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FIELD AND AIRBORNE SPECTRAL CHARACTERIZATION OF SUSPECTED ACID DEPOSITION DAMAGE IN RED SPRUCE (PICEA RUBENS) FROM VERMONT

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I. ABSTRACT

In an attempt to demonstrate the utility of remote sensing systems to monitor sites of suspected acid deposition damage, intensive field activities and aircraft overflights were centered on montane forest stands in Vermont. Throughout the summer and fall of 1984, detailed ecological evaluation, damage assessment, and site selection were conducted at Camels Hump Mountain and other sites of Picea rubens (red spruce) and Abies balsamea (balsam fir) occurrence. Concurrent with overflights on August 17, 1984, field activities consisted of in situ collection of high-spectral resolution leaf and branch spectra (0.4 - 2.4 μm), water potential measurements with Scholander pressure bombs, and collection of leaf samples for anatomical and metal content assessment. In situ data were collected from selected stands of P. rubens considered to be representative of three damage or decline levels (high, medium and low). Remote sensing aircraft data were acquired with the high-spectral resolution Airborne Imaging Spectrometer (AIS), a Thematic Mapper Simulator (TMS), and aerial photographic cameras (black and white panchromatic and false color infrared) onboard a NASA C-130, and the high-spectral resolution Spectron Engineering (SE) 590 spectrometer and Barnes Modular Multiband Radiometer (MMR) onboard a NASA helicopter.

Pressure bomb data indicate that xylem water column tension in trees from the high damage sites are at a higher tension than at the low damage sites by an average of 0.5 MPa (5.0 bars) atmospheric pressure. Average xylem water column tension measured throughout the day of the overflight was greater at the high damage site than at the low damage site. The field spectral data indicated that the reflectance curves from samples collected from the high damage site vegetation differed from those from the low damage site in the following ways. Samples from the high damage site possessed: a reduced and shifted chlorophyll absorption feature in the red region of the visible spectrum, a reduced reflectance along the entire near infrared reflectance plateau (0.7 - 1.3 μm), and a relative increase in reflectance in the 1.6 and 2.2 μm regions of the spectrum. These in situ results suggest that alteration of plant pigment systems, leaf biomass and/or anatomy, and canopy moisture content may characterize damaged stands of P. rubens. Analysis of helicopter spectrometer data indicate the remote detection of the reduced and shifted chlorophyll absorption feature. In comparison to the in situ spectrometer data, reflectance in the near infrared region is higher in the helicopter data acquired from a high damage site when compared with that acquired from a medium damage site. These preliminary data suggest that a syndrome of spectral characteristics exists which may aid in the remote detection of suspected acid deposition damage in red spruce and other species using airborne spectrometers and radiometers. In addition, high spectral resolution data will be required, and may provide insight regarding the nature of damage detected.

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II. INTRODUCTION

A. BACKGROUND

Since 1965, red spruce (Picea rubens Sarg.) has shown a marked decline in vigor in the high elevation spruce-fir forests of northeastern United States (Siccama, et al., 1982; Vogelmann, et al., 1984). Other members of the montane forest, including beech (Fagus grandifolia Ehrh.), sugar maple (Acer saccharum Marsh.) mountain maple (A. spicatum Lam.), striped maple (A. pensylvanicum L.), white birch (Betula papyrifera Marsh. var. cordifolia (Regel) Fern.) and balsam fir (Abies balsamea (L.) Mill.) have experienced less dramatic declines throughout this time period (Vogelmann, et al., 1984). Although the specific cause of the forest decline has been disputed, there is mounting evidence that high inputs of air pollutants (H^+, SO_2, NO_3^-, Pb, Cd, Cu, Zn) into high elevation forests may be a significant factor.

Camels Hump Mountain, located in the Green Mountains of northern Vermont, has been the site of long term ecological investigations, beginning in 1965 when vegetational, meteorological and soils data were collected along a transect on the western slope (Siccama, 1974). Subsequent studies along this transect (Siccama, et al., 1982; Vogelmann, et al., 1984) have indicated that since 1965, the forests of this area have been under high levels of stress, resulting in decreases in basal area, density, biomass and vigor, and increases in levels of mortality.

Because of (a) the presence of an extensive data base, (b) the marked vegetational damage symptoms apparent, especially in red spruce, and (c) the influx of high levels of air pollutants into the region (Sherbatskoy and Bliss, 1984), Camels Hump Mountain was chosen as a study area for the current investigation. In addition, a low damage site in Ripton, Vermont, approximately 40 km south of Camels Hump, was included in the study.

B. REMOTE SENSING

Remote sensing systems provide a means of monitoring native vegetation in a number of ways. Discrimination and mapping of native tree species may be done using the spectral and spatial resolution capabilities of multispectral scanners such as the Thematic Mapper (TM) of Landsats 4 and 5, and airborne Thematic Mapper Simulator (TMS) systems (Milton and Mouat, 1984; Rock, 1982). The spectral regions covered by the TM/TMS sensors provide data valuable in assessing a variety of types of vegetation anomalies associated with geochemically induced soil conditions (Goetz, et al., 1983; Milton and Mouat, 1984; Rock, 1984). High spectral resolution remote sensing systems allow improved mapping capabilities (Goetz, et al., 1983; Rock, 1983, 1984) as well as detection of subtle spectral features associated with damage due to heavy metal-related geochemical stress (Chang and Collins, 1983; Collins, et al., 1983; Milton, et al., 1983).

