical properties do not change significantly if material is held at temperatures below 10 degrees C for up to 10 days. We shipped materials in insulated containers with chemical ice coolers.

Scope and Status. Materials were shipped for 8 dates by UCSB field personnel. Results of optical analyses of these materials done at JSC exist on computer tapes at UCSB and LARS. These data must be reduced and made available to canopy modelers at UCSB and other institutions. Microwave properties were analyzed at Univ. of Kansas and Univ. of Michigan and results are held at Univ. of Michigan.

Task 6. Initial Study of Additional Species and Stand-Types.

Objectives. In order to characterize vegetation characteristics for the entire study area, it is necessary to study additional dominant species and mixed stands. This year we established sample sites and acquired detailed ground-truth (see description of "ultra-sites" below) and radiometric data for jack pine and mixed aspen-jack pine stands.

Approach. Plot selection and measurement were as described for aspen and black spruce ultra-sites (see next task). Spectral data collection is described in Task 9. Two jack pine stands and three mixed sites were sampled by this procedure. Spectral data were gathered for 12 jack pine stands and 8 mixed stands sampled by the earlier (1983) procedure.

Scope and Status. Site selection and sampling was done by

ASPEN: Bark Area Index vs. Biomass

Superior National Forest, MN

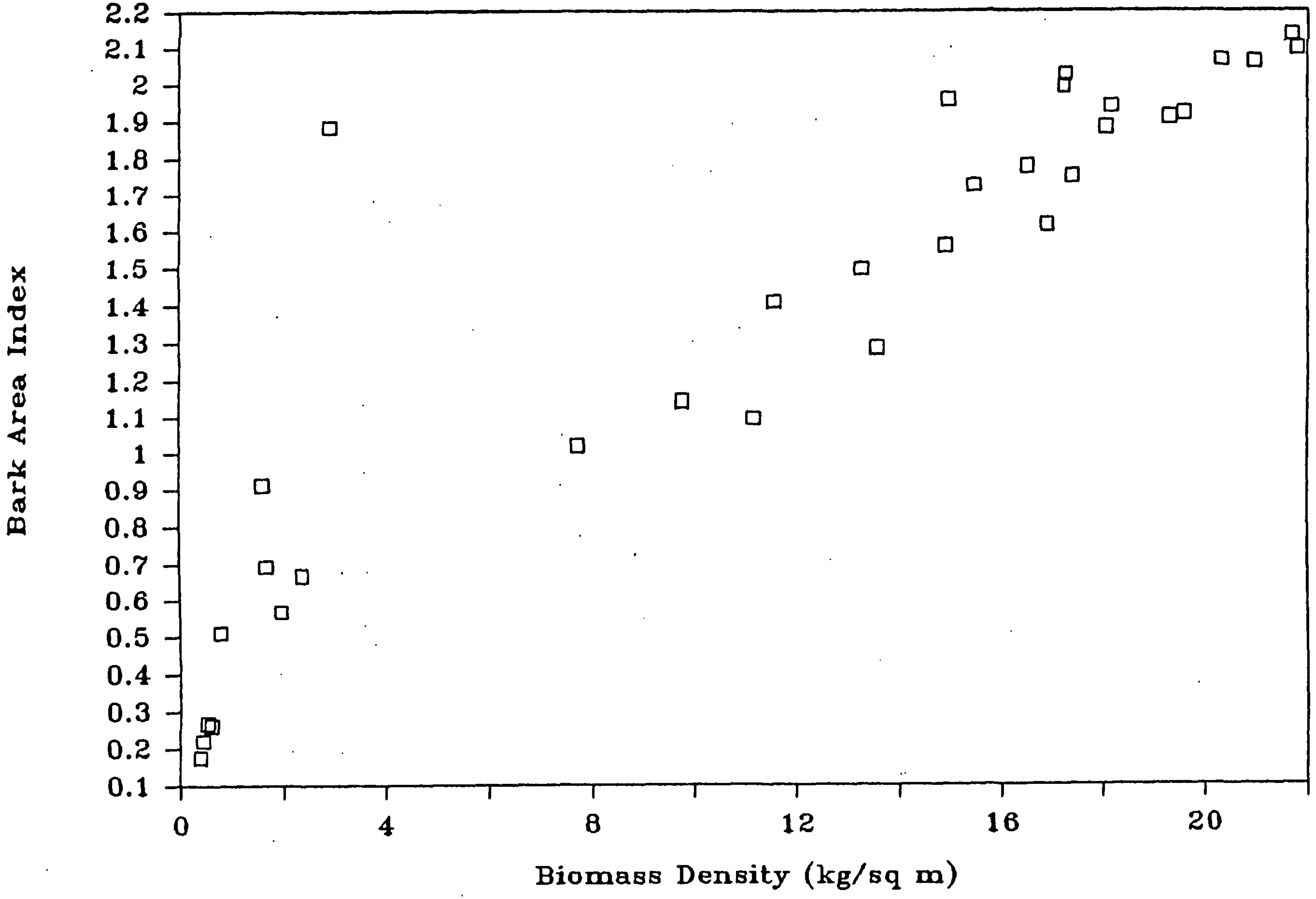


Fig. 14

UCSB field personnel. Data have been partially entered and proof-read. Analysis will be done by UCSB personnel.

Task 7. Intensive Study of Aspen and Black Spruce "Ultra-Sites".

Objectives. In order to test, compare, and improve the utility of canopy reflectance models in our work, we must have a better understanding of the interactions between three-dimensional stand structure and canopy reflectance. Both horizontal and vertical distribution of biomass and surface components of vegetation will affect spectral response by determining shadowing effects, view-angle and sun-angle effects, radiation attenuation, etc.

