Remote Sensing of Vegetation Responses to Natural and Cultural Environmental Conditions

N. M. Milton
U. S. Geological Survey, Reston, VA 22092
D. A. Mouat
Desert Research Institute, University of Nevada, Reno, NV 89512

ABSTRACT: An understanding of vegetation responses to changes in the geochemistry of the surface and near surface environment allows geoscientists and others to develop strategies for lithologic discrimination, mineral resource analysis, and environmental hazard assessment. The location and magnitude of environmental damage can be assessed using remote sensing techniques developed for geologic applications using reflectance of stressed plants.

INTRODUCTION

STUDY OF THE SURFACE and near surface environment often involves direct examination of lithologic, geochemical, geomorphic, and/or environmental hazard factors. The process is time-consuming, and when vegetation obscures the surface, the process is even more tedious. Vegetation is usually ignored, even though vegetation parameters which are responsive to changes in the geochemistry may be used to derive geologic and environmental information. This strategy, which often involves remote sensing techniques, forms the basis of geobotany.

This paper outlines the different vegetation responses to geochemical conditions at varying scales. These responses include changes in taxonomic, structural, and spectral characteristics (Mouat, 1982). Case studies, including greenhouse, airborne, and satellite experiments, are presented to illustrate scale-dependent geobotanical responses and to suggest strategies for the use of geobotany in geologic and environmental studies.

VEGETATION RESPONSES TO GEOCHEMICAL CONDITIONS

Taxonomic vegetation responses include the distribution patterns of plant species whose presence or abundance are affected by soil geochemical conditions. Vegetation assemblages may be unique or at least largely restricted to a particular set of soil geochemical conditions.

Plant species whose presence is determined by soil geochemistry are often referred to as indicators. The two principal types of indicator plants are universal indicators and local indicators. The universal indicators are found only on specific soil conditions. Examples of universal indicators include the zinc indicator, calamine violet (*Viola calaminaria*) and the copper flower (*Becium homblei*). The latter does not grow in soils having less than 100 ppm Cu and can tolerate concentrations as high as 5000 ppm Cu (Rose *et al*., 1979). Local indicators reflect changing lithology or soil geochemical conditions in restricted areas. These species will more likely occur in specific areas but may also grow in other areas. Several species of *Astragalus* are useful local indicators of selenium (a pathfinder element for uranium) in the Colorado Plateau (Cannon, 1957).

Serpentine areas in many parts of the world provide an example of vegetation assemblages whose presence indicates soil geochemical conditions. The associated species respond to elemental anomalies, especially Mg/Ca, Ni, and Cr, as well as to different soil moisture conditions. In northwestern California and southwestern Oregon, serpentine vegetation is distinctive in floristic composition and physiognomy (Figure 1) (Whittaker, 1960). In the Great Basin regions of Nevada, areas of certain types of hydrothermal alteration support vegetation types different from those in surrounding non-altered areas of the same rock types (Billings, 1950; Milton and Purdy, 1983).

FIG. 1. Photograph from helicopter platform of a natural vegetation boundary near Mike's Gulch in Josephine County, southwestern Oregon. Sparse vegetation on the right is composed of scattered Jeffrey pine (Pinus jeffreyi), manzanita (*Arctostaphylos* spp.), and grasses and is growing over ultramafic rocks. Dense vegetation on the left is composed of Douglas fir (*Pseudotsuga menziesii*), black oak (*Quercus kelloggii*), incense cedar (*Libocedrus decurrens*), and a variety of smaller trees and shrubs. The underlying rocks are graywackes of the Galice Formation. Photo by N. Milton.

Structural responses to substrate conditions include morphological changes in individual plants or in plant assemblages. These changes can include leaf appearance (color and shape), flower and fruit shape and appearance, and the stature of the plants. Changes in plant community structure primarily involve vegetation density and stature. In areas of heavy-metal anomalies, for example, changes in total plant biomass toward less dense or more open conditions are common. Stunted vegetation or even barren ground are typical responses to geochemical soil anomalies. Cu-enriched areas in Katanga are bare to grass-covered within a generally closed canopy forest (Brooks and Malaisse, 1985).

Chlorosis, or the yellowing of leaves, can be considered a plant structural response to changes in soil geochemical con-

0099-1112/89/5508–1167$02.25/0

ditions. When the rate of chlorophyll synthesis does not equal the rate of chlorophyll degradation, chlorosis occurs. Chlorosis, then, is a deficiency of chlorophyll pigment in green vegetation which affects the ability of the plant to photosynthesize and produce carbohydrates. Severely chlorotic vegetation has a pale or bleached appearance. Chlorosis is especially prevalent when nutrient imbalances or anomalous concentrations of various elements and minerals occur in the soil (Brooks, 1972).

