Detecting Air Pollution Stress in Southern California Vegetation Using Landsat Thematic Mapper Band Data

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ABSTRACT: Landsat Thematic Mapper (TM) and aircraft-borne Thematic Mapper simulator (TMS) data were collected over two areas of natural vegetation in southern California exposed to gradients of pollutant dose, particularly in photochemical oxidants: the coastal sage scrub of the Santa Monica Mountains in the Los Angeles basin, and the yellow pine forests in the southern Sierra Nevada. In both situations, natural variations in canopy closure, with subsequent exposure of understory elements (e.g., rock or soil, chaparral, grasses, and herbs), were sufficient to cause changes in spectral variation that could obscure differences due to visible foliar injury symptoms observed in the field. TM or TMS data are therefore more likely to be successful in distinguishing pollution injury from background variation when homogeneous communities with closed canopies are subjected to more severe pollution-induced structural and/or compositional change. The present study helps to define the threshold level of vegetative injury detectable by TM data.

INTRODUCTION

COLOR INFRARED PHOTOGRAPHY has been used to detect moderate levels of stress in forest and shrub canopies over limited areas (e.g., Murtha, 1982). The development of satellite-mounted multispectral sensors such as the Multispectral Scanner (MSS) and Thematic Mapper (TM) aboard Landsats 4 and 5 has held the promise of repeated survey of stressed vegetation over larger areas, ultimately at reduced cost. In a study of the severe phytotoxic effects of sulfur dioxide and heavy metal pollution from the Sudbury smelters, Pitblado and Amiro (1982) found that MSS data were most useful in detecting major patterns of change in phytomass, using the normalized difference of infrared and red bands as an index. Allum and Dreisinger (1987) were also able to use MSS data in Sudbury to detect major differences in vegetative cover in a ten-year interval. Neither of these studies detected subtler changes in vegetation due to moderate foliar injury to existing vegetation.

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Rock, Vogelmann, and coworkers (Rock *et al.*, 1986; Vogelmann and Rock, 1986) have used simulated Thematic Mapper (TMS) data from the NS-001 sensor aboard aircraft to detect differences in damage to red spruce forests in the Camel's Hump area of the Green Mountains of Vermont, an area subjected to acid deposition and ozone. They found that the 1.65/1.23 μm (NS-001 TMS bands 6/5) and 1.65/0.83 μm (NS-001 TMS bands 6/4, or Landsat TM bands 5/4) ratios were useful in discriminating high from low damage sites. The high damage sites at Camel's Hump had tree mortality up to 26 percent, with many dead standing trunks and branches; low damage sites had mortality levels as low as 3 percent with few, if any, dead branches. Under such circumstances, canopy openings at high-damage sites could contribute reflectance from the broadleaved trees and ferns in the understorey (Vogelmann and Rock, 1986). The extent to which such understorey contributions helped to differentiate high from low damage sites with TMS data remained unresolved in the studies cited.

We have used aircraft-derived TMS and Landsat TM data to examine spectral changes arising from low to moderate foliar injury symptoms characteristic of ozone damage in two areas of southern California. In the Los Angeles basin of coastal

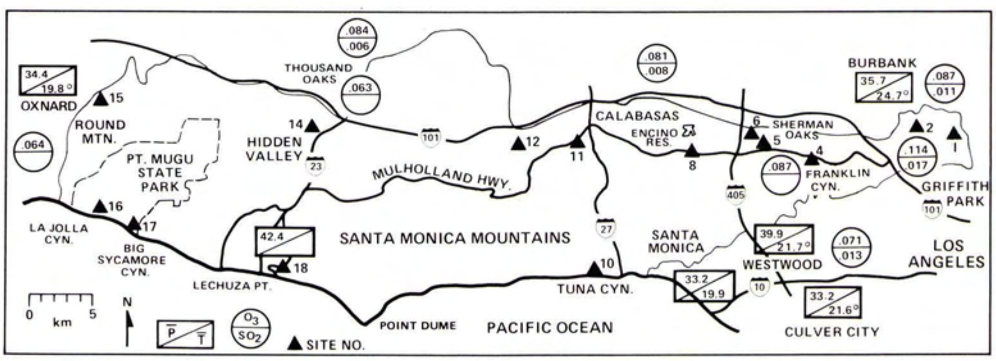

FIG. 1. Santa Monica Mountains, California (thin solid line). Mean annual precipitation (P, cm/yr) and temperature (T, °C)) shown in boxes; mean annual maximum hourly ozone and sulfur dioxide concentrations, μl/l, shown in circles; triangles denote field study sites.

