ABSTRACT OF THE THESIS OF

Richard W. McCreight for the degree of Master of Science in Forest Science presented on April 19, 1983

Title: Detection of 2,4-D Herbicide Damage Using Ground-Based Spectral Measurements: Implications for Remote Sensing

Abstract approved: Signature redacted for privacy.

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Spectral patterns of three brush species under the influence of herbicide treatment were investigated to evaluate the effectiveness of monitoring forest vegetation management using ground-based and remote sensing techniques. Foliage of Pacific rhododendron (Rhododendron macrophyllum D. Don), golden chinkapin (Castanopsis chrysophylla Dougl.), and hairy manzanita (Arctostaphylos columbiana Piper) sprayed with 2,4-D herbicide had midday reflectance measurements within 4 months of treatment that were 10 to 30 percent lower than adjacent plants with no signs of damage. The differences in reflectance were most pronounced in the near-infrared versus the visible portion of the electromagnetic spectrum and varied by species. Differences persisted under varying direct solar intensity, displayed only a weak association with seasonal plant moisture stress or canopy cover, and could be used to detect 2,4-D herbicide damage. Existing remote sensing techniques may provide a means of collecting such data in a scientific and cost-effective manner, enabling the researcher to better understand the inherent and manipulated growth characteristics of forest vegetation subjected to management.

Detection of 2,4-D Herbicide Damage Using Ground-Based Measurements: Implications for Remote Sensing

by

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A THESIS

submitted to

Oregon State University

in partial fulfillment of
the requirements for the
degree of
Master of Science

Commencement June 5, 1983

APPROVED:

Signature redacted for privacy.

5/9/83

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ACKNOWLEDGEMENTS

Assistance was provided by Dr. Peyton W. Owston, Project Leader of the Reforestation Project, Forestry Sciences Laboratory, Corvallis, Oregon, and members of his staff who contributed their time and resources for the fulfillment of this research.

Special thanks are extended to Dr. John D. Walstad, Program Leader of the Forestry Intensified Research Program and Associate Professor of Vegetation Management, Oregon State University. His receptivity to ideas and constructive comments were invaluable.

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Considerable research has shown the effectiveness and economic advantage of using remote sensing to detect and monitor vegetation growth patterns and trends, diseases, mortality and defoliation by leaf-eating insects (Reeves 1975). Few studies, however, have related herbicide treatments to changes in spectral properties of damaged plants. Such knowledge is important for evaluating the potential utility of remote sensing in forest vegetation management where herbicide treatment is extensively used, often in remote areas, and under varied conditions.

The present study was initiated to assess the potential of ground-based spectral measurements in the visible and near-infrared to detect biological damage caused by the aerial application of 2,4-dichlorophenoxy acetic acid (2,4-D) herbicide for forest vegetation management. Three dominant southwestern Oregon brush species were studied in the field during the summer of 1981, four months after 2,4-D treatment. The plants' basic spectral characteristics, damage gradients, contrasts in reflectance data, and associations with seasonal plant moisture stress and individual canopy cover were investigated. Contrasts in plant reflectance which could be detected over larger areas by using airborne spectral scanners or photographic systems are presented and discussed in light of certain operational considerations.

BACKGROUND

Intensive forest management emphasizes the need for site-specific evaluation of competitive vegetation and the brush control necessary to allow establishment of high yield conifer plantations. Approximately 77 million hectares (two-fifths) of the commercial timberland in the United States (excluding Alaska and Hawaii) is producing forest products at less than capacity, due primarily to competing, undesired vegetation (Walker 1973). The high cost and magnitude of the problem nationwide has led to increasing use of herbicides for forest vegetation management (Council for Agricultural Science and Technology 1978). Herbicides are used for preparation of sites for tree establishment and for selective weeding to release preferred species from competing woody plants (Byrnes 1960, Bey et al. 1975).

2,4-D Herbicide Treatment

Despite the more recent development of many other herbicides, the phenoxy herbicides remain major tools in vegetation management (Emmelin 1977). Of these, 2,4-D is by far the most common compound used because of availability, cost, and effectiveness in most situations (Council for Agricultural Science and Technology 1978). The most common uses are suppression of broad-leaved plants in the presence of grasses, conifers, or certain legumes (Klingman and Ashton 1975). The herbicide is usually applied in the form of water-soluble amines or oil-soluble esters for convenience in handling and application by aircraft, ground broadcast sprays, and individual plant treatment (Byrnes 1960).

Phenoxy herbicides, such as 2,4-D, are plant growth regulators with selective phytotoxicity. Broadleaf species are especially prone to damage. The chemical is absorbed by plant foliage, roots and soft stem tissue, accumulating in the actively growing parts of roots and stems (Crafts 1964). The result is interference with cell division and enlargement causing variations of necrotic, chlorotic and malformed stems and leaves. The phytotoxicity of phenoxy herbicides is known with reasonable accuracy for hundreds of species of plants (Way 1969); but nothing short of a thorough knowledge of the response of each kind of plant under prevailing conditions has made possible the effective use of these chemicals (Klingman and Ashton 1975).