The influence of acid deposition on Picea rubens is not well understood, but may involve mobilization of endogenous and/or exogenous soil metals (Cronan and Schofield, 1979), which in turn could result in subtle, but characteristic spectral shifts in the foliage of the affected vegetation (Collins, et al., 1983). Canopy dryness may result from either the direct or indirect effects of acid deposition damage, since this appears to be a common vegetation response to metal damage (Goetz, et al., 1983). Existing remote sensing systems (such as the SE590, AIS and TM/TMS) may be used to monitor sites known to be affected, allowing detection of damage, quantification of levels of damage, and mapping of areal extent of damage.

During the weeks of August 13 and 20, 1984, NASA personnel from both the Goddard Space Flight Center (GSFC) and the Jet Propulsion Laboratory (JPL), joined with faculty and students from the University of Vermont (UVM), to collect field data in support of concurrent acquisition of airborne and ground-based data remote sensing data. This report presents the preliminary findings of some of these activities.

III. MATERIALS AND METHODS

Sites Chosen: A total of eight spruce stands, representing a gradient from low to high levels of damage, are included in this study. These include seven from Camels Hump Mountain, Vermont, and one from Ripton, Vermont (Table 1). A "high damage" site and a "medium damage" site on Camels Hump and a "low damage" site from Ripton were selected for more extensive study using Scholander pressure bombs and portable field spectrometers and radiometers.

Damage Level Evaluation: Each site was assigned a damage value based upon the amount of red spruce foliar damage visually apparent. Circular plots (0.1 acre or 0.04 ha) were used as sampling units. Each spruce occurring within a circular plot that contributed to the forest canopy was assigned a size class and a damage class. Size classes were as follows: (a) 0 to 2.5 cm diameter at breast height (dbh); (b) 2.5 to 10 cm; (c) 10 to 20 cm; (d) 20 to 30 cm; (e) 30 to 40 cm; (f) 40 to 50 cm dbh. Damage classes were as follows: 1) 0-5% damage ("damage" referring to percentage of needles missing from the live crown); 2) 5-10%; 3) 10-25%; 4) 25-50%; 5) 50-75%; 6) 75-99%; 7) 100% damage (i.e., recently dead).

Spruce damage per circular plot was calculated using the following equation:

$$\sum_{i=1}^{k} s_i \cdot w_i / \sum_{i=1}^{k} w_i$$

where k is the number of individuals, s_i represents the midpoint of the range of the damage category of the individual, and w_i represents the midpoint of the range of the size class for that individual (i.e., the weighting factor). Average damage per site was estimated by averaging the 0.04 ha circular plot values. Theoretically, damage values may range from a minimum of 2.5% (lowest possible damage) to a maximum of 100% (highest possible damage).

Percentage balsam fir damage was also calculated at each site. Each fir that contributed to the forest canopy from within the plots analyzed was assigned a size and damage class (the same classes as were used for spruce damage calculations). Fir damage was then calculated using the above equation.

TABLE 1

Summary data including site elevations, spruce mortality and damage. Those sites examined in greater detail and described in this paper are indicated with an asterisk (*). Percentage spruce damage values include standard deviations among .04 ha circular plots.

Site		Elevation (in meters)	Number Circular Plots	Number Spruce Indivduals (2.5 cm or greater dbh)	Percentage Spruce Mortality	Percentage Spruce Damage
Camels Hump	1	579	5	155	3.9	11.8 ±4.2
	2	594	5	163	0.6	11.9 ±2.9
	3	701	4	91	4.4	24.6 ±7.1
	*4	792-838	9	370	10.5	34.9 ±9.6
	5	914	9	262	18.3	61.2 ±7.4
	6	945	10	396	31.1	68.5 ±7.0
	*7	853-1006	8	132	24.2	76.0 ±11.2
Ripton	*1	442	8	162	21.0	22.7 ±9.4

Percentage spruce mortality and percentage fir mortality were also calculated for each site. This evaluation consisted of dividing the number of recently dead spruce or fir trees (i.e., those still retaining small twigs) of 2.5 cm dbh or more by the total number of spruce or fir trees occurring on the plots analyzed above.

A. IN-SITU ASSESSMENT

Spectral Measurements: Field activites included *in situ* spectral data acquisition from several specimens of *Picea rubens* in the spectral region 0.4 - 2.4 μm, using both a high spectral resolution spectrometer and two broad-band radiometers outfitted with filters duplicating TM spectral coverage. Both radiometers also provided spectral data at 1.0 - 1.3 μm, a spectral region not covered by the orbital TM. Healthy sunlit branches with needles attached were collected for spectral analysis with a set of extendible pruning shears. These branches were immediately placed on a background consisting of four layers of black plastic and spectral data were collected. Even at the high damage site, only the healthiest branches were collected for assessment. A fresh barium sulfate panel was used as a reference with the radiometer, while Fiberfrax was used with the field spectrometer. The field spectrometer which was used was the Visible/Infrared Intelligent Spectrometer (VIRIS) developed by GER[1]. This instrument delivers spectral coverage from 0.4 to 2.5 μm with a nominal spectral resolution of 3.8 nm. The VIRIS simultaneously acquires data from both the target (spruce branches) and a Fiberfrax reference standard.

[1]The reference to manufacturer does not imply endorsement by the National Aeronautics and Space Administration (NASA).