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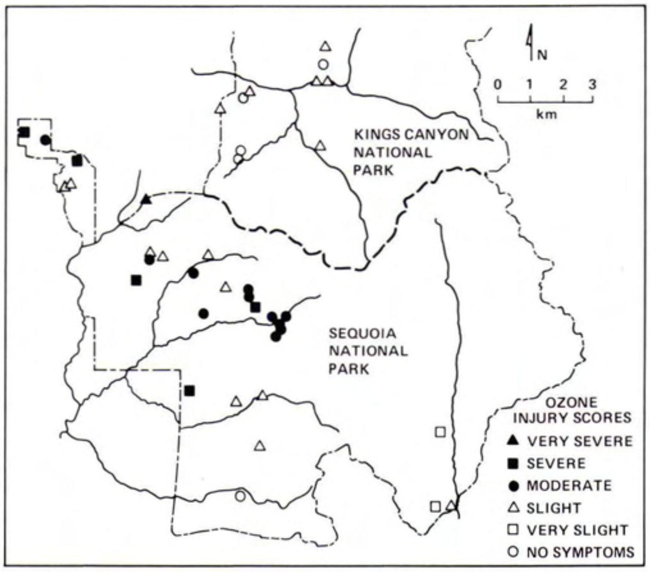


FIG. 2. Location of 42 yellow pine study sites in Sequoia/Kings Canyon National Parks in the southern Sierra Nevada of California, scored for foliar ozone injury symptoms in the NPS study. Adapted from Wallner and Fong (1982); published with authors' permission.

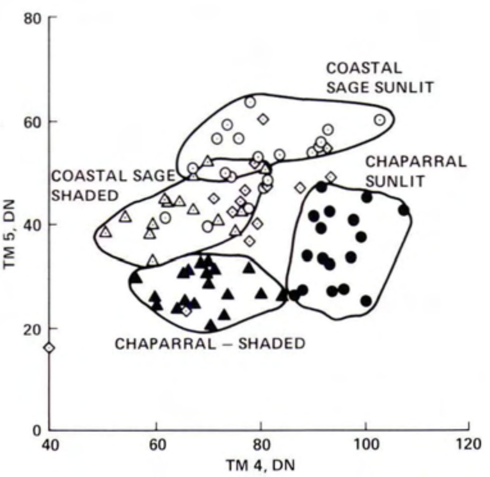


FIG. 3. Coastal sage and chaparral training sites clustered in relation to TM 4 and 5 spectral DN values. Open diamonds are field sites shown in Figure 1.

southern California, we observed changes in coastal sage scrub along the 52-km axis of the Santa Monica Mountains. Some preliminary results of this study were reported by Price and Westman (1987). In the southern Sierra Nevada mountains, we observed changes in yellow pine forests (*Pinus jeffreyi* Grev. & Balf. in A. Murr., *P. ponderosa* Laws.) in Sequoia/Kings Canyon National Parks. Spectral changes in Jeffrey pine under ozone and/or acid mist stress in laboratory fumigation chambers have been reported (Westman and Price, 1988), as have chemical changes with pollution exposure under laboratory and field conditions in Sequoia/Kings Canyon (Westman and Temple, 1988). Air pollution damage at these study sites is evident from characteristic foliar damage symptoms for ozone, and some premature senescence of older foliage, but the levels of structural change are substantially less than at high-damage sites at Camel's Hump, or at Sudbury. Hence, the present study examines the extent to which moderate, rather than extreme, vegetation damage induced by air pollution can be detected using Thematic Mapper band data.

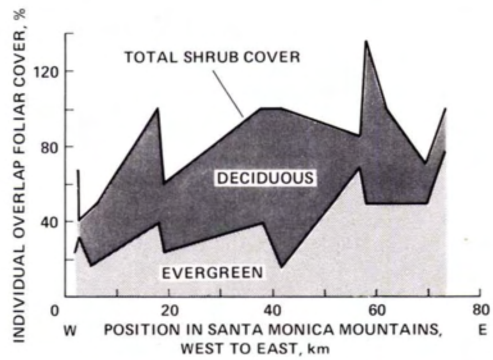


FIG. 4. Changes in the individual overlap foliar cover of evergreen and deciduous shrub elements in the coastal sage scrub field sites of Figure 1.