Site-Specific Treatment Evaluation

Research is being directed in part at providing additional site-specific data on efficacy and selectivity of current forest vegetation control methods and their short- and long-term effects on the ecosystem. This is part of a 10-year, comprehensive multiagency research program known as FIR (Forestry Intensified Research)[1] which

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[1]"Reforestation and Forest Productivity in Southwestern Oregon: Problem Analysis and Proposed 10-year Research Program," an unpublished Problem Analysis prepared by P.W. Owston and D.P. Lavender. November 1979. Report on file at USDA Forest Service, Pac. NW For. and Range Exp. Stn., Corvallis, OR.

is underway in southwestern Oregon. Scattered throughout the forest lands of this region are brushfields ranging in size from a few hectares to serval thousand hectares. Brush species are primarily the broad-sclerophyll type, characterized by woody, evergreen plants, often forming chaparral which is almost impenetrable.

Evidence shows that many of these brushfields once supported excellent stands of timber and are potentially productive commercial forest lands if effective and efficient brush control methods can be found and implemented. Probably more important is the prevention of new brushfields. Quantitative, _in situ_ information should resolve major conflicts on choice of treatment, provide insight on the effects of alternative practices, and identify techniques suitable for severe sites where reforestation is difficult[1].

One problem is that field surveys of such conditions are conducted using laborious, time-consuming, and expensive methods. The surveys sometime require so much time that the areas covered intially may be significantly changed by the time the survey is completed. Consequently, there is a lack of appropriate data on which to base decisions related to forest management. In practical terms, more must be done with less. New approaches are necessary to achieve vegetation evaluation and treatment monitoring in a scientific and cost-effective manner.

Impications for Remote Sensing

Remote sensing offers some possible solutions to this dilemma. *In situ* data can be aquired from different parts of the electromagnetic spectrum including the visible, near-infrared, thermal, and microwave for numerous reflectance spectra of a surface (e.g., vegetation) under varying conditions and at often equal accuracy, less cost, less time, and with fewer people than by conventional ground survey methods (e.g., Aldrich 1979).

Interactions between matter and energy provide the basis for this approach. The incident solar radiation that is not absorbed by the plant canopy or soil surface is reflected and can be detected by any number of airborne remote sensors, ranging from photographic cameras to multispectral optical/mechanical scanners. Absorbed energy re-emitted as thermal radiation is also detectable by infrared and multispectral scanners.

The wavelengths within the electromagnetic spectrum that are of greatest interest to the remote sensing community are wavelengths which extend from 0.30 to 15 micrometer (μm), although most research efforts have been limited to the 0.40 - 1.10 μm area because of limited sensor technology (Williams and Stauffer 1979). The 0.30 to 15 μm spectrum can be further subdivided into four regions known as the visible (0.38 - 0.72 μm), near-infrared (0.72 - 1.3 μm), middle-infrared (1.3 - 3.0 μm) and thermal or far-infrared (7.0 - 15.0 μm).

(Swain and Davis 1978). The various spectral regions correspond to atmospheric transmission windows and express different information about vegetated surfaces.

Solar radiation at the earth's surface consists of energy contained mostly within wavelengths extending from the ultraviolet (0.3 µm) to the infrared (4.0 µm) with the peak energy emission in the visible at about 0.5 µm. In terms of total radiation, 59 percent of the available solar energy occurs in the wavelength interval below 0.73 µm, while 41 percent falls in the wavelength interval from 0.73 µm to 4.0 µm (Pease 1972). Radiation beyond 4.0 µm represents thermal energy emission. According to the laws governing energy emissions of blackbodies, the maximum intensity of energy emission would occur around 5 to 15 µm (Drying 1973).

The importance of sensing in different regions of the spectrum can be illustrated by considering plants in their habitats. Plants are adapted to absorbing or reflecting energy from different portions of the electromagnetic spectrum based on certain physical and metabolic properties. For example, plants strongly absorb blue and red radiation to provide the initial energy required for photosynthesis. In contrast, most plants are reflective to green radiation and highly reflective to near- and mid-infrared radiation to avoid protein denaturation through over-heating. In the far-infrared region, plants take on the characteristic of a grey body, absorbing and then re-emitting energy to facilitate radiative cooling (Gates et al. 1965).

In general, all green plants have evolved similar spectral characteristics, but quantitatively they can differ considerably. When solar radiation comes into contact with a plant, it is reflected, transmitted, or absorbed by the leaves. This interaction is dependent upon many factors, including wavelength, leaf orientation, cuticular composition and structure, cellular organization, intercellular air space, cyctoplasmic inclusions, pigments, water content, emissivity characteristics, and temperature (Table 1). Once the leaves are developed on a plant, their spectral properties remain fairly stable unless affected by a stress-induced "strain" or natural aging (Puritch 1981).