Phenology, or the timing of plant physiological events, may be considered a structural characteristic. Changes in phenological events may directly reflect geochemical conditions. Early leaf flushing or senescence and premature or retarded flowering and fruiting are typical responses. Autumnal senescence is a natural decrease in the amount of chlorophyll pigments in leaf tissues and is accompanied by color changes in the leaves. Schwaller and Tkach (1980) found that premature senescence anomalies of sugar maple (*Acer saccharum*) and yellow birch (*Betula allegheniensis*), as determined by a leaf collection experiment and aerial photography, coincided with areas of Cu anomalies in Michigan.

Spectral responses to substrate conditions can reflect the unique spectral properties of the species or vegetation types or the manner in which morphological changes affect plant spectra. Changes in spectral responses may be due to the effects of particular soil geochemistry on plant metabolism. A typical plant spectral reflectance curve is shown in Figure 2. In the visible portion of the electromagnetic spectrum (0.4 to 0.7 micrometres (μm)), low reflectance results from the absorption of light by plant pigments. A rapid increase in reflectance occurs between 0.68 and 0.78 μm, followed by high reflectance in the near-infrared (0.78 to 1.2 μm) due to scattering and re-radiation of energy from cell wall interfaces. Through the shortwave-infrared (1.2 to 2.5 μm), reflectance gradually decreases owing to increasing absorption by water within the leaves (Knipling, 1970; Gates, 1980).

Although the general shape of the spectral curve is similar for all green vegetation, variations in amplitude of the curve occur in different species and under different conditions of water and other growth factors. Spectral reflectance of vegetation communities, then, is a composite of the reflectance of the component plants and varies with floristic composition, physiognomy, and vigor of the plants.

REMOTE SENSING INSTRUMENTS

The laboratory, field, airborne, and satellite sensors discussed in this paper cover a wide range of spectral and spatial characteristics. These instruments are not necessarily the only or even the best choices for the particular application, but they are the ones used in the case studies, and they represent the state-of-the-art for operational sensors.

For laboratory spectral reflectance measurements of greenhouse-grown plants, a Beckman 5240* spectrophotometer having a Halon-coated integrating sphere was used. Reflectance was measured relative to a Halon standard in the 0.4 to 0.8 μm region. The field of view is a circle approximately 2 cm in diameter.

Two instruments were used in field-based studies. The Geophysical Environmental Research (GER), Inc., field spectroradiometer has 512 spectral bands between 0.4 and 2.5 μm. Spectral resolution is about 4 nanometres (nm) in the visible and increases to about 10 nm in the shortwave-infrared. At approximately 1 m above the sample, the field of view is a rectangle about 2 cm by 10 cm. The Barringer hand-held ratioing radiometer (HHRR) holds ten filters which can range from 3 nm to Landsat Multispectral Scanner (MSS) or Thematic Mapper (TM) bandpasses (see Table 1). The HHRR can also provide ten reflectance channels in a non-ratioing mode. From the height of 1 m, the field of view is a rectangle approximately 4 cm by 20 cm.

Airborne data were acquired for several studies using the NASA airborne Thematic Mapper Simulator (TMS) (a modified Daedalus 1268) instrument. Of the 12 spectral channels available, the wavelength regions used in the studies are shown in Table 1. When the Daedalus instrument is used in the case studies, TM-equivalent channels are given in the text for ease of relating to possible satellite applications. Airborne data were also acquired using the GER spectroradiometer, configured with 512 channels between 0.26 and 1.0 μm. The instrument is described in Collins *et al.*, 1983.

Satellite data from the Landsat Multispectral Scanner (MSS) and Thematic Mapper (TM) instruments are collected in wavelengths shown in Table 1. Channels selected for particular studies are specified in the descriptions of the case studies.

CASE STUDIES

TAXONOMIC AND STRUCTURAL RESPONSES

Studies using taxonomic and structural differences in vegetation have been conducted in both the eastern and western United States. For remote sensing of vegetation types, low resolution data such as that acquired from airborne or satellite Multispectral Scanners, Thematic Mappers, and Thematic Map-

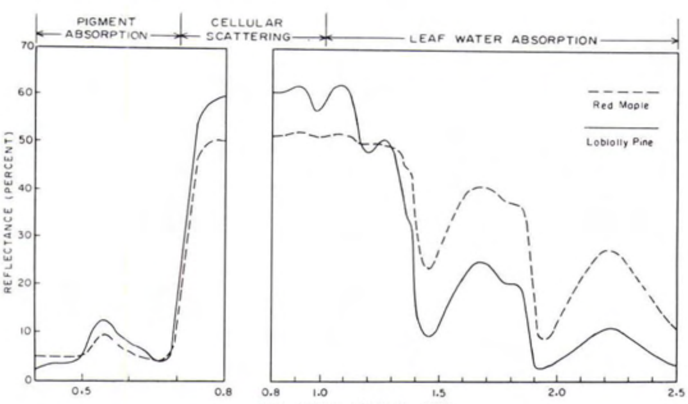

FIG. 2. Spectral reflectance curve of typical green vegetation. Greenhouse-grown red maple (*Acer rubrum*) and loblolly pine (*Pinus taeda*) were measured on a laboratory spectrophotometer. Each curve is a mean of ten measurements.