SANTA MONICA MOUNTAINS STUDY AREA

The Santa Monica Mountains occur as an east/west-trending coastal range flanked by the City of Los Angeles and the San Fernando Valley (Figure 1). High pollutant emissions, particularly from the urbanized eastern end, are shifted by wind and topographic influences to result in geographic gradients. A typical summer pattern involves buildup of photochemical oxidants during the daytime, with higher levels occurring on the San Fernando Valley side (north), at the eastern end of the mountains, and at higher elevations (Figure 1; cf. Westman, 1988). Sulfate and nitrate deposition pose a particular hazard to vegetation in the form of acid mist, which has a predominantly coastal distribution (Shikaya *et al*., 1984). Suspended sulfates and nitrates tend to be higher at the eastern end of the mountains (Calif. Air Resources Board, 1986a).

Major plant communities in the Santa Monica Mountains are chaparral, coastal sage scrub, oak and riparian woodlands, and grassland. Fumigation chamber studies have revealed a particularly high sensitivity of some coastal sage species to damage from levels of ozone occurring in the region (Preston, 1986; Weeks, 1987). Unlike chaparral, which is an evergreen-dominated shrubland, coastal sage scrub is dominated by facultatively drought-deciduous shrub species (Westman, 1981a). As the summer dry season progresses in this Mediterranean-type climate, coastal sage dominants drop first their large, early-season leaves, then their smaller late-season leaves; in dry years, shrubs can be virtually leafless by autumn (Westman, 1981b). Ozone has been shown to accelerate premature leaf drop in a variety of species, including coastal sage scrub (Preston, 1986). Hence, assuming a homogeneous floristic composition, one might expect an earlier and more extreme leaf loss in stands of coastal sage on the northern and eastern side of the Santa Monicas, where ozone levels are greatest. A field survey, comparing foliar damage symptoms in coastal sage scrub observed under fumigation with ozone or sulfur dioxide to those in the Santa Monica Mountains, provided some evidence for an increase in intensity of the most characteristic pollution symptom (mainly ozone-induced) per species toward the eastern end of the Mountains (Westman 1985). Leaf chemical changes in the field compared to those in the chambers also supported the hypothesis that ozone was causing increased leaf drop and leaf stunting toward the eastern end of the Mountains (Westman, 1988; Price and Westman 1987).

SOUTHERN SIERRA NEVADA STUDY SITE

Yellow pine forests at 1600 to 2500 m elevation in Sequoia and Kings Canyon National Parks (southern Sierra Nevada, east