Remote Sensing of Vegetation Damage

By identifying the reflectance pattern of normal healthy plants, clues can be obtained as to changes in reflectance that may occur as a consequence of strain. Levitt (1972) defined strains as the chemical or physical changes that occur in plants as a result of stress. He further divided strains into two types; one that is reversible upon release of stress (elastic strain) and one that is irreversible (plastic strain). Strains are, therefore, the physiological state of the plant that occurs as a result of stress. Elastic strains, being reversible, are usually of short duration. An example of this is the effect of diurnal water stress on transpiration. It is the longer-lasting plastic strains that usually

Wavelength (μm)	Basic Rationale for Monitoring Vegetation
0.45 - 0.52	Sensitivity to chlorophyll and carotinoid content.
0.52 - 0.62	Slight sensitivity to chlorophyll plus green region characteristics.
0.63 - 0.69	Sensitivity to chlorophyll
0.74 - 1.10	Sensitivity to vegetation density or biomass.
1.55 - 1.75	Sensitivity to water in plant leaves.
2.08 - 2.35	Sensitivity to water in plant leaves.
10.4 - 12.5	Thermal properties.

Table 1. List of spectral regimes and the basic rationale for monitoring vegetation (from Tucker 1978).

cause damage and are generally detected by remote sensing (Puritch 1981).

Murtha (1978) summarized the effects of physiological damage on spectral reflectance patterns for the visible and near-infrared wavelengths. The first change in the spectral reflectance pattern is hypothesized to occur in the near-infrared, although research to date indicates that this may be species dependent. With deterioration of chloroplasts, the second change in spectral reflectance is the shifting of the green peak towards the red wavelength, causing the yellowing of the foliage. The final generalized change is a continuing shift of the visual peak towards the red, resulting in a reddening of the dead foliage. Near-infrared reflectance may increase or decrease at this point, depending on whether the foliage is air-dry or wet, respectively. Morphological damage can also produce some deviation from a normal pattern because of crown deformation and integration of background surface spectra with defoliation.

The type and degree of strain resulting from various stresses is very important for assessing damage using remote sensing. The problem lies in the fact that each stress will cause its own syndrome of responses in the plant, although often these responses are common to more than one stress (Puritch 1981). Therefore, to understand the potential utility of remote sensing for evaluating herbicide or other treatments in forest vegetation management requires establishing the spectral response(s) and degree of discrimination between treated and untreated plants under field conditions.

Few studies have related herbicide treatment to spectral patterns, although case applications demonstrate the potentials. Examples include work in which infrared photography was found to indicate the stage at which chlorophyll became inactive during experiments on weed control and defoliation (Anon. 1953). Tueller et al. (1981) analyzed brush control on rangelands with airborne radiometers using narrow waveband filters. Waveband ratios were then used as a means of estimating the relative proportions of green vegetation, bare soil, and standing dead vegetation plus litter. Results indicated variations in reflectance associated with brush control using plowing, burning and chemical methods.

PROCEDURE

Foliar reflectance at midday (1000 to 1400 PDT) of selected Pacific rhododendron (*Rhododendron macrophyllum* D. Don), golden chinkapin (*Castanopsis chrysophylla* Dougl.) and hairy manzanita (*Arctostaphylos columbiana* Piper) plants was measured under clear skies at 0.10 µm intervals between the wavelengths of 0.45 to 1.05 µm during August and September, 1981. Reflectance, the ratio of reflected to incident radiant energy, was calculated using a tripod-mounted ISCO[2] Model SR spectroradiometer with a fiber-optics extension probe positioned (level) 15 cm above the canopy.

The ISCO spectroradiometer is a portable, battery-operated instrument with a true cosine-response. The use of a wedge interference filter system enables the spectrum to be scanned at a spectral resolution (bandwidth) of 0.015 µm in the visible and 0.03 µm in the near-infrared. The analog output, corrected for sensor bias, represents the spectral irradiance received by the detector and is measured in $\mu w\ cm^{-2} \mu m^{-1}$. The instrument is calibrated with the use of a standard light source, traceable, either directly or indirectly, to the National Bureau of Standards. The radiant energy output of the standard approximates the spectral distribution curve of a hypothetical blackbody radiator. After calibration, instrument

[2]Trade and company names imply no endorsement or preferential treatment of the product cited.

accuracy is on the order of ±7 percent at the longer wavelengths and ±10 percent at the shorter wavelengths. Most of this error comes from uncertainties in the standard and essentially cancels out when calculating reflectance values (i.e., the ratio of reflected to incident radiant energy).

Measurements were aquired from an approximately 10-year-old clearcut located in the Cow Creek reforestation unit (T32S, R10W, Sec. 2, Willamette Meridian) on the Siskiyou National Forest in southwestern Oregon. Portions of the area had been aerially sprayed with 2,4-D herbicide at 3.4 kg acid equivalent per hectare in May, 1981. Two adjacent plots, 61 m square and separated by a 30.5 m wide buffer strip, were used to contrast sprayed and unsprayed plants. Each plot was situated on an east aspect and 40 percent slope (Figure 1). Sixteen sample points in each plot, arranged in a systematic matrix with a random start, were used for measurements. The individual of each species, between 0.6 to 1.5 m in height, closest to each point was studied. In the case of hairy manzanita, only 6 plants were found in the untreated plot that met the height criteria.

