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RESEARCH

Remote Assessment of Forest Health in Southern Arizona, USA: Evidence for Ozone-Induced Foliar Injury

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ABSTRACT / This paper examines possible ozone-induced foliar injury to ponderosa pine areas in the Rincon Mountains of southern Arizona from 1972 to 1992. Spatiotemporal differences in a satellite-derived vegetation index (VI) are examined with respect to antecedent moisture conditions, temporal variations in ozone exposure levels, and measured foliar injury values from 1985. Seasonal ozone exposure levels (SUM60 and W126) increased from 1982 to 1998 and were significantly correlated ($r = 0.49$ and 0.53, $\alpha = 0.05$) with annual population totals in the Tucson area. Extensive masking of satellite images from 1972, 1986, and 1992 resulted in two optimal change detection areas, with one site, TVWMica, exposed mostly to the Tucson air pollution plume, while the other site, EMica, was more protected from Tucson-derived pollution. An overall increase in VI from 1972 to 1992 at both sites appears to have been caused by an increase in moisture availability. Larger foliar injury values in 1985 were associated with a smaller increase in VI (i.e., a smaller increase in green leaf biomass) from 1972 to 1986. From 1972 to 1986 and from 1986 to 1992, VI values at TV/WMica increased at a slower rate compared to those at EMica. The reduced increase in "green-up" may have been caused partially by ozone-induced foliar injury and resulting decreases in green leaf biomass. However, these spatial differences in VI values may have also been caused by a number of other factors. Results nevertheless reveal the strong possibility of distinct, topographically based, spatial variations in ozone-induced foliar injury within the Rincons.

Coniferous forests in the "sky islands" of the southwestern United States are a valued resource, resulting partially from their relatively small coverage of the region's landscape. For example, coniferous forests comprise just 1% of the Tucson, Arizona, region's total area (Diem and Comrie 2000). Like other forests, sky island forests are affected by a variety of stressors that affect their overall health. Major causes of stress include natural competition, climate, biological factors (e.g., insects and fungi), chemical deficiencies or excesses, and direct human disturbance (e.g., logging) (Cowling 1989). These, however, are not the only stressors.

Forests within and/or proximate to urban, industrial, and mining areas have been found to be affected by air pollution, a form of indirect human disturbance. Ozone, which is a secondary air pollutant formed by the oxidation of volatile organic compounds (VOCs) in the presence of nitrogen oxides (NO_x) and sunlight (Chameides et al. 1992), is the only regionally dispersed air pollutant that has been rigorously proven to cause detrimental effects on forests (Bates and Sizto 1987; Woodman 1987; Cowling 1989). Even though forests might not be located near urban areas, ozone can be transported hundreds of miles downwind from urban sources and persist for hours [United States Environmental Protection Agency (U.S. EPA) 1984]. Rural, western atmospheres can have high ozone concentrations, for between 1980 and 1988, 56% of ozone monitoring sites in or near western forests exceeded the federal ozone standard at least once (Böhm and Vandetta 1990). For the most part, ozone-related tree damage is caused by absorption of sublethal amounts of pollutants over a long period of time (Reich and Amundson 1985). Shorter exposure to relatively high concentrations, such as those higher than 80 ppb, can also cause injury (Böhm et al. 1995). Chronic exposure to ambient ozone can cause substantial loss of vigor, which can in turn lead to increased susceptibility to additional stresses (e.g., drought and insects), abnormally high tree mortality, and potential changes in forest structure and function (Miller et al. 1982).

Ozone and Forest Health in the Western United States

In the western United States, most research concerning ozone and forest health has been conducted in the ponderosa pine (*Pinus ponderosa* Laws) and Jeffrey pine (*Pinus jeffreyi* Grev. and Balf.) forests in California's San

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Bernardino Mountains and Sierra Nevada Mountains. Damage to those ozone-sensitive pine species is indicated by chlorotic mottling, tip necrosis, reduced needle retention, tufted crowns, reduced needle length, reduced needle density, and reduced growth (Innes 1992). In addition to the direct impacts of ozone, trees in an advanced state of chlorotic decline are attacked more frequently by both the western pine beetle and the mountain pine beetle than are healthy trees (Cobb 1968).