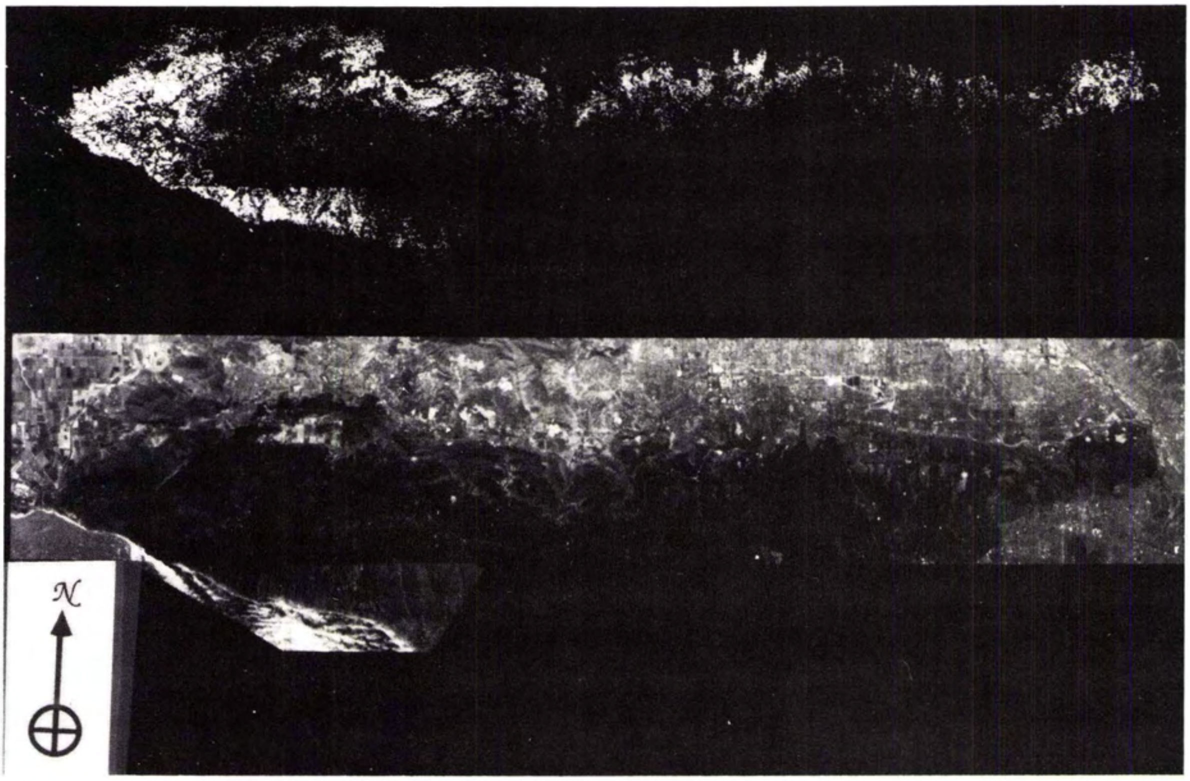


FIG. 5. TMS image (Bands 4,3,1) of the Santa Monica Mountains (lower), with location of coastal sage (P > 0.7) derived by supervised classification (upper).

of Fresno, California; 119° E, 37° N) have been studied for visible ozone injury symptoms by the National Park Service (NPS) for several years. During 1980 to 1982 42 sites of Jeffrey pine, ponderosa pine, or both were scored for injury on a six-point scale, using chlorotic mottle of needles, and premature needle loss as criteria for injury (Wallner and Fong, 1982; Warner *et al.*, 1982) (Figure 2). Most sites showed slight or moderate injury to foliage, but low mortality of individuals or branches. Ozone levels in the summer can reach 0.11 μl/l at Giant Forest (1950 m), a level sufficient to cause foliar injury to yellow pines in fumigation experiments (e.g., Miller *et al.*, 1963; Westman and Temple, 1988). Studies of potential acid deposition effects in the study area are in progress (California Air Resources Board, 1986b).

Chaparral, mixed herbaceous vegetation, and granitic rock outcrops are the most common subcanopy elements in the yellow pine forests of the area.

METHODS

SANTA MONICA MOUNTAINS

Daedalus AADS-1268 Thematic Mapper Simulator (TMS) data were collected from a NASA ER-2 aircraft over the Santa Monica Mountains on 27 August 1985. TMS data were collected along the northern flank of the range from Round Mountain to Griffith Park at 1300 PDT; a coastal flightline was flown from Round Mountain to Point Dume at 1415 PDT. The coastal data were coregistered to the inland data using nearest-neighbor resampling, and the two data sets were mosaicked into a single image. The six TMS bands that correspond to Landsat Thematic Mapper (TM) bands 1(420 to 450 nm), 2(520 to 600 nm), 3(630 to 690 nm), 4(760 to 900 nm), 5(1550 to 1750 nm), and 7(2080 to 2350 nm) were used in further analyses.

In a supervised classification of the vegetation, 31 sites of coastal sage (including seven field sites shown in Figure 1) and 43 chaparral sites were located on color infrared aerial photos taken in early October 1985, and on the TMS imagery. The mean size of sites was 4.6 ha (73 pixels), with a standard deviation of 5.4 ha (87 pixels); while 80 percent of the sites were less than 6.3 ha (100 pixels), the remainder ranged from 6.3 to 31 ha. Each site on the TMS image was noted as sunny or shaded based initially on topographic position in relation to sun angle on the photographs, and verified by the position of shadowed slopes on the TMS imagery. Means and variances of recorded intensities (Digital Number, or DN, values) in the six bands for all pixels in each training site were computed. A Bayesian maximum-likelihood classifier was used to sort all pixels in the image into classes of differing probability of membership in one of four spectral classes composed of training sites for coastal sage or chaparral, sunny or shaded. The pixels in the image classified as sunlit or shaded coastal sage with a probability greater than or equal to 0.7 corresponded most closely to the expected range of coastal sage, both from field observations (April, September 1986; May 1987) and a vegetation map (Nuno, 1980) derived from field survey (Burke, 1943). A "coastal sage" map was generated by assigning all pixels classified as coastal sage with P > 0.7 a DN value of 255, and remaining pixels a DN = 0.