In August, study plants were subjectively assigned, on the basis of visual appearance, to the following categories: (1) healthy plants with no evidence of herbicide damage; (2) slightly damaged plants showing some sign of deformed, chlorotic and/or necrotic tissue, but less than 25 percent of the foliage so damaged; (3) moderately damaged plants exhibiting 25 to 75 percent foliage

Figure 1. Black and white copy of aerial color infrared photograph taken over the study site in August, 1981. The plot on the left was sprayed with 2,4-D herbicide, while the right hand plot served as a control.

discoloration and some stem damage; and (4) severely damaged plants exhibiting 25 to 75 percent foliage and stem discoloration and some stem damage; and (4) severely damaged plants with 75 to 100 percent foliage and stem kill.

Seasonal plant moisture stress and canopy cover (an indicator of background surface influence on foliar reflectance data) were also recorded for each individual. Moisture stress was determined by taking predawn measurements with a Scholander pressure chamber during the August and September sampling periods. Canopy cover was determined from 7.5 mm, fisheye photographs taken looking upward beneath each plant in August.

Exposure was made on Kodak HCL-135 high contrast film during periods of diffuse light to avoid sun-fleck error. Percent canopy cover was derived visually from the photographs using an equidistant, grid cell overlay, and was later confirmed by machine analysis[3].

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[3]Miller, G.P. 1981. Analysis of radiant environment in forest canopies; technique and application. M.S. Thesis, Washington State University, Pullman, WA. (In preparation).

RESULTS AND DISCUSSION

Foliar reflectance values showed little difference between August and September sampling periods despite substantial differences in solar spectral intensity (Table 2). Spectral reflectance of the foliage did vary, however, between species in the treated and untreated (control) plots, with the largest contrast found in the near-infrared portion of the spectrum (Figure 2). Plants in the control displayed typical reflectance curves associated with healthy vegetation, i.e., absorption in the blue and red wavebands and high reflectance in the near-infrared. Those in the sprayed plot displayed a slight change in the visible region, notably an increase in red reflectance. More obvious was a relatively large decrease in near-infrared reflectance, suggestive of changes in leaf cellular arrangement, cell wall/air interfaces, and leaf orientation.

The spectral contrast between plots was further analyzed by individual wavelength using a t-test of differences with 79 degrees of freedom. The results showed that when data at wavelength 0.55 μm (green) and 0.65 μm (red) for all species was grouped by plot, there was no significant difference between the group means for the treated and untreated plots at the 5 percent level. However, when the same comparison was made in the near-infrared (wavelength 0.95 μm) there was a significant difference between the two plots.

In general, the level of herbicide-induced stress appeared to exert a greater influence on the foliar reflectance than did the

Date	Reflectance (%) at wavelength 0.95 (µm)						Solar spectral intensity at wavelength 0.95 um ($\mu w\ cm^{-2}\ \mu m^{-1}$)		
	Control			Treated					
	Pacific rhododendron								
15 August	50.1	±4.6	(15)*	39.7	±7.1	(16)	12.8	±0.89	(31)
16 September	49.5	±5.1	(14)*	41.3	±7.7	(16)	8.5	±0.71	(30)
	Golden chinkapin								
15 August	53.0	±6.7	(16)	42.5	±13.9	(15)*	13.9	±0.92	(31)
16 September	52.5	±6.7	(15)*	43.3	±11.1	(15)*	8.0	±0.67	(30)
	Hairy manzanita								
15 August	38.7	±6.2	(6)*	28.5	±7.1	(13)*	12.1	±0.84	(19)
16 September	40.1	±5.1	(6)*	28.4	±7.3	(13)*	9.2	±0.73	(19)

* Sample size less than 16 reflects missing data due to measurement error, or lack of study plants in the case of hairy manzanita.

Table 2. Mean foliar reflectance, ± 1 standard deviation, at wavelength 0.95 µm of Pacific rhododendron, golden chinkapin, and hairy manzanita classified according to exposure to 2,4-D herbicide. Sample size is given in parentheses. Measurements were made at midday (1000 to 1400 PDT) during periods of clear sunlight using a portable spectroradiometer positioned 15 cm above the canopy.