Approach. On certain test sites (designated as "ultra-sites") intensive studies were conducted to characterize horizontal and vertical vegetation distribution by component. On these sites a complete census of trees was made (as opposed to sampling only in sub-plots as in 1983) and all stems were mapped. Understory and sub-canopy were more thoroughly sampled and quantified also. We have selected and sampled three ultra-sites each of aspen and black spruce. Sites are distributed over the full range of site density and LAI. This work required development of innovative sampling techniques and resulted in a data set for analysis of vegetation structure superior to any extant data set that we are aware of.

Scope and Status. Field measurements for this task were conducted by UCSB personnel. A large portion of the data has been entered and some proof-reading done. Data analysis is under way at UCSB.

Task 8. Experimental Manipulation of Aspen Understory

Objectives. This task was designed to test the hypothesis that lack of spectral response to canopy LAI in aspen stands during the summer of 1983 is due to effects of understory and sub-canopy LAI.

Approach. Experimental manipulations were made on three selected aspen plots. Each is paired with a nearby "ultra-site". All understory and sub-canopy foliage was removed and kept from regrowth during the 1984 growing season. Comparison of the spectral response of these plots with the similar, paired ultra-sites should help evaluate the effects of understory and subcanopy.

Scope and Status. Sites were cleared and maintained by UCSB personnel. Repeated removal of foliage was required through the summer. Spectral data from Barnes radiometer and TMS have been registered for these sites, but analysis and modelling is in early phases.

Task 9. Multispectral Sensing of Forest Biomass, LAI, and Net Primary Production

Objective. This task is intended to evaluate the performance to be expected from multispectral (optical and microwave) approaches to the problem of estimating biomass, leaf area index, and net primary production for forests.