TABLE 1. SPECTRAL PARAMETERS OF AIRBORNE AND SATELLITE INSTRUMENTS USED IN THE STUDIES DESCRIBED IN THIS REPORT.

Wavelength (micrometre)	Thematic Mapper Simulator (TMS) bands	Thematic Mapper (TM) bands	Multispectral Scanner (MSS) bands
0.45- 0.52	2	1	
0.50- 0.60			4
0.52- 0.60	3	2	
0.63- 0.69	5	3	
0.60- 0.70			5
0.70- 0.80			6
0.76- 0.90	7	4	
0.80- 1.10			7
1.55- 1.75	9	5	
2.08- 2.35	10	7	
10.4 -12.5	12	6	

* Any use of trade names is for descriptive purposes only and does not imply endorsement by the U.S. Geological Survey.

per Simulators are used, and the spectral bands used are somewhat broad (Table 1).

Southwest Oregon. In northwestern California and southwestern Oregon, the highly complex geology is comprised of an ophiolite complex formed in a spreading back-arc basin which was sandwiched between volcanic arc complexes. The ophiolite consists of olivine-rich peridotites, including dunite, harzburgite, and pyroxenite, which may or may not be sepentinized. In addition, gabbros, diorite dikes, and mafic volcanics are abundant in the area (Harper, 1984).

The large diversity of vegetation types growing in this area is related to microclimate, land-use history, and lithology (Kruckeberg, 1954; Whittaker, 1960; Mouat *et al*., 1982; Frenkel and Kiilsgaard, 1983; Morrissey *et al*., 1984). The natural vegetation occurring on the peridotites is more stunted and open than the vegetation growing on the volcanics. The composition of the ultramafic vegetation is heavily ericaceous in the understory and coniferous in the relatively sparse canopy, whereas the vegetation growing on the volcanics has a more mixed understory and broadleaved as well as coniferous species in the more dense canopy. Thus, a combination of taxonomic and structural responses of vegetation to substrate is important here.

Ground spectral measurements acquired by Milton and Mouat (unpublished data) using the GER spectroradiometer showed that the dominant plant species are separable on the basis of their spectral characteristics. Because these dominant species are associated with specific lithologies, airborne TMS data were used to discriminate the vegetation types. Vegetation types were correlated with rock types using field observations, and thus associated substrates were identified on the imagery. Statistical tests were used to correlate vegetation, substrate, and remote sensing data. The vegetation associated with ultramafics was clearly separable from other vegetation with the use of the airborne TMS data. TM-equivalent bands 3, 6, and 7 (Table 1) were particularly well suited for separating vegetation classes associated with ultramafic rock types. TM-equivalent bands 2, 3, and 4 (Table 1) were selected as optimal for differentiating all vegetation classes (Morrissey *et al*., 1984).

Virginia Piedmont. In the eastern deciduous forest of Virginia, specific taxonomic composition of the forest canopy is associated with the Chopawamsic Fm, a gold-bearing metavolcanic unit in the central Piedmont (Pavlides *et al*., 1982). Dry soil conditions of the metavolcanic areas support a forest dominated by chestnut-oak (*Quercus prinus*), a species which prefers drier conditions than does the surrounding forest composed of mixed oaks (*Q. alba* and others). Chestnut-oak also occurs locally on highly aluminous schists and upland gravel deposits, both of which also produce dry soil conditions. Along road traverses, chestnut-oak was generally not found on granites, gneisses, gabbros, non-aluminous schists, and early Mesozoic basin sediments (Figure 3) (Milton *et al*., 1989a).

Landsat MSS data, acquired in early winter, were processed using an inverted principal component (IPC) transformation of the four bands. Picture elements of interest were defined based on hue in the IPC image. One pixel group coincided with the metavolcanic zone, upland gravels, and aluminous schists. Other rock units did not classify with these areas (Krohn *et al*., 1981; Schmidt and Koslow, 1986; Milton *et al*., 1989a).