Smith (1981) noted that, in the San Bernardinos, an average 30-year-old ponderosa pine that grew during a time period (1941 to 1971) with relatively high pollution levels was considerably smaller than a similar tree that grew during a low-pollution time period (1910 to 1940). Also in the San Bernardinos, from 1978 to 1988, decreases in ozone injury were linked to decreased ozone concentrations (Miller et al. 1989). A similar relationship between ozone and forest health was found in the Sierra Nevadas. Symptoms of ozone injury to pines have been documented within a 500-km-long area on the western side of the southern Sierra Nevadas (Warner et al. 1982). Williams et al. (1977) found ozone injury predominantly in the low-elevation ponderosa pine forests on ridges that rise abruptly from the San Joaquin Valley floor. Most injury occurred at middle elevations due to concentration of pollutants at inversion boundary zones on rising mountain slopes. Concerning tree growth in the southern Sierra Nevadas, Jeffrey pines with symptoms of ozone injury had 11% less radial growth than pines without ozone injury; sites with reduced growth faced the San Joaquin Valley (Peterson et al. 1987).

Remote Sensing of Pollution Damage

Satellite data have proven useful for detecting vegetation stress, including pollution-induced stress (Vogelmann 1988; Hagner and Rigina 1998). In areas where no ground truth is available, remote sensing can still be used to identify where vegetation is stressed with the aid of vegetation indices. The simple vegetation index (VI), which is the ratio of near-infrared to red reflectance, is significantly correlated with the total green leaf biomass (Tucker 1979). Therefore, temporal changes in VI values provide a means for deciding whether a vegetation canopy has been significantly altered (Nelson 1983). Nevertheless, some researchers have found that air pollution injury is 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 (Westman and Price 1988).

Purpose and Goals

The purpose of this paper is to assess the capability of multitemporal satellite imagery for uncovering circumstantial evidence of ozone-induced foliar injury in ponderosa pine areas of the Rincon Mountains of southern Arizona. The three major goals are (1) to establish a link between 1985 field-based foliar injury values and image-based VI changes from 1972 to 1986, (2) to establish a link between temporal variations in VI values and expected ozone exposure levels, and (3) to provide useful preliminary results on which future studies can be based.

Study Region

The Rincon Mountains (~32°N latitude and ~110°W longitude) are located east of Tucson in southern Arizona (Figure 1). Saguaro National Park (SNP) East contains most of the mountainous areas. The Rincons are rugged mountains with an elevation range of approximately 1600 m (~1000 to ~2600 m a.s.l.) and an especially steep eastern face. Mica Mountain and Rincon Peak are the two highest points in the Rincons. Vegetation consists generally of Sonoran desert scrub (i.e., palo verde and mesquite) at lower elevations, Madrean evergreen woodland (i.e., juniper and evergreen oak) at middle elevations, and Madrean montane conifer forest (i.e., pine and Douglas-fir) at higher elevations. On the Rincons and most of the Southwest's other "sky islands," ponderosa pine is the most common montane tree and often grows in pure stands (Brown and Lowe 1983). Two varieties of ponderosa pine in the Rincons are Arizona pine [*P. ponderosa* var. *arizonica* (Engelm.) Shaw] and Rocky Mountain ponderosa pine [*P. ponderosa* var. *scopulorum* (Engelm.)] (Little 1976).

The upper elevations of the Rincons have a warm temperate climate, with average annual temperatures around 9°C (~50°F) and an annual precipitation total of approximately 780 mm (~31 in.) (Figure 2). Daily maximum temperatures reach 25°C (~77°F) during June and July, while daily minimum temperatures drop to −4°C (~25°F) in January. The Rincons have a bimodal precipitation regime with relatively wet winters and summers. In winter, midlatitude storms move through the region (Comrie 1996). During July and August, a monsoon-like circulation advects the bulk of the moisture from the eastern tropical Pacific Ocean and the Gulf of California (Adams and Comrie 1997).