Approach. From studies supporting other tasks, and from other sources, models relating spectral properties (radar backscatter and optical reflectances in various bands) to canopy properties (biomass, LAI, and production) are being developed. To test and develop these models, we have acquired microwave back-scattering data from the "ultra-sites" and manipulated sites described above and a sub-set of sites sampled in 1983. A C-Band scatterometer has been mounted on the helicopter, along with the 8-band Barnes radiometer previously used, and both instruments were used, as in 1983, to take data directly over study sites while the helicopter hovers above them. Canopy reflectance models have suggested that maximum useful information may be obtained from non-nadir view of the ground-truth sites. Accordingly, both instruments have been mounted on a movable cradle allowing aiming at desired angles.

Spectral data were taken during five helicopter missions, from spring, prior to leaf-out, through autumn, after leaf-drop. Data were acquired over ultra- and manipulated sites and a subset of other sites. Data were taken at view angles of 0, 10, 20, 30, and 50 degrees and into, away from, and at right angles to the sun.

In conjunction with scatterometer observations from the hovering helicopter, concurrent measurements were made on the ground of soil moisture content, soil texture, soil roughness, amount of dew, etc.

Work with the scatterometer in 1984 is intended to test calibrating procedures, develop techniques and equipment, and obtain a first approximation of the utility of this technique.

Additional spectral data were acquired using TMS and AIS from C-130 aircraft, based at Ames Research Center, flying at 2000 and 5000 feet at several dates during 1984.

Scope and Status. JSC personnel have devised the instrumentation for this task. JSC, LARS, and UCSB personnel served as instrument operators in the helicopter. UCSB field personnel made concurrent measurements on the ground. Synthesis and evaluation of C-band data will continue to involve personnel from both UCSB and JSC. These data are still being digitized and calibrated. Spectral data now reside at LARS and UCSB. Analysis of these data in conjunction with ground-truth data will be done at UCSB.

Task 10 Ground-Truth Measurements for Other Spectral Data Sets.

Objectives. Spectral data sets over the SNF study region have been obtained from TMS, flown in mazes by C-130 aircraft, and for transects over a range of vegetation from the Barnes radiometer carried by the helicopter. This task will provide ground-truth for calibration and interpretation of these data sets.

Approach. Ground measurements for this task were made on plots located according to statistically appropriate sampling of the area for which remotely-sensed data are available. Sampling strata were determined by preliminary interpretation and classification of spectral data and inspection of aerial photos and maps. For TMS grid data, a broad range of vegetation was sampled. Sampling was by standard forestry techniques and involved less detail than sampling of intensive study sites.

Scope. Sampling was designed and done by UCSB field personnel. Ground-truth data have been entered into computer files yet, and analysis for estimation of LAI and biomass density is under way. TMS data have been partly registered and are held at UCSB and Goddard.

Task 11. Continued Development of Use of Canopy Reflectance Models for Estimation of Vegetation Characteristics.

Objectives. Work with reflectance models in 1983 has been important in assisting experimental design for future work. We will continue to use models to evaluate results and make further plans. In addition, efforts to develop inversions of models to be used in estimation of LAI, biomass, etc., will continue. As our understanding of forest structure and model behavior increases these efforts should become more productive.

Approach. Continued development and revision of models, in connection with new data on vegetation characteristics were to be carried out. Model inversions were to be applied to spectral data to verify models. This work has involved joint efforts by modellers at UCSB, SUNY, and other cooperating institutions, and forest ecologists at UCSB.

Task 12. Presentation of Results.

Objectives. In addition to internal reports, findings of this study should be presented at professional meetings and in scientific journals. Presentations in the fields of geography, remote sensing, forestry, and ecology will all be involved.

Approach. Several presentations at professional meetings of remote sensing specialists and ecologists have been made during 1984 by workers from UCSB and JSC. A number of manuscripts are in preparation, and others will be initiated when data are fully transferred and catalogued so that analysis can be resumed.

4.0 TRANSFER OF DATA AND MATERIALS FROM JSC TO OTHER CENTERS

This section details the disposition and condition of the wide range of data collected in the COVER project, computer programs developed, and other materials which were removed from JSC following termination of Earth Resources Research. Table 3 summarizes classes of material that were addressed in this effort. Following sections describe work done in transferring, documenting, and processing each type of material.