The accuracy of this classification was checked by selecting 20 locations on the "coastal sage" map in a stratified random pattern across the length of the Mountains, and checking the identity of the vegetation type against color infrared photographs (stereo pairs).

In order to correlate TMS band data with increases in pollution

TABLE 1. EXPECTED TRENDS OF CHANGE IN SPECTRAL REFLECTANCE VALUES UNDER ALTERNATIVE HYPOTHESES OF CAUSATION, AND OBSERVED TRENDS ON SITES OF INCREASING POLLUTANT DOSE AT TWO SOUTHERN CALIFORNIA LOCATIONS. CORRELATION COEFFICIENTS FOR SITES OF COASTAL SAGE WITH POSITION ALONG THE GRADIENT OF INCREASING POLLUTANT DOSE ARE SHOWN. *P ≤ .05; **P ≤ .01.

	EXPECTED TRENDS					OBSERVED	
[REFERENCE]	INCREASING WATER STRESS (at constant LAI) [1,2]	DECREASING OF LAI Broadlvs [2] Conifer [3]	EFFECT OF NON-TARGET REFLECTANCE (SANTA MONICAS) Dry herbs/grass. Chap-arral Bare soil [4]	EFFECT OF NON-TARGET REFLECTANCE (SEQUOIA N.P.) Meadow Chap-arral Rock [4]	AIR POLLUTION EFFECTS ON PINE NEEDLES [1]	SANTA MONICAS 31 SITES ALL PIXELS	SEQUOIA N.P. (T-TEST, N=39)
TM 3	↑	↑ ↑	↑ ↓ ↑	↑ ↑ ↑	↑	↑ .39* ↑ .12*	↓ N.S.
TM 4	↑ MOD. STRESS ↓ EXTREME STRESS	↓ –	↓ ↑ ↓	↑ ↑ ↑	↓	↑ .49* ↑ .22*	↑ N.S.
TM 5	↑	↑ ↑	↑ ↓ ↑	↑ ↑ ↑	—	– .14 – -.12	— N.S.
TM 7	↑	↑ ↑	↑ ↓ ↑	↓ ↑ ↑	—	– .11 – -.06	↓ N.S.
TM 4/3	↓	↓ ↓	↓ ↑ ↑	↑ ↓ ↓	↓	↑ .16 ↑ -.22*	↑** (NONE VS MED.)
TM 5/4	↑	↓ ↓	↑ ↓ ↑	↓ ↑ ↑	↑	↓ -.50** ↓ -.37*	— N.S.

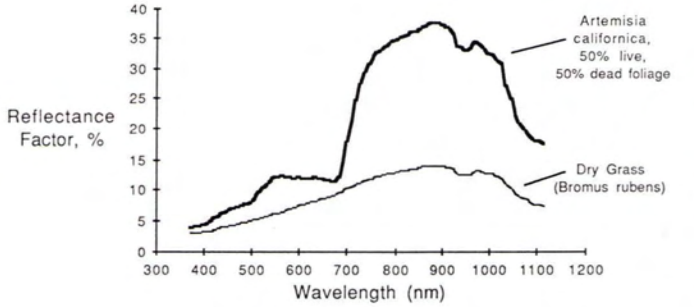
REFERENCES: [1] Westman and Price, 1988
[2] Ripple, 1986
[3] Peterson et al., 1987
[4] This paper

dose in the field, the simplifying assumption was made that pollution loads increase monotonically toward the east. As a surrogate for pollution dose, spectral data were correlated with line number on the imagery, because the image lines ran west to east. This assumption is supported both by the ambient air quality monitoring data for ozone (Figure 1) and by field observations of foliar damage symptoms (Westman 1985). Only three sites from the coastal flightline were included in the training set of 31, and these three sites were from the cleaner western Santa Monicas, west of Point Dume. Hence, the correlation with line number is a correlation of the western Santa Monicas (Valley or coastal side) with points east of Thousand Oaks on the Valley side only.

To expand the sample size of coastal sage for correlation with the east-west pollution gradient, we also correlated all pixels classified as coastal sage with P > 0.7 against line number. To eliminate any potential problems with differences in sun angle between the two flightlines, only the inland flightline data were used for this portion of the analysis. We further corrected the inland flightline data for limb brightening, the artifactual tendency for columns of spectral data (along the flightline direction) to exhibit increased radiances at increasing distances from target nadir. We corrected the data using a column-averaging program (COLAVE) developed at NASA Ames Research Center. The average spectral values for 80 lines of each column derived from an urban area of homogeneous composition across the image were fitted to a quadratic equation; this, in turn, was used to transform other column values across the image.