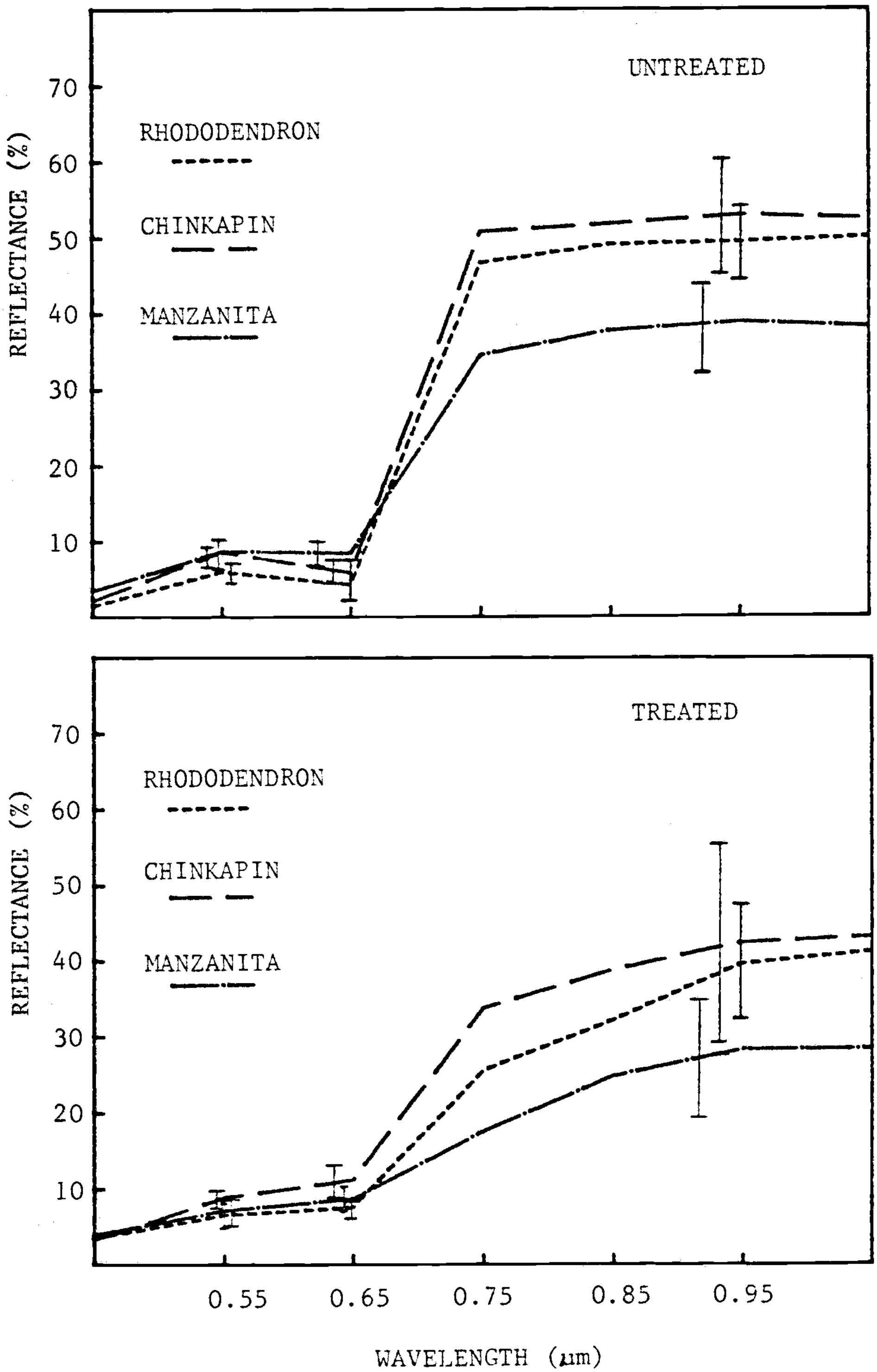

Figure 2. Spectral reflectance curves of untreated and 2,4-D herbicide treated plants. Each reflectance curve is an average of plot spectroradiometric data representing the visible (0.45-0.72 µm) and near-infrared (0.72-1.05 µm) portions of the spectrum. Standard deviation bars are shown for three representative wavelengths.

level of moisture stress or canopy cover at the time the reflectance measurements were made. Regression analysis revealed only a weak correlation between spectral reflectance and plant predawn moisture status[4] or canopy cover. Predawn moisture stress in the control was relatively low for both sampling periods. August values ranged from 0.55 to 0.95 MPa and increased to 0.55 to 1.40 MPa by September. Hairy manzanita had the highest moisture deficit for both periods, while golden chinkapin had the lowest. Comparing these data to spectral measurements of reflectance at wavelength 0.95 um revealed correlation coefficients of -0.22 to 0.22 for Pacific rhododendron and golden chinkapin respectively; hairy manzanita was near zero.

Canopy cover of individual plants varied substantially within species (standard deviation ±15 percent). The species means ranged from 54.9 to 61.5 percent in the treated plot and 56.2 to 62.2 percent in the control. However, the correlation between reflectance at wavelength 0.95 μm and canopy cover was near zero for all species except Pacific rhododendron (r^2 = 0.22) in the treated plot. It was also noted that this species displayed the greatest leaf deformation following 2,4-D application.

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[4]Data represent "healthy" plants in the untreated plot. Variation in the treated plot made comparisons invalid.

Spectral Indications of 2,4-D Herbicide Damage

Ocular estimates of damage based on ground observations revealed variation within and between species in the sprayed plot (Figure 3). Hairy manzanita displayed the most severe damage. Pacific rhododendron and golden chinkapin were moderately to severely damaged in most cases. Some individuals of all three species showed little effect, however.

Spectral measurements were grouped for individual plants of each species by damage level. Mean reflectance values were used from the control plot for contrasting healthy versus moderately to severely damaged plants. The resulting data were depicted in terms of spectral reflectance curves (Figure 4). The curves contrast damage level by wavelengths for the the three levels of damage (none, moderate, severe).