Water potential measurements. Simultaneous with field spectral data acquisition, xylem water column tension was measured with two Scholander pressure bombs. The pressure bomb analysis was conducted on small branches collected at the same time as those for spectral analysis.

B. AIRCRAFT DATA COLLECTION

Two NASA aircraft were deployed in support of this research activity; a C-130 operating out of the NASA/Ames Research Center at Moffett Field, California, and a Bell UH-1B Iroquois helicopter from NASA's Wallops Flight Facility at Wallops Island, Virginia. The sensors carried onboard the C-130 included the JPL AIS, the NS-001 (TMS), and aerial photographic cameras containing both black and white (B&W) pancromatic film and false color infrared (CIR) film. The NS-001 version of a TMS was selected because it provides band coverage in the 1.0 - 1.3 μm spectral range (again, a region not covered by the orbital TM on-board Landsat 4 and 5). The Camels Hump Mountain study area was overflown by the C-130 on August 17, 1984, at approximately 15:20 eastern daylight savings time (EDST) at an altitude above the ground of approximately 4.8 km (16,000 feet). Camels Hump Mountain was overflown again with the same instrument package on September 8, 1984 (10:35 - 11:31/EDST) due to a malfunction of the AIS instrument during the earlier overflight. Since AIS and TMS data are not included in this report, details regarding the aircraft sensors are not included here. Vane, et al. (1983) and Richard. et al. (1978) provide additional information on the AIS and TMS, respectively.

The Bell UH-1B helicopter carried a Barnes Model 12-1000 MMR radiometer, a SE590 spectrometer, two 35 mm flight research cameras (fitted with normal and telephoto lenses), and a B&W video camera. All five devices were mounted on the nose of the helicopter as shown in Figure 1, and all but the video camera were triggered by a common switch to ensure simultaneous acquisition of data. Both the Barnes radiometer and the SE-590 spectrometer were fitted with lenses having a 1^{o} instantaneous-field-of-view (IFOV). This IFOV, coupled with a nominal hovering altitude of 300 meters (1000 feet) above the ground, yielded a ground sample resolution of approximately 5.5 meters (18 feet) in diameter. The Barnes radiometer provides discrete bandwidths duplicating TM/NS-001 TMS spectral coverage, and the SE-590 spectrometer provides high spectral resolution over the 0.4 - 1.0 μm region, with a nominal spectral resolution of 2.34 nm.

The helicopter was used to collect spectral data over four sites on Camels Hump Mountain between 14:23 and 15:23 EDST on August 17, 1984. Location of preselected research plots was facilitated by the deployment of white, helium-filled weather balloons at each site. A total of approximately 220 spectral measurements were acquired over the four sites.

To facilitate the calibration of the radiometer and spectrometer data following the mission,

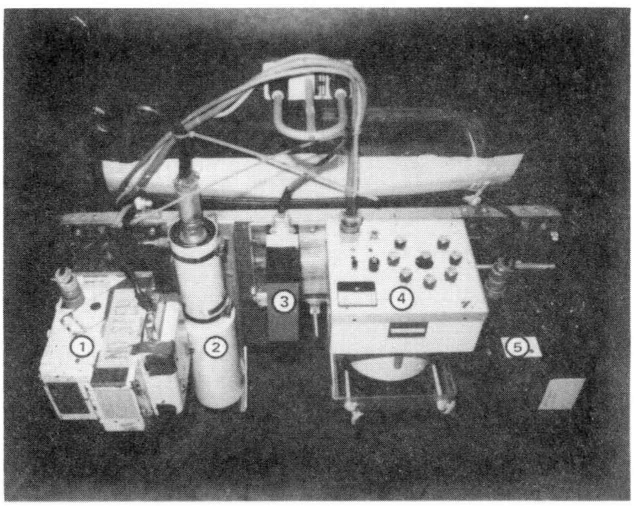

Figure 1. Photograph of the instrumentation package mounted on the nose of the helicopter. The instruments included: (1) 35 mm flight research camera with a normal lens, (2) a black and white video camera to provide real-time readout to CRT's in the helicopter, (3) Spectron Engineering SE590 spectrometer optical head, (4) Barnes MMR radiometer, and (5) 35 mm flight research camera with a telephoto lens. Devices 1, 3, 4 and 5 were triggered simultaneously for all observations, and the video camera provided continual coverage.

a calibration site was established on the southwest flank of Camels Hump at an elevation of approximately 550 m (1800 feet). At this site, which was no more than 5 km from any of the research plots, the following devices were set up: (a) a duplicate radiometer and spectrometer which took reference scans of a barium sulfate panel every two minutes, (b) a pyranometer to continuously record incoming solar radiation, and (c) a 6 m by 6 m white canvas panel that the helicopter could hover over at altitudes of 30 to 60 m to obtain reference scans or readings immediately before and after the data collection mission. This canvas panel had been previously calibrated against the barium sulfate reference panel (Williams, et al., 1984).

IV. RESULTS AND DISCUSSION

A. DAMAGE LEVEL EVALUATION

Spruce stands showed marked differences in levels of spruce damage (see Table 1), with mean values from 11.8 to 76.0%. At Camels Hump Mountain, percentage mortality closely paralleled damage values (r^2 = 0.90), ranging from 0.6 to 31.1%.