4.1 Vegetation Canopy Data

This data set consists of intensive measurements made by UCSB (NASA-funded) field crews of forest stand structure and pattern and of biophysical characteristics and dimensional relationships for single trees in several important boreal forest types in the Superior National Forest study area. The data set is unique and of special value in its precise registration with spectral data obtained from helicopter and aircraft overflights. Data were entered from field data sheets at JSC (1983 field season) or in the field (1984), proof-read, and transferred to JSC for analysis.

Stand types studied were black spruce in lowland stands (35 stands), trembling aspen (33 stands), jack pine (12 stands), and aspen-jack pine mixes (10 stands). Sampled stands were distributed through all stand ages, heights, and densities. For sacrificed trees (for dimension analysis) of aspen (56 trees) and spruce (32 trees) detailed measurements of dimensions and of biomass and leaf area were made.

Data from sacrificed trees were used to develop transformations of over-all tree dimensions for biomass and leaf area. These transformations, applied to tree dimensions measured on sample plots, allow accurate estimation of plot-level variables such as biomass density and leaf area index (LAI). Under this funding these data sets were collected, documented, and transferred to UCSB and Goddard in formats compatible with computers at these institutions.

Analyses of these data have continued under this funding, and we have produced definitive estimates of biomass and LAI for our study stands. These estimates are unique in the literature of such studies in including measures of associated variance, partitioned by source. This analysis of statistical uncertainty will allow future workers to qualitatively improve approaches to biomass and LAI estimation. These results have been presented at professional meetings and are in preparation for publication.

Data on phenological patterns - time and rate of leaf expansion - in aspen and black spruce were documented and

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TABLE 3

EARTH RESOURCES RESEARCH DATA AND ANALYSIS

I. Vegetation Data

- Plot data
  - Aspen
  - Spruce
  - Jack Pine
  - Mixed species

- Dimension Analysis Data
  - Aspen
  - Spruce

II. Understory data

- Phenology - photography

III. Remote Sensing Data

- 1983 Barnes radiometer data
- 1983 70mm photography
- 1983 LARS data
- 1983 spectral properties of spruce needles
- 1983 spruce needle area/weight ratio & photos
- 1983 C-130 Thematic Mapper simulator data
- 1983 hemispherical photography

- 1984 Barnes radiometer data
- 1984 70mm photography
- 1984 C-band scatterometer data
- 1984 spectral properties of spruce needles

IV. Analytical Computer Programs

- Dimension analysis
- Variance estimates
  - Plot data
  - Dimension analysis
- Computer models of canopy reflectance

V. Remote Sensing Interpretation Computer Programs

- Calibration for Barnes radiometer
- Classification programs
- Classification results
- Analysis of C-band scatterometer

analyzed at UCSB. Results are incorporated in temporal modelling work currently under way at Goddard.

The data set documented and transferred includes extensive ground photography of sample plots and trees, currently held at UCSB.

4.3 Understory Vegetation Data

Extensive measurements were taken of various aspects of understory vegetation. On sample plots, herb and shrub layer cover and species composition were measured and shrub stems were counted and measured. 45 stems each of the two major shrub species (mountain maple and hazel-nut) were cut for dimension analysis. Phenology of leaf expansion was measured for these two species in spring 1984. These data are also accompanied by extensive photo-documentation. These data are held at UCSB and Goddard.

4.4 Remotely Sensed Spectral Data

Remotely sensed data collected for this project are of four primary types: 1) data from helicopter-mounted Barnes radiometer (and simultaneous data from identical calibration instrument at ground site); 2) data from C-130-mounted Thematic Mapper Simulator; 3) aerial photography from helicopter (70 mm format) and C-130 (9x9 inch format); and 4) C-band scatterometer data. The first 3 types were gathered in both the 1983 and 1984 seasons. Scatterometer data were collected only in 1984, and remain at Johnson Space Center where they are being analyzed under separate funding by Dr. David Pitts.