Motor vehicles are the primary sources of the Tucson region's ozone precursor pollutants (i.e., VOCs and NO_x) (Diem and Comrie 2001). Tucson's motor vehi-

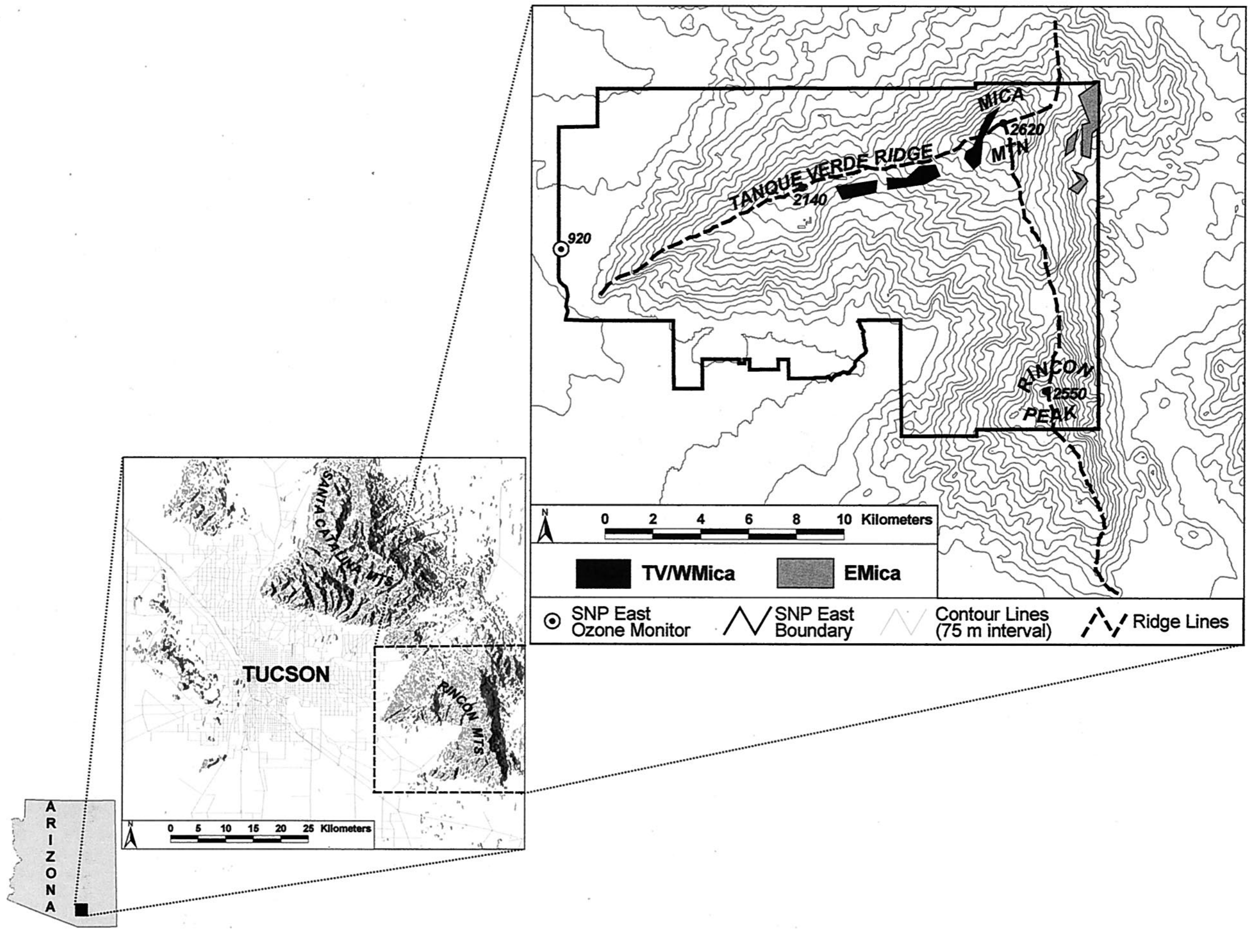

Figure 1. Map of the study region showing the locations of the two study areas, TVW/Mica and EMica, in the Saguaro National Park East portion of the Rincon Mountains as well as their proximity to Tucson.

cle usage has increased as its population has increased, which is mostly at the urban–rural fringe. For example, as the region's population total exploded from approximately 265,000 to over 800,000 people from 1960 to the late 1990s, the average daily vehicle miles traveled (VMT) increased from over 1 million to over 20 million [Pima Association of Governments (PAG) 1996, 1998].