Pacific rhododendron and golden chinkapin displayed a 3 to 5 percent increase in red reflectances and little change in the blue and green wavebands with damage. Reflectance in the visible region is known to respond directly to herbicide-induced stress via the degeneration of chlorophyll. With degeneration of chlorophyll, reflectance in the green region remains virtually unchanged, but the red reflectance increases, causing the color of the leaves to shift from green to yellow to orange and finally to deep brown (Fox 1978). Hairy manzanita, on the other hand, generally exhibited a decrease

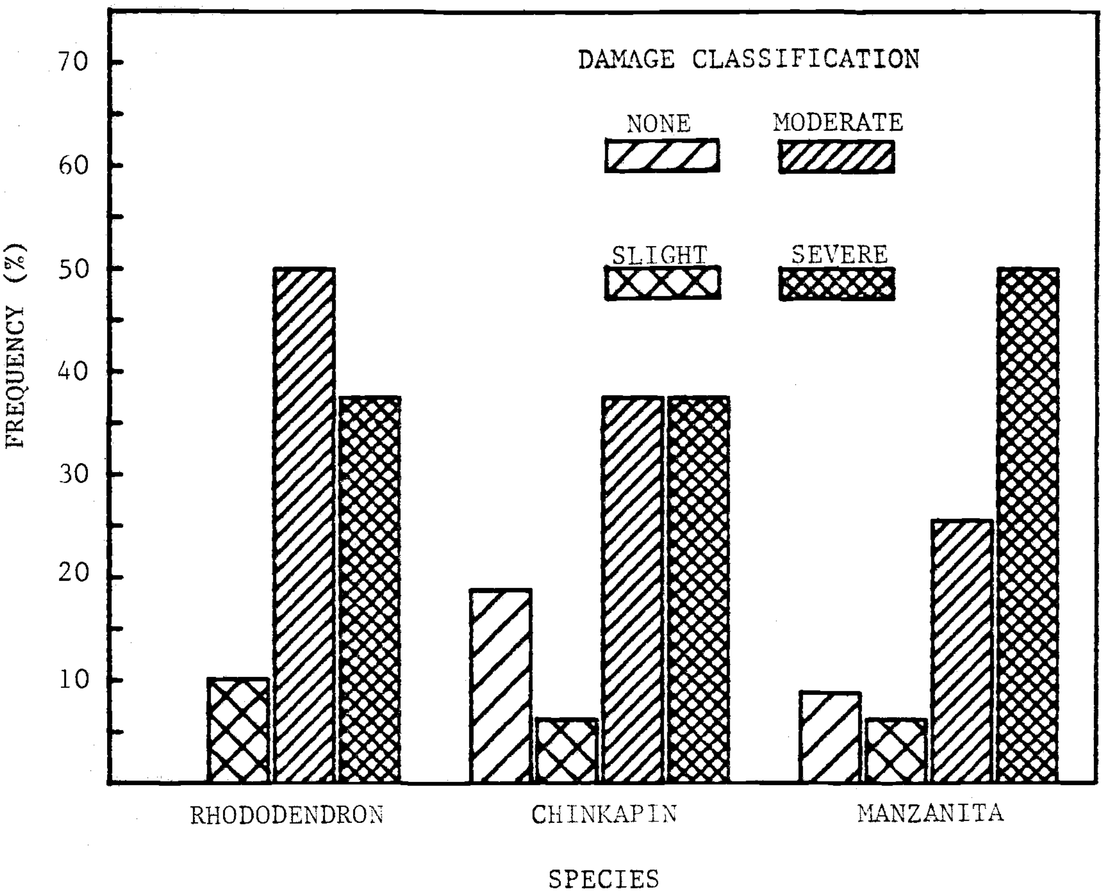

Figure 3. Observed brush damage by species four months after the aerial application of 2,4-D herbicide. Damage classification is based on the following criteria: (1) healthy plants with no sign of damage; (2) slightly damage plants showing some sign of deformed, or chlorotic and/or necrotic tissue, but less than 25 percent of the foliage so damaged; (3) moderately damaged exhibiting 25 to 75 percent foliage discoloration and some stem damage; (4) severely damaged plants with 75 to 100 percent foliage and stem kill.