The data were also checked for differences in atmospheric path radiance across the pollution gradient, by examining differences in spectral band values against a dark background (a series of eight reservoirs in the Santa Monica Mountains). No significant differences were observed, and no atmospheric correction therefore made.

Reflectance data (400 to 1100 nm) from shrub canopies of individual coastal sage species were collected in the field on cloud-free days near solar noon in early May 1987 in the Santa Monicas using a Spectron SE-590 spectroradiometer, and ra172tioed to reflectance from a barium sulfate plate taken within a minute of the initial measurement. The sensor was mounted 1 m above the canopy, causing approximately 670 sq cm of canopy area to fill the field of view. Reflectance data in the 400-



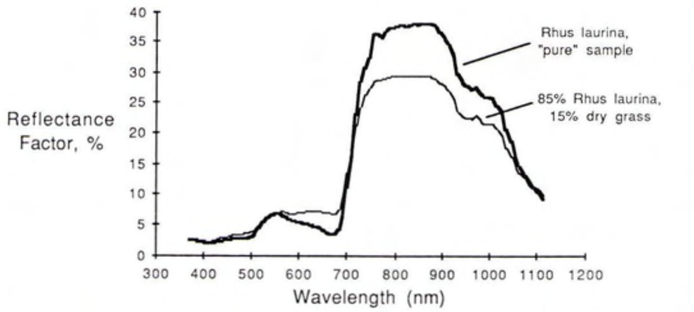


FIG. 6. Reflectance spectra (relative to barium sulfate reflectance) of a drought deciduous coastal sage shrub (*Artemisia*), dry grass, an evergreen shrub (*Rhus*), and a *Rhus*-grass mixture measured in the Santa Monica Mountains with a Spectron SE-590 spectroradiometer.

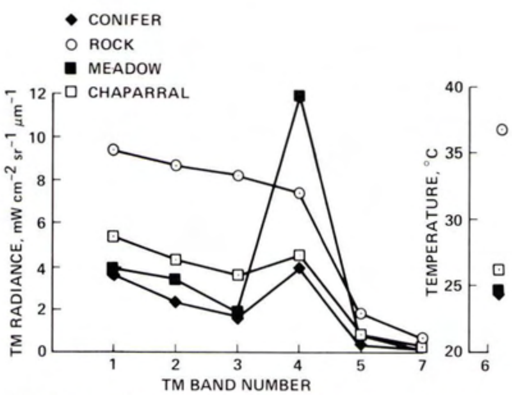


FIG. 7. TM radiance values in seven bands for four pure landscape elements in Sequoia/Kings Canyon National Park.

2400 nm range were also measured in April and September 1986 using the Barringer Refspec IIA spectrometer, and were ratioed to a barium sulfate plate.

SOUTHERN SIERRA NEVADA

Coordinates of the 40 yellow pine sites surveyed for foliar injury (Figure 2) were obtained from a National Park Service topographic map using a digitizing tablet, and used to locate the sites on a nearly cloud-free Landsat-5 TM scene of Sequoia-Kings Canyon National Parks from 7 July 1984. Means and variances of spectral bands for a 3 by 3 pixel window were computed for each site. Digital numbers (DN) were converted to radiance values, and band 6 DN values were converted to at-satellite temperatures, using conversion factors of Markham and Barker (1986). Based on the similar radiances observed in TM bands 4 to 7 for three dark targets (Hume, Moose and Sequoia Lakes) spanning the study region, no correction for additive path radiance from the atmosphere was applied. In addition, spectral mean values for several homogeneous cover types (closed-canopy conifer stands [not yellow pine], bare granite, meadow, chaparral) were obtained. One outlier site with clearly aberrant spectral values was deleted.

The remaining 39 yellow pine sites were grouped into four foliar injury classes based on NPS injury scores: none ($n=7$); very slight to slight ($n=16$); moderate ($n=10$); severe or very severe ($n=6$). Sites were scored by the NPS based on the average of ten individuals, three branches per individual. Individuals with diffuse chlorotic mottle (characteristic of ozone damage) were considered to have "very slight damage" if only fifth year or older needles showed mottling. If fourth year needles showed injury, the injury rating progressed to slight, for third to moderate, for second to severe, and for current, very severe (Wallner and Fong, 1982).