Data

Data used in this study consist of multitemporal satellite imagery, monthly precipitation and drought index records, monthly ozone exposure levels, annual population estimates, digital, georeferenced fire perimeter and vegetation maps, and plot-specific foliar injury data. Three Landsat Multispectral Scanner (MSS) scenes were acquired from the Arizona Regional Image Archive (ARIA); the scenes correspond to late September/early October of 1972 (9/27), 1986 (10/7), and 1992 (10/7). This is the optimal time of year to assess ozone-induced damage, for it is at the end of both the growing season and the ozone season, thus maximum cumulative ozone-induced foliar injury should be present. The scenes were part of the North American Landscape Characterization (NALC) project and have a spatial resolution of 60 m. Sohl and Dwyer (1998) provide a comprehensive overview of the NALC project. The reflectance bands of interest in this study are the red hand (0.6–0.7 μm) and the farthest near-infrared band (0.8–1.1 μm). A companion digital elevation model (DEM) with the same spatial resolution as the MSS scenes was also acquired from ARIA. Monthly precipitation and Palmer Hydrological Drought Index (PHDI) data from 1970 to 1992 were obtained from the National Climatic Data Center (NCDC) for the southeastern Arizona climate division (Division 7). Monthly precipitation and temperature from 1965 to 1981 were obtained from the National Climatic Data Center