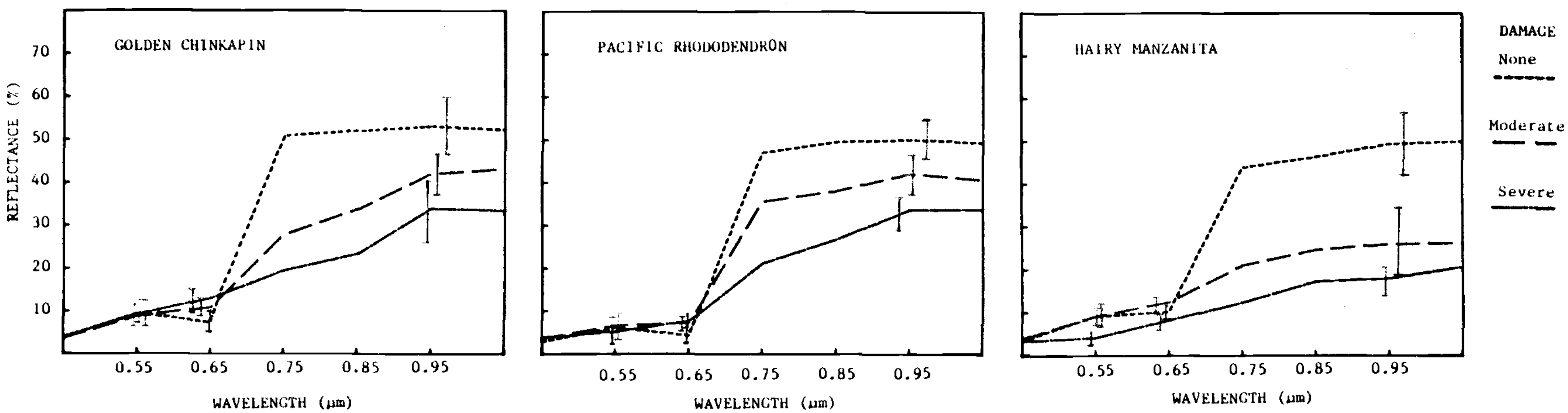

Figure 4. Spectral reflectance curves, ±1 standard deviation, contrasting golden chinkapin, Pacific rhododendron, and hairy manzanita by damage level four months after treatment with 2,4-D herbicide.

in reflectance with damage at all visible wavebands, indicative of black coloration, and perhaps, advanced chlorophyll degeneration.

In contrast to the subtle changes in the reflectance in the visible portion of the spectrum, a 10 to 30 percent decrease in reflectance was noted in the near-infrared portion of the spectrum for moderately to severely damaged plants of all three species. Relative discontinuities among cell membranes, crystals, cell walls, and surrounding protoplasm within the palisade parenchyma (Gates 1970) and spongy mesophyll tissue in leaves (Gausman 1974) contribute to the reflectance of near-infrared radiation (Gausman 1977). Decreases in near-infrared reflectance have been associated with stunted and more compact cell arrangement in studies of leaf senescence, salinization, and moisture stress (Knipling 1967; Gausman et al. 1969; Kramer 1969; respectively). Therefore, a reduction of near-infrared reflectance would be expected in situations where 2,4-D herbicide inhibits growth.

As Puritch (1981) points out, however, the near-infrared reflectance of a leaf is the net result of many interacting factors. For example, if reduced water content predominates, the near-infrared reflectance will increase due to more porous mesophyll tissue in the leaves (Gausman 1974); at other times compact leaf structures will be the major influence and near-infrared reflectance will decrease. Thus, both time and plant characteristics can affect the near-infrared response to stress.

In an effort to test whether foliar reflectance values could be used to distinguish damage classes, the following analysis was done. Spectral data for wavelength 0.95 µm was combined for August and September and fitted to normal (Gaussian) frequency distributions for moderately to severely damaged plants and for healthy plants by species (Figure 5). The distributions of foliar reflectance values for healthy and damaged plants were not mutually exclusive. When, however, the point of intersection between the two distributions was used as a discriminator to classify the original data, it predicted whether an individual plant was healthy or moderately to severely damaged significantly better than by chance alone (Table 3). For example, based on a reflectance discriminator at 45 percent, 33 percent of the golden chinkapin plants were classified as damaged; the actual incidence was 38 percent. In the case of Pacific rhododendron, 42 percent of the plants were damaged based on a discriminator value of 44 percent, compared to 51 percent actually observed. And 55 percent of the hairy manzanita individuals were damaged using a discriminator value of 33 percent, compared with 63 percent observed in the field.

Utility of Remote Sensing and Operational Considerations

These spectral responses could be useful for providing information about vegetation types, their condition, and coverage using remote platforms (e.g., aircraft and satellites) equipped with photographic and/or electrical sensors designed to selectively respond to radiation from different parts of the electromagnetic