The seven sites from Camels Hump form four statistically significant groupings of spruce damage levels (Student's t-test). These are sites 1 and 2, sites 3 and 4, site 5, and sites 6 and 7. The damage levels for the Camels Hump sites are highly correlated with elevation (r^2 = 0.93; see Figure 2). The most damaged sites are located at relatively high elevations, whereas the least damaged sites are located at relatively low elevations.

It should be noted that damage in spruce at Ripton 1 was perhaps deceivingly high (spruce damage = 22.7%). At this site, mortality was notably high (21.0%), perhaps due to "overmaturity". Since trees "recently dead" were included in estimates of damage, the high percentage of mortality greatly increased damage values. At this site most of those trees still living appeared vigorous

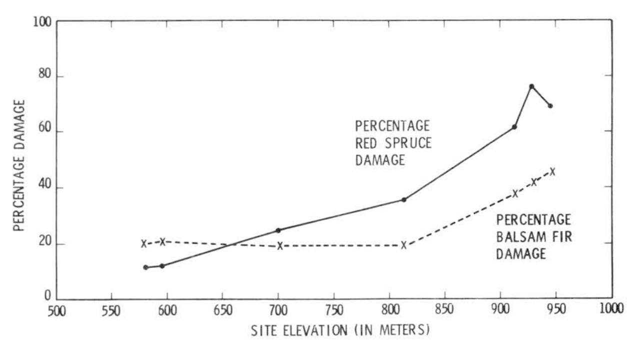

Figure 2. Elevation versus percentage red spruce and balsam fir damage for seven sites on Camels Hump Mountain, Vermont.

and healthy, and these were the source of branches used for in situ spectral assessment and collection of pressure bomb data.

Balsam fir damage (Table 2) ranged from 19.0 to 43.8% at the Camels Hump sites. There appears to be a good correlation between fir damage and spruce damage values at these sites ($r^2 = 0.88$) (see Figure 2). Those sites that have the highest spruce damage values also have the highest fir damage values; those sites with the lowest spruce damage values have the lowest fir damage values. As was found for red spruce, balsam fir damage is positively correlated with increasing elevation ($r^2 = 0.69$).

B. IN-SITU DATA ASSESSMENT

Spectral Data: A comparison of several in situ reflectance curves of foliage and branches collected from different specimens of *Picea rubens* from the same site is likely to show a high degree of variability in terms of amplitude, at least along portions of the curve not influenced by pigments. This variability is due to the limited FOV of the VIRIS and the natural variability in the state of health seen within a given site. To depict this variability, mean reflectance ±1 standard deviation (S.D.) data from both high and low damage sites are presented in Figure 3. The spectral data presented for each site are considered as highly representative of the spectral properties of low damage and high damage specimens of *Picea rubens*. No in situ spectra were acquired for *Abies balsamea*. Note that there is significant overlap in the visible portion of the spectrum, as well as at longer infrared (IR) wavelengths, especially beyond 2.0 μm. Note, however, that little overlap occurs along the near infrared (NIR) plateau (0.75 - 1.35 μm).

As noted above, the variability among reflectance curves represented in Figure 3 is due to factors such as variations in the state of health of the branch specimen selected, and the actual portion of the branches viewed by the spectrometer (amount of leaf material relative to amount of branch and shadow). In all cases, an attempt was made to include equal amounts of leaf material for spectral assessment, as determined by looking through the spectrometer viewfinder. At each site, only the most healthy branches collected (as determined visually) were used for spectral assessment and pressure bomb measurements.

The most obvious difference in the spectral data acquired from the two sites (Figure 3) is variation in reflectance along the NIR plateau. Since reflectance features in this region of the curve may be related to the leaf biomass, state of cellular health (amount of intercellular airspace to cell wall/cytoplasm volume), the type of cellular arrangement, and degree of hydration of leaf tissue (Ustin, et al., 1985; Goetz, et al., 1983; Gates, 1970; Gausman, et al., 1977, 1978), reduced reflectance along the NIR plateau for those specimens collected from the high damage site suggests a change in one or more of these leaf cellular properties.

The reduced absorption (increased reflectance) centered at approximately 0.68 μm, characteristic of all of the spectral curves acquired from the high damage site, suggests a reduced photosynthetic capability for trees from this site. Absorption in this region of the visible spectrum is related to the chlorophyll pigment within the leaf tissue (Gates, 1970), and such a reduced absorption will likely result in a lower net primary productivity. Leaf area assessment for specimens used in acquiring these spectral measurements suggest, however, that leaf biomass differences are not statistically significant above the 80% confidence level.

The individual in situ spectral curves presented in Figure 4 were selected as characteristic of spruce from both high and low damage sites, and illustrate an additional spectral feature not readily apparent in the mean spectral data presented in Figure 3. In addition to the amplitude variations noted above, it is significant to note that a subtle variation occurs in the position of

TABLE 2

Summary of data for balsam fir mortality and damage.