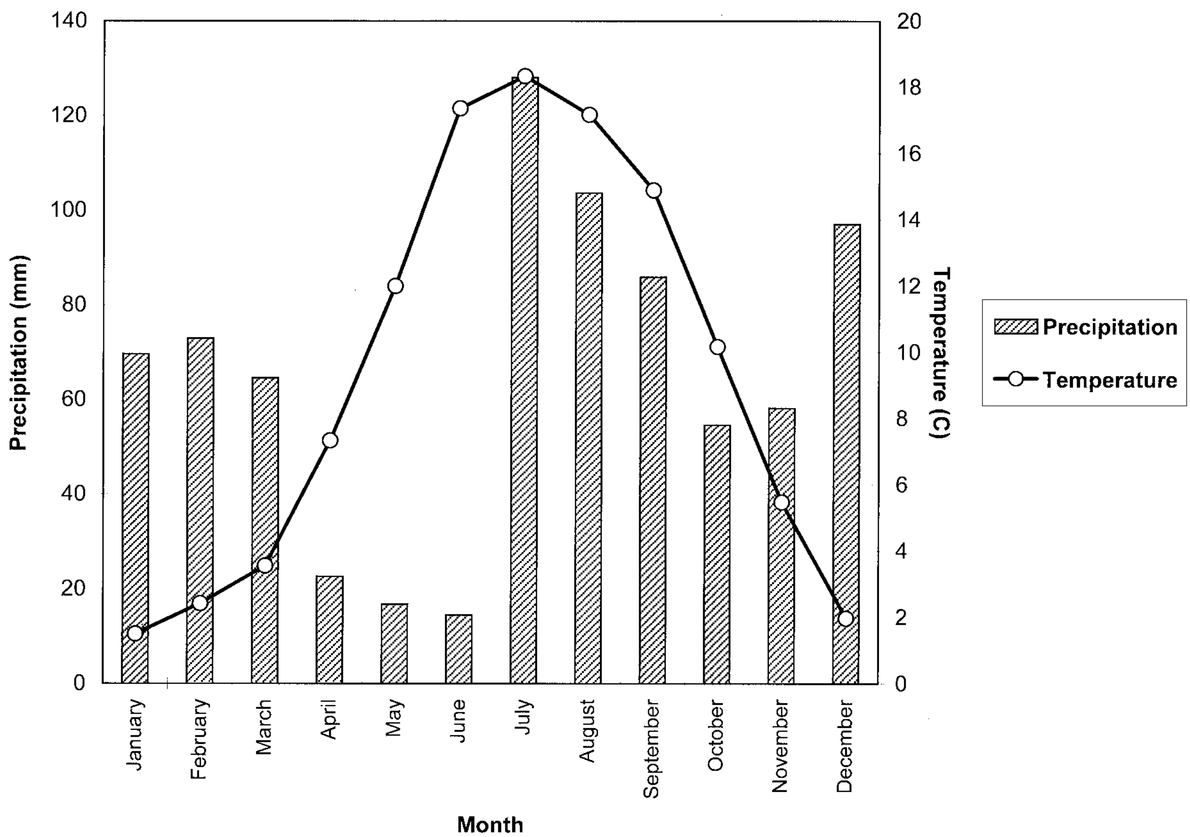

Figure 2. Climograph for the Palisades Ranger Station (~2,200 m a.s.l.) in the Santa Catalina Mountains. Similar temperature and precipitation regimes exist in ponderosa pine areas in the Rincon Mountains.

(NCDC) for the Palisades Ranger Station in the Santa Catalina Mountains. Hourly ozone data measured by a continuous monitor at the western edge of SNP East from 1982 to 1998 were acquired from the United States Environmental Protection Agency. Annual population estimates were provided by the Pima Association of Governments (PAG). A digital vegetation map of the area, which is part of the Arizona GAP Project, was provided by the The University of Arizona's School of Renewable Natural Resources. Digital maps of burned areas from 1946 to 1992 within SNP East were obtained from the park. Finally, foliar injury data for 14 ponderosa pine plots collected during a 1985 field survey in SNP East were obtained from a national park service report (Duriscoe and Selph 1985).

Methods

This study's methods included examining historical ozone exposure levels at the western boundary of SNP East, examining antecedent moisture conditions in southeastern Arizona, estimating ozone levels at ponderosa pine areas in the Rincon Mountains, relating changes in a vegetation index (VI) from 1972 to 1986 with 1985 foliar injury values at ponderosa pine plots, and determining and explaining changes in VI values from 1972 to 1986 and from 1986 to 1992.

Examinations of Ozone Exposure Levels

Monthly SUM60 and W126 ozone levels were calculated for each summer month (April through September) at SNP East from 1982 to 1998. SUM60 is an ozone exposure index that is the sum of all hourly concentrations ≥60 ppb (parts per billion). W126 is a sigmoidally weighted exposure index that gives more weight to higher hourly average concentrations and less weight to less biologically effective concentrations. Hourly ozone concentrations were weighted with the following equation:

$$W_i = [1 + M{*}e^{-(A{*}C_i)}]^{-1}$$

where M and A were assigned values of 4403 and 126 ppm^{-1}, respectively. W_i is the weighting factor for concentration i, and C_i is the concentration of i (Lefohn and Runeckles 1987). Using the above values, minimal weight was given to values lower than 0.04 ppm, while maximum weight was given to values higher than 0.1 ppm. These indices are commonly used to quantify the impact of ambient ozone on vegetation damage (Lefohn and others 1988). Pearson product–moment correlation coefficients were used to determine if significant relationships exist between exposure levels and population totals from 1982 to 1998.

Average daily exposure levels were estimated for Mica Mountain (2620 m a.s.l.) by scaling the exposure levels at SNP East's continuous monitor, which is located in the valley on the fringe of the urban area. The scaling factor was estimated by calculating a ratio of exposure levels from April through September of 1997 acquired at two similar downwind environments in the Phoenix, Arizona, area. Fountain Hills (35 km northeast of Phoenix) and Mt. Ord (2180 m a.s.l. and 80 km northeast of Phoenix) were considered analogous to Tucson's SNP East monitor and Mica Mountain, respectively. Therefore, the scaling factor produced from the Mt. Ord-to-Fountain Hills ratio and the exposure levels at the SNP East monitor were used to estimate daily exposure levels at Mica Mountain.

Examinations of Multitemporal Satellite Data

Image Preprocessing. The three MSS scenes were tested and corrected for atmospheric path radiance (i.e., atmospheric scattering) of visible wavelengths with the iterative band ratioing procedure described by Crippen (1989) and Patterson and Yool (1998). Basically, this procedure examines the ratio of visible to near-infrared reflectance with respect to shadows. Digital numbers were subtracted from the visible band until shadows in the visible/near-infrared ratio image disappear (Patterson and Yool 1998).