California Aggregates Study. A research study employing airborne TMS data was initiated by the Naval Civil Engineering Laboratory (NCEL) in 1987 to determine whether vegetation characteristics could be used to discriminate parent materials suitable for aggregate source material (Minor *et al*., 1988). At the Ft. Hunter Liggett Reservation in west-central California, a field sampling strategy was designed to characterize the vegetation and parent materials within each of the two major aggregate sources, material derived from alluvium and residuum (or bedrock). Transects were randomly selected at two test sites, and detailed vegetation, soils, and geologic information were gathered. Reflectance was measured using the HHRR in the nonratioing mode with Landsat TM-equivalent bandpass filters. The HHRR data were used to analyze specific vegetation growing in anomalies as depicted on the TMS images. Airborne TMS imagery was acquired on 24 April 1987, a date selected to maximize vegetation phenological differences. Image processing schemes enhanced reflectance differences between potential source aggregate and surrounding materials. The schemes included a thermal band composite (TM-equivalent bands 6, 5, and 1 in red, green, and blue (RGB), respectively), principal components (PC) composites, and a composite employing PC2, PVI, and PC3. "PVI" is a linear recombination which approximates a perpendicular vegetation index (Elvidge, 1985). On the PC2, PVI, PC3 image, the species compositional differences of a site associated with an aggregate source derived from residuum were demarcated. Image differences were also evident associated with a site derived from alluvium. This latter site is associated with moisture stress caused by aggregate size and sorting within the alluvium. The alluvium best suited for aggregate source material was better drained and thus caused the overlying annual vegetation to desiccate before the vegetation in surrounding areas.

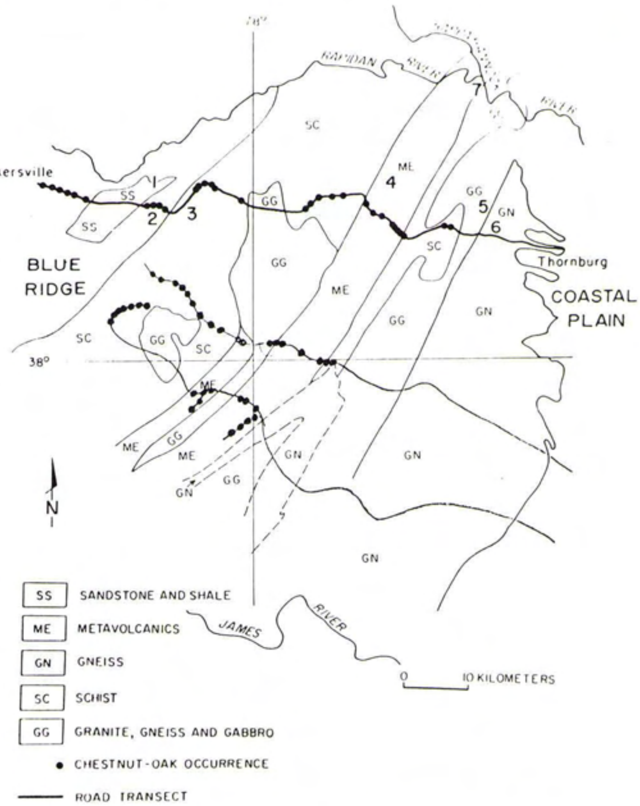

FIG. 3. The distribution of chestnut-oak (*Quercus prinus*) along road transects in the central Virginia Piedmont (from Milton *et al*., 1989a).

Spectral Reflectance Responses

Greenhouse Studies. In greenhouse experiments, Horler *et al*. (1980), Chang and Collins (1983), and Milton *et al*. (1988; 1989b) observed spectral changes in plants grown in substrates enriched with various metallic elements. The diagnostic reflectance change observed was a shift to shorter wavelength of the long-wavelength edge (red edge) of the chlorophyll absorption band centered near 0.68 μm (Figure 4). In field studies, the red edge shift was correlated with soil geochemistry, but not with biogeochemical concentrations. For this reason, a metal/nutrient interaction was proposed to explain an indirect, rather than a direct, effect of metallic elements on spectral reflectance (Milton *et al.*, 1989b). In further greenhouse studies, the red edge shift was observed in plants grown in a phosphorus-deficient medium (Milton, unpublished data).

Other spectral reflectance changes which occur in greenhouse-grown plants stressed with metallic elements or nutrient deficiencies include increased reflectance in the green and yellow portions of the spectrum (0.55 to 0.65 μm) and either increased or decreased reflectance on the infrared plateau (0.80 to 1.4 μm) (Figure 4).

Field-Based Studies. Field studies were carried out using the portable GER spectroradiometer in areas having As or Cu and Co anomalies, and spectra were compared with those acquired in background areas. Spruce (*Picea engelmannii*) and subalpine fir (*Abies lasiocarpa*) growing over Cu- and Co-enriched soils displayed increased reflectance in the green and yellow regions, but the red edge shift was too small to be statistically significant (Purdy *et al.*, 1986). In desert shrubs growing in As-enriched soils, a significant red edge shift, as well as increased reflectance in the green region, were observed in sagebrush (*Artemisia tridentata*), snowberry (*Symphoricarpos albus*), and juniper (*Juniperus monosperma*) (Eiswerth *et al.*, 1989).