The TM bands and band ratios were tested for significant differences between injury classes using both analysis of variance and t-tests. Levene's test for equality of variance, the Brown-Forsythe test for significance of F with inequality of variance, and Bonferroni's test for significance of t were used (BMDP program 7D; Dixon, 1985). In order to control for differences in canopy closure between sites, a subset of 19 sites was located on 1:20,000-scale color infrared photographs exposed from NASA's C-130 aircraft on 7 October 1986. Canopy closure was estimated visually from the stereo pairs under magnification. Tests of difference in spectral values between injury classes were repeated on a subset of ten sites with canopy closure 80 percent or more, and nine sites with canopy closure less than 80 percent.

RESULTS AND DISCUSSION

SANTA MONICA MOUNTAINS

Means of TM bands 4 and 5 for 31 coastal sage and 43 chaparral training sites are shown in Figure 3, along with field study sites of coastal sage shown in Figure 1. Some of the field study sites were chosen because of their location along the gradient rather than their homogeneity and extent, and contained small patches of coastal sage intermingled with chaparral or grass; these sites fell outside the clusters of training sites. As one progresses eastward in the Santa Monicas, coastal sage stands occur in smaller patches, the contribution of evergreen species increases, and total shrub canopy density (measured as individual overlap foliar cover; Westman (1981a)) increases (Figure 4 and field observation).

The change in the patch size and homogeneity of coastal sage along the west-east gradient affected classification accuracy. Figure 5 shows the TMS-derived map of coastal sage scrub using the classification based on 31 training sites. In the western 40 km of the range, all 16 validation sites chosen from Figure 5 by stratified random sampling were indeed located in coastal sage; within the eastern 10 km of the range, classification accuracy dropped to 33 percent. Pixels containing a mixture of dry grass and evergreen chaparral with smaller amounts of coastal sage shrubs (a vegetative composition that is increasingly common in the eastern Santa Monicas) appeared to be classed as coastal sage in this easternmost section of the range, based on comparison with color infrared photographs.

Table 1 shows the correlation of TMS band and band ratio data for coastal sage with line number, east to west along the range and pollution gradient, from low pollutant exposure to high. The first set of values are for the 31 training sites. Sunlit and shaded sites were combined; correlations for the combined set tended to be near the lesser value for sunlit or shaded alone. The second set of values is for the inland, limb-brightening-corrected data for all n pixels classified as coastal sage ($n = 25{,}889$). Correlations were substantially higher before correction for limb-brightening.

In addition, expected trends of change along the gradient, based on theory and other empirical studies, are listed for four alternative hypotheses of causation: increased moisture stress toward the east (due to higher summer temperatures; Figure 1); changes in leaf area index (LAI) of the vegetation due to changes in canopy density or composition; changes in extent or nature of non-target reflectance (dry herbs/grasses, chaparral, or soil elements in pixel); and effects of ozone on leaf structure. The expected influences of non-target elements on coastal sage reflectance were derived from an examination of field spectra. An example contrasting the influence of grass on reflectance from a drought-deciduous or evergreen shrub is shown in Figure 6.

Trends are consistent between the set of 31 training sites and the full set of 25,000 pixels, though the increased variance in vegetation type in the full data set probably resulted in the reduced strength of correlation. Although no single hypothesis predicts all the observed trends, the hypothesis that best explains the strongest trends is the one suggesting that the evergreen chaparral component becomes more abundant in the coastal sage toward the east. This hypothesis is supported by field observations, the limited field data plotted in Figure 4, and spectral trends except for TM 3. The increased exposure of soil toward the east is the next most consistent hypothesis.

The results suggest that the changes in spectral reflectance toward the east are a reflection primarily of changes in the vegetative structure and composition of coastal sage scrub toward the east in the mountains. From the western Santa Monicas at Pt. Mugu State Park to the east at Griffith park, coastal sage vegetation changes from dense, pure, extensive stands typically dominated by black and purple sage (*Salvia mellifera* Greene; *S. leucophylla* Greene) to increasingly infrequent, small, and heterogeneous stands where the sage dominants are lesser elements, mingled with evergreen chaparral shrubs (*Rhus laurina* Nutt. in T. & G., *R. integrifolia* (Nutt.) Benth. & Hook.; *Heteromeles arbutifolia* M. Roem.) and patches of bare soil. The abundance of pure chaparral increases toward the east as well. Compared to the spectral effects induced by this change in vegetative structure and composition, the increases in foliar injury symptoms in coastal sage dominants toward the east are apparently too subtle to predominate in influence upon TMS data.