Considerable masking (i.e., exclusion) of pixels within the images was performed before image analyses were conducted. All areas that either had burned or were obscured by clouds or cloud shadows were excluded from analysis. Analyses were further confined to forest-covered, ponderosa pine pixels within the national park. Forest-covered pixels included all pixels except those with normalized difference vegetation index (NDVI) values in 1972 less than 1 standard deviation below the mean of all NDVI values within the national park. The NDVI is similar to the simple VI, for it is the ratio of near-infrared minus red reflectance divided by the sum of near-infrared and red reflectances. This additional procedure helped to exclude pixels with recently burned vegetation, pixels with large proportions of exposed rock, and pixels that might have been misclassified as ponderosa pine areas. Finally, pixels classified as "ponderosa pine" in the GAP vegetation database were identified and the non-ponderosa pine pixels were subsequently discarded from the study.

Image Analyses. Since a major factor affecting forest vigor is available moisture, time series of antecedent summer (April through September) PHDI and winter (November through February) precipitation were constructed so that observed variations in moisture availability could assist in explaining major spectral differences between the three dates. The PHDI has been found to be highly positively correlated with ponderosa pine growth in the Front Range of the Colorado Rocky Mountains during the summer months (Peterson et al. 1993), while in the southern Sierra Nevadas, winter (October through March) precipitation is an important variable related to Jeffrey pine growth (Peterson and others 1987). Differences in growing-season PHDI and lagged (previous two winters) wintertime precipitation totals in southern Arizona among the three dates were examined with Mann–Whitney U tests. The Mann–Whitney U test is a nonparametric test for testing hypotheses about whether two samples differ.

Uni- and multitemporal variations of the aforementioned simple VI were examined. Manipulations of VI values were intended to facilitate links between forest stress and the two stress factors (moisture and ozone). Comparisons were made between 1972 to 1986 VI changes and results from the 1985 field survey of ozone damage to verify the link between ozone damage and VI changes. Since most of the 14 plots were not located in "pure" ponderosa pine areas (as determined from the GAP vegetation database), these comparisons were not limited to ponderosa pine pixels. Mann–Whitney U tests involving the top four injury plots and bottom four injury plots were used to determine whether evidence existed for VI changes being associated with foliar injury. Finally, for the TV/WMica and EMica areas, VI values were calculated for 1972, 1986, and 1992, while VI differences were calculated for the 1972 to 1986 and 1986 to 1992 time periods. Student's t tests, which are parametric tests for comparing the means of two groups, were used to test for differences between pixel values at TV/WMica and those at EMica.

Results

Historical Variations in Ozone Exposure Levels at SNP East

Ozone exposure levels generally increased from 1982 to the late 1990s (Figures 3 and 4). Substantial month-to-month changes in exposure levels result primarily from the strong influence of meteorological conditions on peak ozone concentrations (Rao and