High Resolution Airborne Studies. High resolution spectral changes were documented in airborne biophysical surveys of forests growing over various soil geochemical anomalies (Collins *et al.*, 1983; Milton *et al.*, 1983; Power and Milton, in press). The high resolution GER radiometer was used to acquire spectral data over three different coniferous and deciduous forests in the eastern and western United States. The data were analyzed for the presence of the red edge shift, and areas of anomalous vegetation exhibiting this shift were correlated with soil geochemistry. The following case studies illustrate two of these studies.

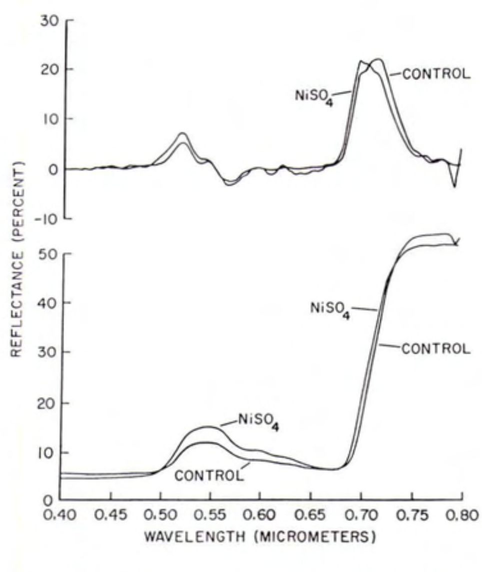

FIG. 4. Lower curves: laboratory spectral reflectance measurements of greenhouse-grown hosta (*Hosta ventricosa*) plants doped with NiSO4 (N=5) relative to control plants (N=34). The location of the red edge is defined as the inflection point on the first derivative spectra (upper curves). The magnitude of the shift of the red edge to shorter wavelength is about 16 nm. (From Milton *et al.*, 1988).

North Carolina Eastern Deciduous Forest. In the Carolina slate belt of central North Carolina, volcanic intrusions are associated with hydrothermally altered aureoles in the host rock, generally low-grade metamorphic rocks derived from volcanic tuffs and flows and volcanic sediments. The altered zones are highly siliceous and in many places highly aluminous and are considered to be part of a gold porphyry system. At Pilot Mountain, a hydrothermally altered monadnock within the slate belt, anomalous concentrations of Cu, Mo, and Sn are associated with the altered zone (Schmidt, 1985; Milton *et al.*, 1983).

The GER airborne radiometer was flown over Pilot Mountain in early October, 1981. Spectral data were analyzed using a waveform technique to detect the red edge shift. The two major zones of anomalous vegetation are located on the north and south slopes near the crest of the mountain, in approximately the same location as the areas of maximum Cu, Mo, and Sn concentrations (Figure 5). In addition, the small altered zone in the northwestern portion of the study area, verified by field checking, was found by its spectrally anomalous vegetation.

Vermont Northern Hardwoods Forest. In the northern hardwoods forest of New England, data were acquired with the GER airborne radiometer over part of the Vermont Copper Belt. Data analysis was carried out as described in the North Carolina study, using a waveform analysis to detect the red edge shift. Spectral anomalies in the vegetation were associated with zones of hydrothermal alteration, and, in some cases, with known mineralization (Power and Milton, in press). Other spectral anomalies in this area remain to be field checked.

Washington Environmental Studies. An on-going investigation jointly carried out by NCEL and the Desert Research Institute aims to develop geobotanical techniques to identify, assess, and monitor environmental contamination near Bangor, Washington. Objectives of the investigation are to determine the elemental content of vegetation growing in areas affected by environmental contamination and to determine narrow- and broad-band spectral characteristics of vegetation growing in the areas of environmental contamination.

At an electroplating acid waste dump, reconnaissance revealed that Douglas fir (*Pseudotsuga menziesii*) was ubiquitous throughout the area. Consequently, Douglas fir was sampled along a transect that passed through the site. Reflectance of needles was measured using the HHRR in a non-ratioing mode with five 10-nm bandpass filters located along the red edge (bandpass filter midpoints were 680, 700, 720, 740, and 780 nm) and the first five TM-equivalent channels. Biogeochemical analysis of the needle samples indicated strong positive zinc anomalies near the acid waste dump.

The Douglas fir growing on or near the acid waste site had pronounced spectral anomalies in all five narrow bandpass filters (significant at the 1 percent level using Student's t tests) compared with individuals growing off the site (Figure 6) (Mouat, unpublished data). TM-equivalent channels 1, 2, 3, and 5 were also significantly different. Vegetation growing in the vicinity of the acid waste site also had high zinc concentrations. The results confirm hypotheses (established from laboratory data, as discussed above) that stressed plants exhibit narrow-band red edge anomalies. 780/680 nm and TM-equivalent 4/3 ratios are probably indicative of decreased absorption of chlorophyll at the acid waste site.