Site		Number of Balsam Fir Individuals (2.5 cm or greater dbh)	Balsam Fir Percentage Mortality	Percentage of Balsam Fir Damage
Camels Hump	1	133	9.2	20.3
	2	101	6.9	21.0
	3	148	2.0	19.4
	4	130	8.5	19.0
	5	73	8.2	37.8
	6	242	17.4	41.9
	7	410	8.0	43.9
Ripton	1	0	--	--

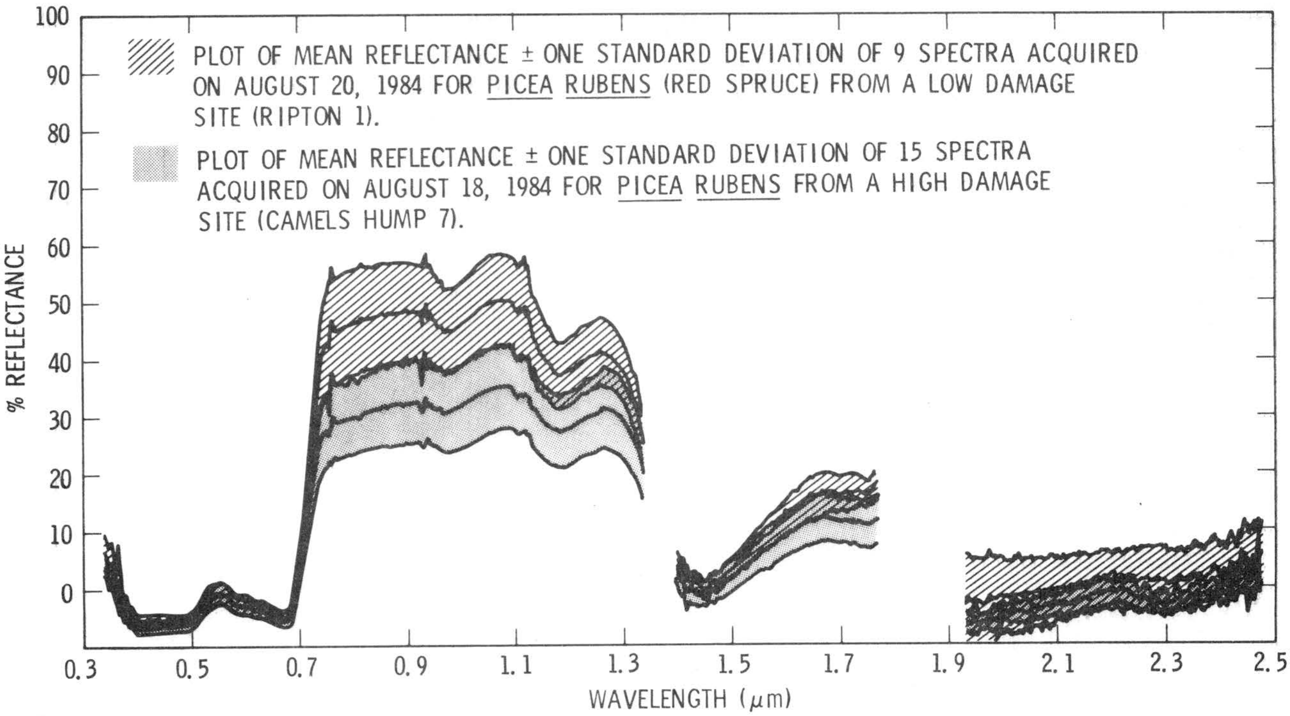

Figure 3. Range data for spectral reflectance curves of Picea rubens (red spruce) from low and high damage sites.

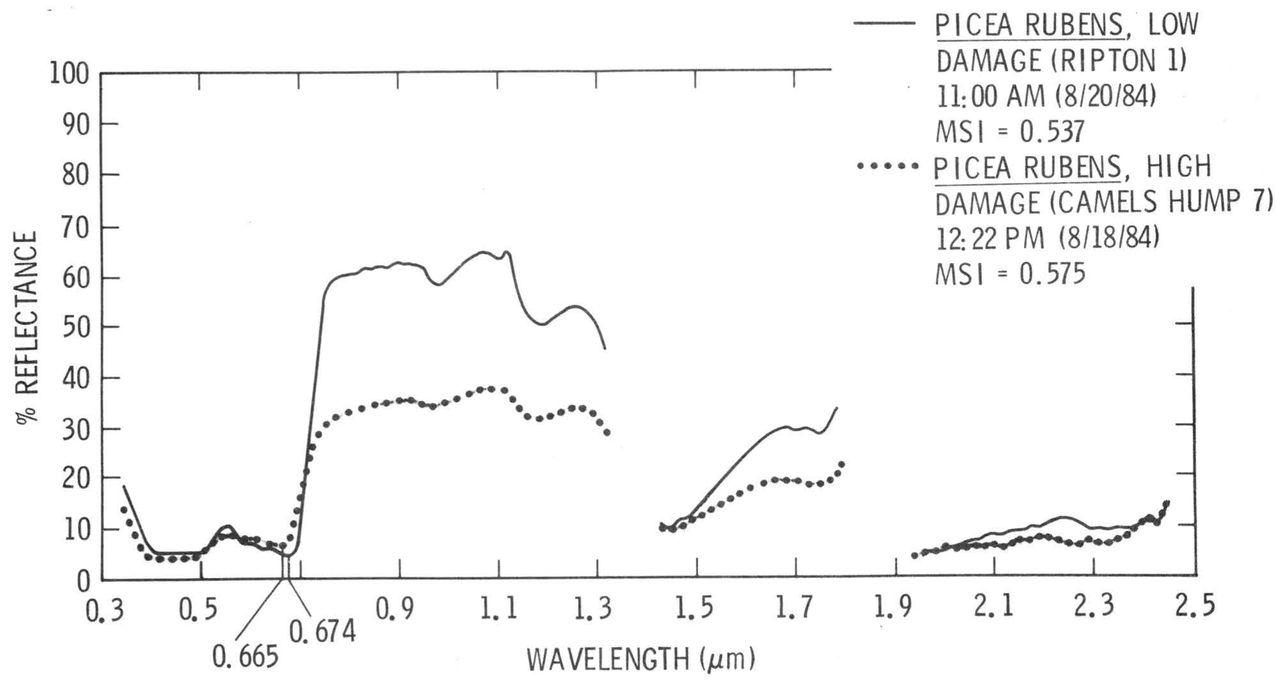

Figure 4. Comparison of spectral reflectance curves for selected plants from suspected acid deposition damage sites.