Spectral data were transfered via magnetic tape to Goddard Space Flight Center, where Dr. Forrest Hall and associates have catalogued and documented them. Barnes radiometer data have been calibrated using measurements by an identical instrument over barium chloride panel at ground calibration site. TMS data have been geometrically corrected for scan-angle effects. Selected portions of the spectral data set have been transferred on tape to UCSB. All data are available for analysis, and are the subject continuing research at both Goddard and UCSB.

Ground sites have been geographically registered to TMS data to allow further analyses.

All aerial photography has been transferred to Goddard Space FLight Center and catalogued. Duplicate sets, covering all study sites for critical dates, are held at UCSB. These are being used in data registration tasks, and in accuracy assessments of classifications of TMS data.

4.5 Other Spectral Data

Measurements of spectral properties of isolated vegetation components were made at LARS/Purdue and at JSC. These data are held and catalogued at Goddard Space Flight Center. They are being incorporated in ongoing canopy reflectance modelling research.

4.6 Analytical Computer Programs

This category of materials includes programs for analysis and reduction of ground-based vegetation measurements and for simulation of forest canopy reflectance.

A large body of sophisticated programs for analysis of ground-based vegetation measurements were developed for studies of aspen and black spruce. These programs are for 1) development and fitting of dimension analysis models for estimation of tree leaf area and biomass by component, 2) application of these models to plot-level measurements, and 3) estimation of statistical error at all stages of analysis (see Section 2. above). A parallel set of programs has been developed for analysis of bark area index and distribution.

These programs were developed collaboratively by ecologists at UCSB and statisticians at JSC. They have been revised, integrated, and documented by researchers at UCSB, and now constitute a valuable package for vegetation analysis of greater detail and accuracy than previously available. These programs, with test applications, are described in manuscripts in preparation for publication. Presentations at professional meetings have elicited strong interest in the package from professional foresters and ecologists.

Computer models of forest canopy reflectance have been transferred to Goddard Space Flight Center and revised to run on resident VAX computers. Models are being further developed and applied by workers at Goddard.

4.7 Remote sensing interpretation computer programs

A number of specialized programs were developed for the COVER project at JSC. These include programs for calibration of Barnes radiometer data and for analysis of C-Band scatterometer data. Calibration programs have been transferred to Goddard and UCSB. They have been revised to run on VAX computers. Scatterometer analysis programs are still in use at JSC.

Other programs developed by the Earth Resources Research group at JSC and used in the COVER project include programs for testing discrimination of vegetation types with spectral data, classification of remotely sensed digital spectral data, and for evaluation and analysis of classification results. These programs have also been transferred to Goddard, where they continue to be developed and applied.

8. SUMMARY

Under NASA-JSC funding for this project, we have generated partial results which have strong implications in the remote sensing of natural vegetation. We have shown that canopy reflectance is highly dependent on species composition, canopy structure, and complex interactions among strata and species involving structure, phenology, etc. We have developed a valuable data base and complimentary sets of software for testing and improving the utility of remote sensing in vegetation studies. Following termination of funding in the midst of this project, we have completed the salvage, transfer, cataloguing, and documentation of an extensive and invaluable set of coordinated data and software.

The value of the data set lies in its extent and in the coordinated research plan under which it was gathered. No other single existing data set permits the combination of accurate estimation of biophysical variables for natural forests and calibration of several levels of precisely registered, remotely sensed data. Without the transfer and documentation of this body of material, carried out in this project, its value would have been lost. Research using this body of material has been facilitated by this effort, and continues at UCSB and Goddard Space Flight Center.

The body of material is also available for use at other academic or governmental centers. We have received strong expressions of interest in using the data and software from a number of researchers at least 6 institutions in several portions of the country. It is expected that collaborative research will continue to produce valuable results from this data base over the next decade or longer.

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