CONCLUSIONS

Taxonomic and morphological responses of vegetation to substrate conditions can be detected by the remote sensing of plant communities. The spectral responses to these taxonomic and morphological changes can be seen along a range of scales using narrow-to broad-band sensors. When plant responses af-

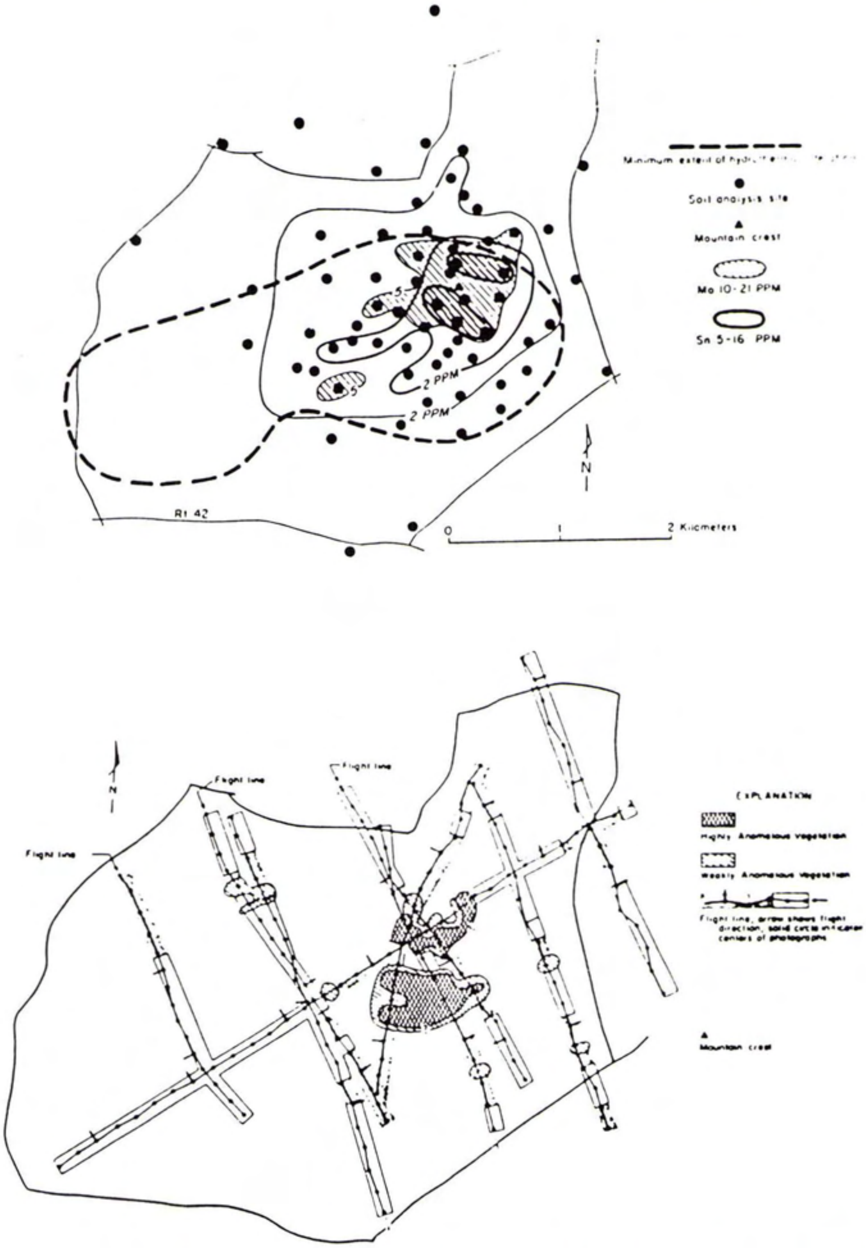

FIG. 5. Soil Mo and Sn values (upper map) and anomalous vegetation reflectance (lower map) at Pilot Mountain, Randolph County, North Carolina. Highest values are north and south of the mountain crest (triangle) (from Milton *et al.*, 1983).

fect the photosynthetic process, high spectral resolution changes occur, and when species compositional differences are involved, lower spectral resolution changes occur. Thus, broadband instruments as well as high spectral resolution systems might be appropriate for a given situation. Spatial resolution of the high spectral resolution sensors, however, is not necessarily high. Spectral response in the form of the red edge shift was detected in both individual leaves (greenhouse experiments) and in plant community canopies (field and airborne studies).