the chlorophyll absorption feature located at approximately 0.67 - 0.68 μm, between spruce at high and low damage sites. The absorption maxima are at slightly different wavelengths, 0.665 μm for the specimen from the high damage site, and 0.674 μm for the specimen from the low damage site. Collins and coworkers (Chang and Collins, 1983; Collins, et al., 1983; Milton, et al., 1983) have noted similar shifts in various types of vegetation growing in soils high in heavy metals such as Cu, Zn, and Pb. The appearance of such a spectral shift to shorter wavelengths (the Collins "blue shift") in the reflectance data acquired for spruce from high damage sites suggests that heavy metal damage may be involved in the forest decline in Vermont.[1] However, it should be noted that little is known regarding the spectral properties associated with other forms of stress-induced damage in vegetation.

The relative height of spectral reflectance maxima near 1.65 and 2.2 μm provide an accurate indication of leaf water content (Rohde and Olson, 1971; Tucker, 1980; Goetz, et al., 1983). Since albedo variations at these wavelengths may be related to variations in the amount of leaf material vs. branch and shadow viewed by the field spectrometers, values for these reflectance peaks should be ratioed against other portions of the curve in order to provide information independent of such instrument-induced artifacts. In this study and others currently in progress at JPL, a ratio of the percent reflectance value for the peak centered at approximately 1.65 μm divided by the percent reflectance value from the peak centered at approximately 1.26 μm has been shown to provide an accurate indication of relative leaf/canopy moisture, when compared with xylem water column tension measurements made with the pressure bomb. This ratio herein is referred to as the Moisture Stress Index (MSI).

As vegetation dries, reflectance at 1.65 μm increases relative to reflectance at 1.26 μm (Goetz, et al., 1983), and the MSI value under these conditions begins to approach 1.0. The lower the MSI value, the greater the moisture content of the leaves. The depth of the water absorption features seen along the NIR plateau (centered at approximately 0.97 μm and 1.2 μm) is also an indication of leaf water content and corresponds well with MSI values. Note the calculated MSI values for the reflectance curves presented in Figure 4, and compare these values with the NIR plateau absorption features. Both spectral properties (MSI values and NIR absorption features) suggest that canopy dryness is greater at the high damage site (Camels Hump 7). The present study suggests that additional vegetation water regime data are needed before firm assumptions regarding canopy moisture levels may be made. Porometer data, plus dry weight to wet weight ratios, are necessary in addition to xylem water tension measurements.

Pressure Bomb Data: Xylem water column tension data collected on August 18, 1984, from the low damage site (Ripton 1) and the high damage site (Camels Hump 7) are presented in Figure 5.

These present data suggest that some differences may exist relative to canopy moisture levels at the two sites, at least during certain times of the day. The lower curve, representing pressure bomb data from the high damage site shows an approximately 0.5 MPa (5 bar) greater negative tension (until early afternoon) compared to the low damage site (upper curve). The influence of shadows, due either to clouds or local site conditions, has a dramatic effect on pressure bomb readings, and that influence can be seen in the hours prior to noon. With the dissipation of morning clouds, branches that were exposed to full sun showed a rapid increase in xylem water column tension within a matter of minutes at both sites. Afternoon clouds resulted in a dramatic reduction in tension at both sites indicating that the two sites were under comparable weather conditions when readings were taken.

Caution should be exercised when inferring information concerning canopy moisture levels from pressure bomb data. Although these data represent a limited number of measurements, certain trends are seen. Early morning readings show lower water column tension than those collected near the solar noon, a fact consistent with our understanding of diurnal transpirational flux seen in other gymnosperms (Running, 1980). The highest tension values reached at the two sites were associated with trees from the high damage site. One may also assume that local site conditions (clouds, shadows) have a marked influence on readings, which must be taken into account in interpreting the results. Moisture Stress Index (MSI) values calculated from spectral measurements agree well with pressure bomb measurements made at each site.

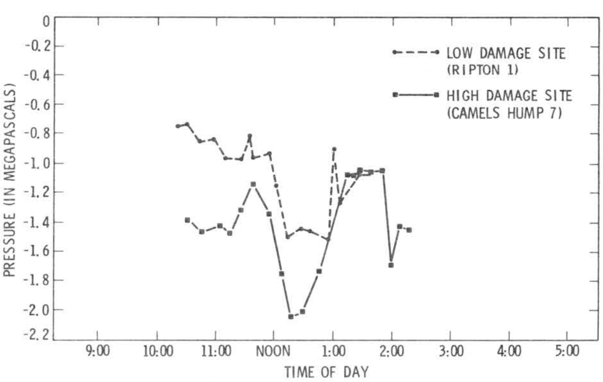

Figure 5. Scholander pressure bomb data acquired on August 18, 1984 for Picea rubens (red spruce).