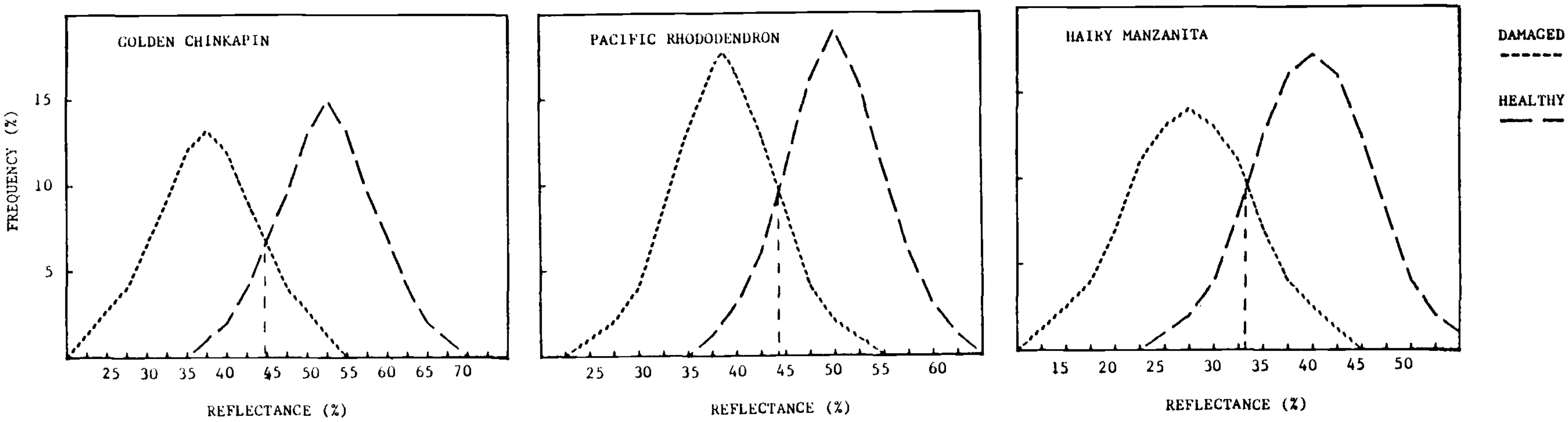

Figure 5. Gaussian frequency distributions of combined foliage reflectance data at wavelength 0.95 µm for healthy and moderate to severely damaged species, showing the crossover point used as a discriminator between the two classes.

GOLDEN CHINKAPIN

Reflectance exceeds 45 %		Category: Damaged		Healthy	Total
Yes		3		32	35
No	estimated	21	21/63=33%	7	28
Total	observed	24	24/63=38%	39	63
	X^2=29.11				

PACIFIC RHODODENDRON

Reflectance exceeds 44%		Category: Damaged		Healthy	Total
Yes		6		27	33
No	estimated	27	27/65=42%	7	32
Total	observed	33	33/65=51%	32	65
	X^2=28.48				

HAIRY MANZANITA

Reflectance exceeds 33%		Category: Damaged		Healthy	Total
Yes		3		11	14
No	estimated	21	21/38=55%	3	24
Total	observed	24	24/38=63%	14	38
	X^2=16.59				

Table 3. Comparison, by species, of observed versus predicted damage incidence for healthy and moderately to severely damaged categories, using 2x2 X^2 contingency tables.

spectrum. Foliage reflectance provides a direct means to measure plant status for different environments and cultural practices. With repeated measurements, vegetation growth patterns (e.g., gains and losses) could also be represented and related back to vegetation type, environment, and treatment.

Considering the spectral data, some indication of the pattern and the intensity of herbicide damage is evident. In general, the greater the degree of herbicide damage,the greater the absorption of near-infrared reflectance in those plants studied (Figure 4). Herbicide damage is also apparent on aerial photographs (e.g., Figure 1) acquired over the study site at the time of ground measurements. Essentially, spectral data, photographically or electronically recorded, can be analysed using photointerpretation and/or clustering classification techniques to produce descriptive cover maps delineating herbicide-induced stress. Resulting area statistics of herbicide damage might be used to document vegetation cover and treatment efficacy. Overlaying these data, for example, with environmental variables, such as slope and aspect, provides an additional means of stratifying treatment effects. In this fashion, potentially troublesome areas might be highlighted that are significant in planning and management practices. Monitoring those areas in proportion to their degree of change over time provides a means of testing the decision strategy used.

Such applications assume that the required level of information (resolution) is comparable to the sensor system employed. These choices are based largely on a general knowledge of the target vegetation growth and damage characteristics under various field conditions. Other factors must be considered as well. Acquistion of spectral data is primarily restricted to clear days to reduce variable solar radiation due to cloudiness. Even so, spectral signals received by a sensor, especially at higher altitudes, are subject to modification due to selective attenuation by the atmosphere. Variation in plant size, and changes in topography and sun angle may result in shaded areas that further influence spectral reflectance measurements. Appreciation of all these processes is essential in selecting the proper time and system for sensing reflectance differences.

CONCLUSIONS

The application of remote sensing technology may assist in vegetation evaluation and treatment monitoring in a scientific and cost-effective manner. This approach assumes that different surface features have different spectral reflectance and emittance characteristics and these differences can be used to identify and describe the features of interest.

Ground spectroradiometric measurements have been used in this study to detect 2,4-D herbicide damage four months after treatment on the basis of spectral reflectance differences. Differences were most pronounced in the near-infrared portion of the spectrum and varied by species. Seasonal plant moisture stress and canopy cover had little influence on measurements under the conditions tested. A 10 to 30% decrease in near-infrared reflectance with damage was noted for all species.

Numerous remote sensing systems are specifically designed to detect and enhance such differences. Their application over remote and/or large areas may provide more real-time, *in situ* data concerning vegetation cover and vigor, which might be used, for example, to help establish treatment priorities in vegetation management. Studies relating vegetation type and treatment (within and between seasons) should help identify the remote sensing technique(s) most appropriate for meeting these information needs.

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