Taxonomic changes were observed at some sites but not at others. Taxonomic changes typically develop more slowly than spectral or structural changes, so that in areas of recent environmental contamination, taxonomic changes may not have had sufficient time to develop. In the example of environmental pollution reported in this paper, spectral response was the only measured vegetation characteristic. These spectral responses were observed to be similar to the spectral responses of vegetation growing in areas of naturally occurring soil geochemical anomalies. Thus, remote sensing and geobotanical techniques used to discriminate soil geochemical conditions associated with cultural phenomena have been shown to be similar to those techniques which were used in more or less natural areas.

Geobotanical remote sensing techniques have been demonstrated to be appropriate to a wide variety of scientific studies. These techniques should also be used in developing strategies for applications in diverse environmental assessments.

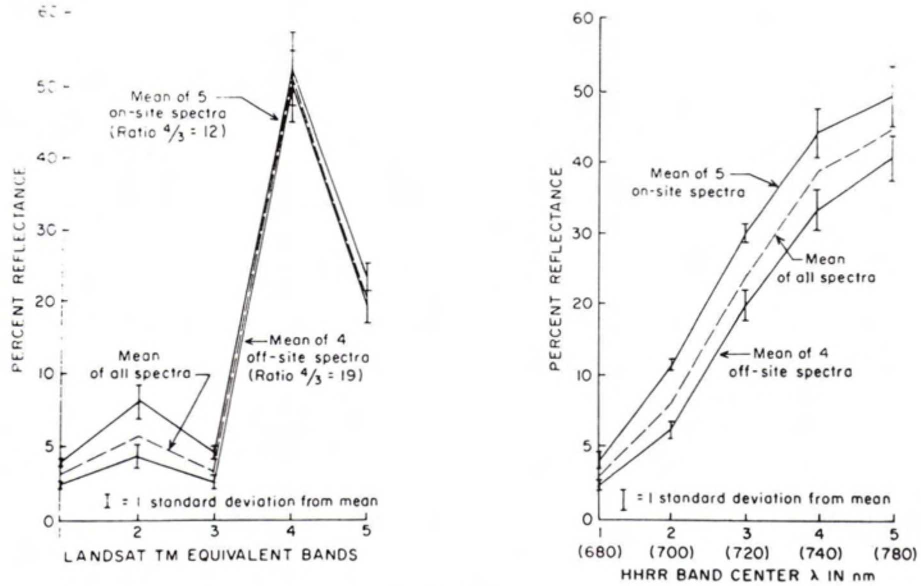

FIG. 6. Field TM-equivalent spectra and Barringer HHRR spectra of Douglas fir (*Pseudotsuga menziesii*) acquired near Bangor, Washington. Vertical error bars represent one standard deviation from the mean. Differences between on-site and off-site spectra were statistically significant (at < 0.05) for TM-equivalent channels 1, 2, 3, and 5 and for all Barringer channels.

REFERENCES

Billings, W. D., 1950. Vegetation and plant growth as affected by chemically altered rocks in the Western Great Basin. *Ecology* 31:62–74.

Brooks, R. R., 1972. *Geobotany and Biogeochemistry in Mineral Exploration*. Harper and Row, 190 p.

Brooks, R. R., and F. Malaisse, 1985. *The Heavy Metal-Tolerant Flora of Southcentral Africa*. A. A. Balkema, 199 p.

Cannon, H. L., 1957. *Description of Indicator Plants and Methods of Botanical Prospecting for Uranium Deposits on the Colorado Plateau*. U. S. Geological Survey Bulletin 1030–M:399–516.

Chang, S. -H., and W. Collins, 1983. Confirmation of the airborne biogeophysical mineral exploration technique using laboratory methods. *Economic Geology* 78(4):723–736.

Collins, W., S. -H. Chang, G. Raines, F. Canney, and R. Ashley, 1983. Airborne biogeophysical mapping of hidden mineral deposits. *Economic Geology* 78(4):737–749.

Eiswerth, B. A., N. M. Milton, and D. A. Mouat, 1989. Spectral reflectance changes in vegetation associated with anomalous concentrations of metallic elements; a potential tool for mineral exploration [abs]. McKelvey Forum, January, 1989, Reno, Nevada. Program with Abstracts, U. S. Geological Survey Circular 1035:15–16.

Elvidge, C. D., 1985. *Separation of Leaf Water and Mineral Absorption in the 2.22 μm Thematic Mapper Band*. Unpublished PhD Thesis, Stanford University, 182 p.

Frenkel, R. E., and C. W. Kiilsgaard, 1983. Vegetation classification and cover in the central Siskiyou Mountains, Oregon. Paper presented to the Association of American Geographers, April, 1983, Denver, Colorado.

Gates, D. M., 1980. *Biophysical Ecology*. Springer-Verlag, N. Y., 611 p.

Harper, G. D., 1984. The Josephine ophiolite, northwestern California. *Geological Society of American Bulletin* 95:1009–1026.