[1] Over a 13 year period from 1966-1979, concentrations of copper, lead, and zinc found in the soil on Camels Hump increased by 23%, 79%, and 27%, respectively (Vogelmann and Klein, 1982).

C. ASSESSMENT OF AIRCRAFT DATA

The radiance data acquired by the Barnes MMR 8-band radiometer and the SE590 spectrometer were calibrated and converted to percent reflectance using the reference scans which were taken over the white canvas panel immediately before and after the data acquisition mission. An example of the type of data recorded by the two instruments is shown in Figure 6. An in-depth discussion of both instruments, as well as practical considerations associated with helicopter data acquisition efforts, can be found in Williams, et. al. (1984). The weather conditions over Camels Hump during the data acquisition were ideal. This can be substantiated by the pyranometer data, which showed a steady, gradual decrease in incoming solar radiation as the afternoon mission progressed, with only minor fluctuations in the curve.

Following calibration, plots of percent reflectance for each observation were generated (see Figure 6) and compared to other plots of data acquired over the same study site. This procedure, when coupled with inspection of the 35 mm aerial photography, was useful for eliminating any bad scans (i.e., ones which hit primarily rock outcrops, missed the plot, etc.) and/or for pooling subgroups of data within a given site. After these intermediate inspection steps were completed, the data for a given site or subgroup within a site were averaged together such that the mean reflectance ± 1 S.D. could be calculated and plotted. Figure 7 is an overlay of the plots of the SE590 spectrometer data showing mean reflectance ± 1 S.D. for the two study sites sampled on Camels Hump (Camels Hump 4, medium damage site and Camels Hump 7, a high damage site). For the medium damage site, a total of 14 observations were used to calculate the mean and standard deviation; for the high damage site, 37 observations were used in the calculations.

Close inspection of the reflectance curves in Figure 7 reveals that the two sets of data are spectrally distinct from one another, especially in the area of sharp rise in reflectance from

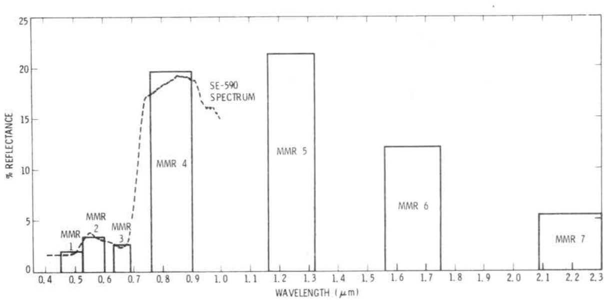

Figure 6. An example of the type of data simultaneously acquired by the SE590 spectrometer and Barnes MMR radio. MMR bands 1-4 and 7 correspond to Thematic Mapper bands 1-4 and 7; MMR6 is equivlent to TM band 5; there is no TM equivalent to MMR band 5.

approximately 0.65 - 0.75 μm. In general, the high damage site is more reflective than the medium damage site throughout the entire range from 0.40 - 1.0 μm. Of particular interest is the offset (blue shift) in reflectance minima between the two curves associated with the chlorophyll absorption feature typically centered at approximately 0.68 μm. For the high damage site (Camels Hump 7), the point of minimum reflectance occurred at 0.653 μm, with a mean reflectance of 2.88%. For the medium damage site (Camels Hump 4), the reflectance minimum occurred at 0.664 μm with a mean reflectance of 2.34%. This subtle shift is on the order of 11 nm to shorter wavelengths and is similar to the 9 nm shift seen in the in situ data presented in Figure 4.

In contrast, however, to the in situ leaf spectra presented earlier, is the higher mean reflectance in the NIR portion of the curve for the helicopter-acquired data from the high damage site. This is just the opposite of what is seen in the field spectrometer data (Figures 3 and 4). It is also in contrast to what might be expected, since higher reflectance by vegetation in this portion of the spectrum is usually attributed to healthier vegetation and/or denser vegetation canopies. At least two factors are probably responsible for this apparent discrepancy between the in situ spectra and that collected from the helicopter. First the in situ spectra are for spruce branches (primarily needles only) sampled from sites of different overall damage (Camels Hump 7 vs. Ripton 1). By comparison, the spectral data acquired from the helicopter represents the overall reflectance from an area 5.5 m in diameter. Sample area of this size can contain entire spruce canopies, other overstory and understory vegetation, branches, trunks, bare soil, rocks, etc. Secondly, it is well known that broadleaved vegetation is more highly reflective in the near IR than coniferous vegetation, and that as the coniferous canopies become more damaged and open at the higher elevation sites, the understory may be invaded by broadleaved species.