Southern Sierra Nevada

The spectral differences between the four yellow pine injury classes were not significant by ANOVA or t-tests either for the full 39 sites, or for the subsets of sites stratified by canopy closure (above or below 80 percent closure), with two exceptions. The decreasing thermal response (TM 6) from none or slight to moderate injury was significant, as was a rise in TM 4/3 from none to moderate injury classes for the full set of 39 sites only. The trends of change (except for TM 6) are shown in Table 1 for the 39 sites. The expected changes in reflectance due to non-target elements were derived from the data in Figure 7, which plots TM values for pure vegetation elements in the Landsat scene, and the standard error range for yellow pine in Figure 8.

The decline in thermal response is consistent with increased exposure of meadow-like herbs (25°C) or chaparral (26°C) beneath yellow pine (28 to 30°C) (Figures 7 and 8); the rise in TM 4/3 is consistent with increased exposure of meadow-like understory (Table 1). Both changes are also consistent with the possibility that healthier sites had more exposed bare granite, either because of a disproportionate amount of bare granite, or of low canopy

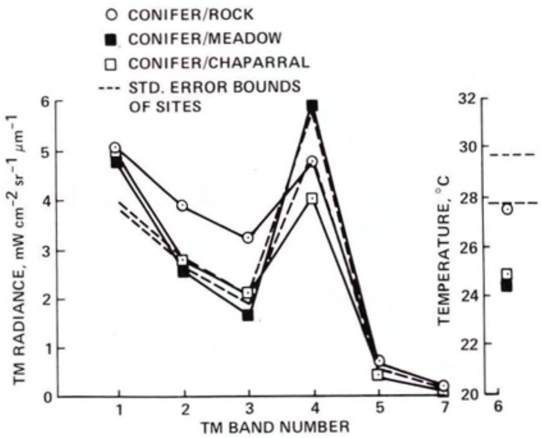


FIG. 8. 3:1 ratio mixtures of spectral values for dense conifer (not yellow pine) with other landscape elements from Figure 7, compared to the range (standard errors) of 42 sites of yellow pine exhibiting no or slight to severe foliar injury in Sequoia/Kings Canyon National Parks.

closure, on sites of slight or no injury. Such a distribution could occur as an artifact of low sample size, even though one would expect canopy closure to increase, rather than decrease, on sites of lesser foliar injury. The latter possibility is reduced by the observation that no significant differences in canopy closure occurred between sites of different injury class in the 50 percent random subsample (ANOVA F-test, $P = 0.27$).

Figure 8 also demonstrates that small openings in the canopy (on the order of 25 percent by area) of conifer stands can cause changes in TM spectral values that exceed the range of standard error bounds in yellow pine sites experiencing current levels of foliar pollution injury. Because yellow pine sites vary in canopy closure by this magnitude and more in the absence of pollution stress (due to other site conditions), Figure 8 helps to document that natural variations in canopy closure, with accompanying exposure of understory elements, can obscure the spectral changes induced by foliar injury on a majority of sites.

GENERAL DISCUSSION

Both case studies in this article have dealt with vegetation in which the extent of documented air pollution injury was limited to chlorosis and necrosis of existing leaves, and some leaf loss due to premature senescence. While such injury may be described as "severe" on a scale of foliar damage, the structural damage falls far short of the major branch and tree mortality present at Camel's Hump or the wholesale change in vegetative composition and biomass that has occurred at Sudbury. In comparison to those situations, the vegetation at the southern California study sites is experiencing only mild structural damage. In both California sites, the trends of spectral change were consistent with those expected from natural structural and compositional variation in the vegetation. While foliar injury attributable to ozone was visible in the field, the injury was insufficient to register as spectral changes above the background variation induced by natural variations in canopy closure and vegetative composition within the target vegetation type.

These findings have value in helping to define the threshold of pollution injury below which TM or TMS data are unlikely to detect pollution stress. In forest or shrubland vegetation that varies in canopy closure naturally by as much as 25 percent, and in which visible pollution injury is limited to foliar damage symptoms, TM data are unlikely to be successful in differentiating classes of pollution injury. In closed canopy situations, where vegetation composition is more homogeneous (such as forest plantations), or in areas where air pollution damage is sufficient to cause marked increases in branch and whole plant mortality above the range of natural mortality, TM or TMS data may well prove useful in determining spatial extent of damage, or changes in degree of damage over time.

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