Horler, D. N. H., J. Barber, and A. R. Barringer, 1980. Effects of heavy metals on the absorbance and reflectance spectra of plants. *International Journal of Remote Sensing* 1:121–136.

Knipling, E. B., 1970. Physical and physiological basis for the reflectance of visible and near-infrared radiation from vegetation. *Remote Sensing of Environment* 1(3):155–159.

Krohn, M. D., N. M. Milton, and D. Segal, 1981. Discrimination of a chestnut-oak forest unit for geologic mapping by means of a principal component enhancement of Landsat multispectral scanner data. *Geophysical Research Letters* 8(2):151–154.

Kruckeburg, A. R., 1954. The ecology of serpentine soils, III. Plant species in relation to serpentine soils. *Ecology* 35:267–274.

Milton, N. M., and T. L. Purdy, 1983. Plant and soil relationships in two hydrothermally altered areas of the Great Basin. *Great Basin Naturalist* 43(3):457–469.

Milton, N. M., W. Collins, S. -H. Chang, and R. G. Schmidt, 1983. Remote detection of metal anomalies on Pilot Mountain, Randolph County, North Carolina. *Economic Geology* 78(4):605–617.

Milton, N. M., C. M., Ager, and M. S. Power, 1988. *Spectral Reflectance Changes in Greenhouse-Grown Metal-Doped Plants*. U. S. Geological Survey Open-File Report 88–57, 13 p.

Milton, N. M., B. A., Eiswerth, and M. D. Krohn, 1989a. Remote sensing in the central Virginia Piedmont. *Remote Sensing in Exploration Geology*, a combined short course and field trip. (Keenan Lee, ed.), AGU Field Trip Guidebook, IGC Meeting, Washington, D. C., July, 1989.

Milton, N. M., C. M. Ager, B. A. Eiswerth, and M. S. Power, 1989b. Arsenic and selenium-induced changes in spectral reflectance and morphology of soybean plants. Submitted to *Photogrammetric Engineering and Remote Sensing*.

Minor, T., D. Mouat, and J. Myers, 1988. Geobotanical determination of aggregate source material using airborne Thematic Mapper data.: *Proceedings, International Symposium on Remote Sensing for Exploration Geology*, Houston, Texas, May 16–19, 1988., pp. 147–157.

Morrissey, L. A., K. J. Weinstock, D. A. Mouat, and D. H. Card 1984. Statistical analysis of Thematic Mapper Simulator data for the geobotanical discrimination of rock types in southwest Oregon. *IEEE Transactions on Geoscience and Remote Sensing* GE-22(6):525–530.

Mouat, D. A., 1982. The response of vegetation to geochemical conditions. *Proceedings, International Symposium on Remote Sensing of Environment, 2nd Thematic Conference on Remote Sensing for Exploration Geology*, Ft. Worth, Texas. pp. 75–84.

Mouat, D., C. Elvidge, and R. Lyon, 1982. Geobotanical techniques for discriminating serpentine rock types in western United States. *Proceedings International Society of Photogrammetry and Remote Sensing Commission VII Symposium*, Toulouse, France, September 1982. 24-VII/2:155–163.

Pavlides, L., J. E. Gair, and S. L. Cranford, 1982. Central Virginia volcanic-plutonic belt as a host for massive sulfide deposits. *Economic Geology* 77(2):233–272.

Power, M. S., and N. M. Milton, in press. Detection of geobotanical anomalies associated with mineralization in the Glens Falls 1 × 2 degree quadrangle. *Mineral Assessment of Glens Falls 1 × 2 Degree Quadrangle* (J. Slack ed.), U. S. Geological Survey Bulletin.

Purdy, T. L., N. M. Milton, and B. A. Eiswerth, 1986. *Spectral Reflectance of Vegetation in the Idaho Cobalt District*. U. S. Geological Survey Open-File Report 86–587, 9 p.

Rose, A. W., H. E. Hawkes, and J. S. Webb, 1979. *Geochemistry in Mineral Exploration*. Academic Press, London, 657 p.

Schmidt, R. G., 1985. *High Alumina Alteration Systems in Altered Rocks and their Significance to Mineral Prospecting in the Carolina Slate Belt*. U. S. Geological Survey Bulletin 1562, 59 p.

Schmidt, R. G., and M. H. Koslow, 1986. *Preliminary Map Showing the Occurrence of Siliceous Rocks in Central North Carolina Derived from Enhanced Principal Components Landsat Images*. U. S. Geological Survey MF 86–17.

Schwaller, M. R., and S. J. Tkach, 1980. Premature leaf senescence as an indicator for geobotanical prospecting with remote sensing techniques. *Proceedings, International Conference on Remote Sensing of Environment*, 14th, Costa Rica. p. 347–358.

Whittaker, R. H., 1960. Vegetation of the Siskiyou Mountains, Oregon and California. *Ecological Monographs* 30:279–338.