As stated in the introductory section of this paper, canopy dryness may result from either the direct or indirect effects of acid deposition (i.e., as a result of damage to the leaf surface or to the rootlets involved in water uptake from the soil). The two methods previously discussed for assessing vegetation canopy moisture levels are the calculation of the MSI values from spectral measurements and measurement of xylem water column tension via the pressure bomb. In situ leaf reflectance measurements (Figures 3 and 4) and pressure bomb data (Figure 5) seem to support the hypothesis of increasing canopy dryness as forest damage levels increase. Additional confirmation of these findings using helicopter spectral data was desired, so the Barnes radiometer near and middle IR data (MMR bands 5, 6 and 7; see Figure 6) acquired from the helicopter were analyzed for the two Camels Hump sites. The mean ± 1 S.D. was calculated for the 14 observations from the medium damage site (Camels Hump 4) and for the 37 observations from the high damage site (Camels

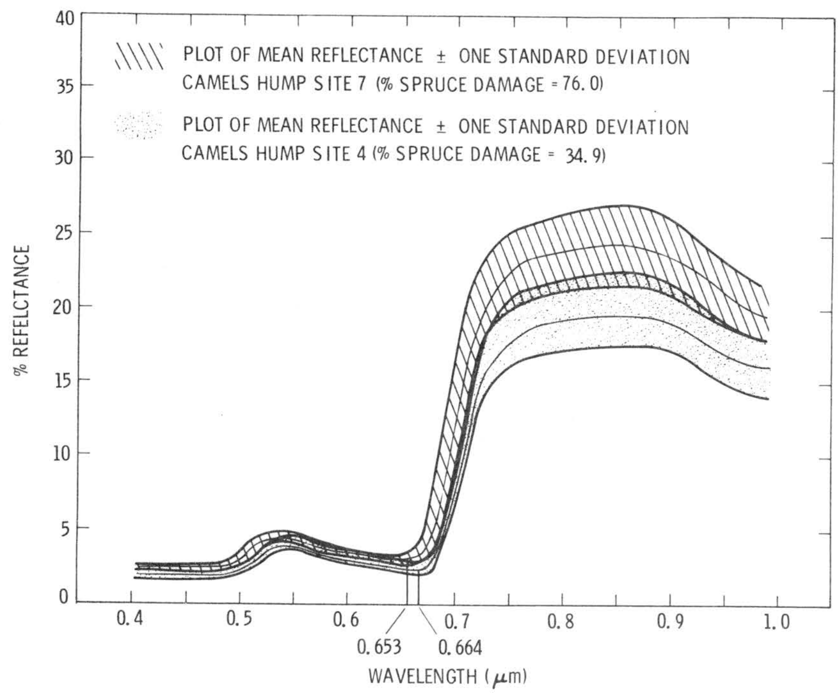

Figure 7. Comparison of helicopter spectral data (SE590) between a high damage site and a medium damage site from Camels Hump Mountain, Vermont. Data were gathered on August 17, 1984.

Hump 7). These data, summarized in Table 3, indicate that reflectance is higher in all three bands for the high damage site, and that there is only a slight overlap in the ±1 S.D. ranges between sites for one of the bands (Band 7). Moisture Stress Index values (MMR6/MMR5) calculated from these data as well as those calculated from in situ measurements suggest that broad-band sensors may be used to infer canopy moisture levels from remotely-sensed data sets.

SUMMARY

1. Marked differences in levels of forest damage were found among studied sites. Elevation was found to be a major factor influencing both red spruce and balsam fir damage, with higher elevation stands generally being more damaged than lower elevation stands. Sites characterized by having high levels of spruce damage also had high levels of balsam fir damage.

2. Both helicopter and in situ spectral data indicate the presence of a "blue shift" at high damage versus lower damage sites.

3. In situ spectral data indicates that leaf and twig specimens from the high damage site are less reflective in the near and middle IR portions of the spectrum. Helicopter data indicate the opposite with the higher damaged site having greater reflectance than the lower damaged site in this spectral region. This discrepancy in results is felt to be a function of the increased presence of highly reflective broadleaved species which invade the high damage sites as the canopy becomes more open.

4. Pressure bomb measurements indicate that xylem water column tension is higher (i.e., more negative) in specimens from high damage sites than from low damage sites. The Moisture Stress Index (MSI) reported here correlate with pressure bomb readings, indicating that remote sensing may be useful in non-destructive monitoring of canopy dryness.

5. A remote sensing approach, employing both broadband and high spectral resolution sensor systems, may allow discrimination and mapping of suspected acid deposition damage. In addition, these data may provide insight regarding the cause of this damage.

CONCLUSIONS

The results of this study suggest that remote sensing will provide a means of monitoring forest damage suspected of being due to acid deposition. Certain spectral features such as altered reflectance along the NIR plateau and variations in relative reflectance at 1.26 μm and 1.65 μm may be detected with broadband sensor systems, while more subtle spectral properties such as the blue shift and fine absorption features along the NIR plateau will require high spectral resolution sensors.

TABLE 3

Summary of reflectance values for Barnes MMR Bands 5, 6 and 7 for high and medium damage sites, as acquired from the helicopter (values in percentage of reflectance relative to reference).

	MMR Band 5 mean ±1 SD	MMR Band 6 mean ±1 SD	MMR Band 7 mean ±1 SD	MSI MMR6/MMR5
High Damage Site (Camels Hump 7)	29.87 ±2.76	17.69 ±1.78	8.68 ±1.08	0.5911 ±0.0359
Medium Damage Site (Camels Hump 4)	23.05 ±2.10	13.52 ±1.63	6.40 ±1.56	0.5846 ±0.0488

At this point in the research, it is very encouraging that a significant shift between reflectance properties acquired at different damage level sites has been identified both in ground spectral data and from an aerial platform some 300 m above the canopy. However, the reader is reminded that these results are preliminary in nature and that additional study of the existing data, as well as the acquisition and analysis of new data, is needed. We plan to acquire a second, more complete set of data this summer (1985), and to augment our field studies with laboratory (greenhouse) experiments in which we have greater control over the myriad of variables which may play a role in generating acid deposition-related forest damage.

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