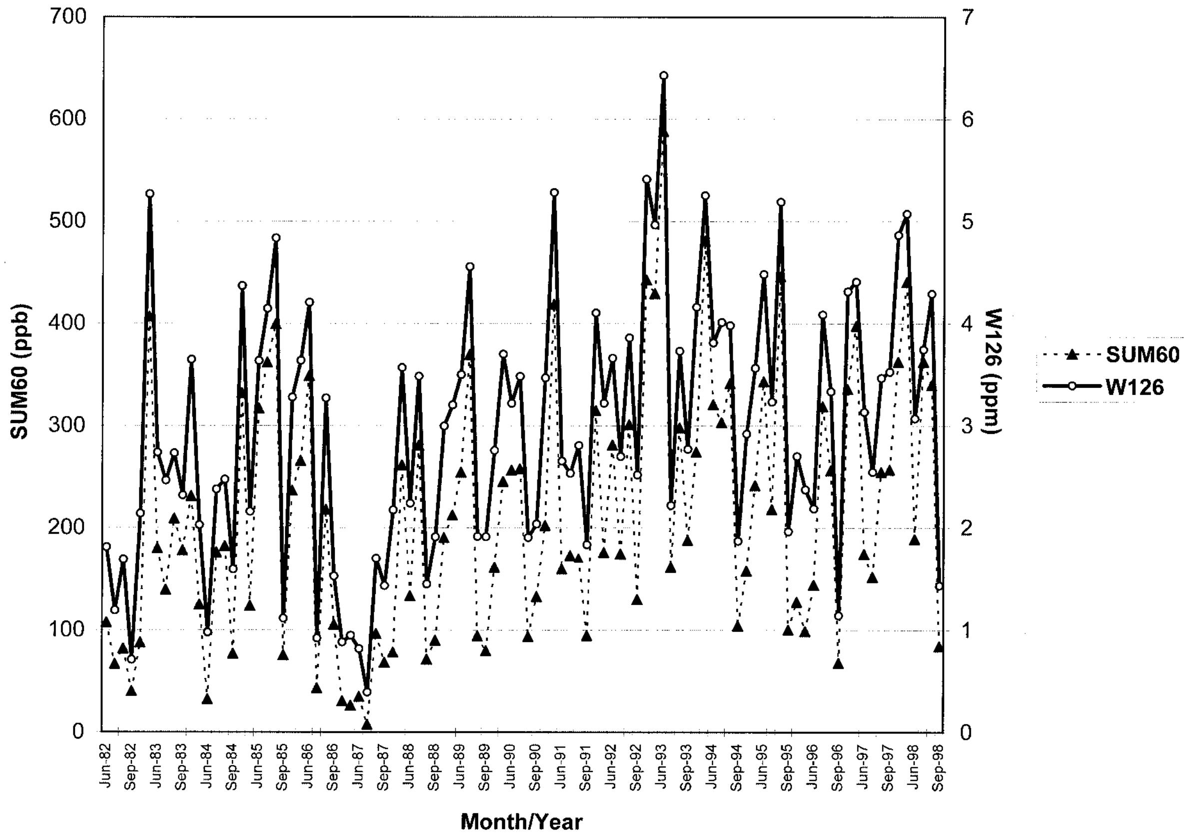

Figure 3. Time series of month-specific, average daily ozone exposure levels (SUM60 and W126) from 1982 to 1998 at Saguaro National Park East's continuous ozone monitor. Levels are presented only for months within the ozone season (April through September).

others 1991). Nevertheless, seasonal SUM60 and W126 levels were significantly correlated ($r = 0.49$ and 0.53, $\alpha = 0.05$) with annual population totals in the Tucson area. Although data for SNP East were not collected prior to 1982, one can infer from the above correlations that ozone exposure levels during the late 1960s and early 1970s were considerably lower than those during the 1980s and 1990s. Although the photochemistry of ozone production is complex, it also likely that exposure levels will continue to increase as the population increases; the population is predicted to exceed 1 million persons by 2010 (PAG 1996).

Estimated Ozone Exposure Levels at Mica Mountain

In several western U.S. areas, upslope flows (i.e., anabatic winds) are thought to be an important mechanism whereby pollutants can be transported from source areas into forests and wilderness areas located in mountainous terrain (e.g., transport of pollutants from the San Joaquin Valley to the Sierra Nevadas) (King et al. 1987). Consequently, peak ozone concentrations can occur at significant downwind distances (i.e., 30 to 150 km) from emission source areas (Seinfeld 1989, Imhoff et al. 1995).

The Phoenix area is no exception, for Mt. Ord has ozone exposure levels that are approximately twice as high as exposure levels at Fountain Hills. Average daily SUM60 values at Mt. Ord and Fountain Hills are approximately 540 and 210 ppb, respectively, while average daily W126 values are 6.1 and 3.2 ppm, respectively. Mt. Ord's exposure level is equivalent to levels found in the central Sierra Nevadas and southern Appalachian Mountains (Lefohn 1992), which are two areas in the United States where substantial ozone-related vegetation damage has occurred.

Similar to the Phoenix area, the Tucson area's mountain-valley circulation should also be conducive to the transport of pollution eastward from the Tucson urban area to downwind, forested areas such as Mica Mountain. Since Fountain Hills and Mt. Ord are analogous to the SNP East monitor and Mica Mountain, it seems logical that ozone exposure levels at Mica Mountain should be about twice as high as levels measured at the SNP East monitor, which are approximately 250

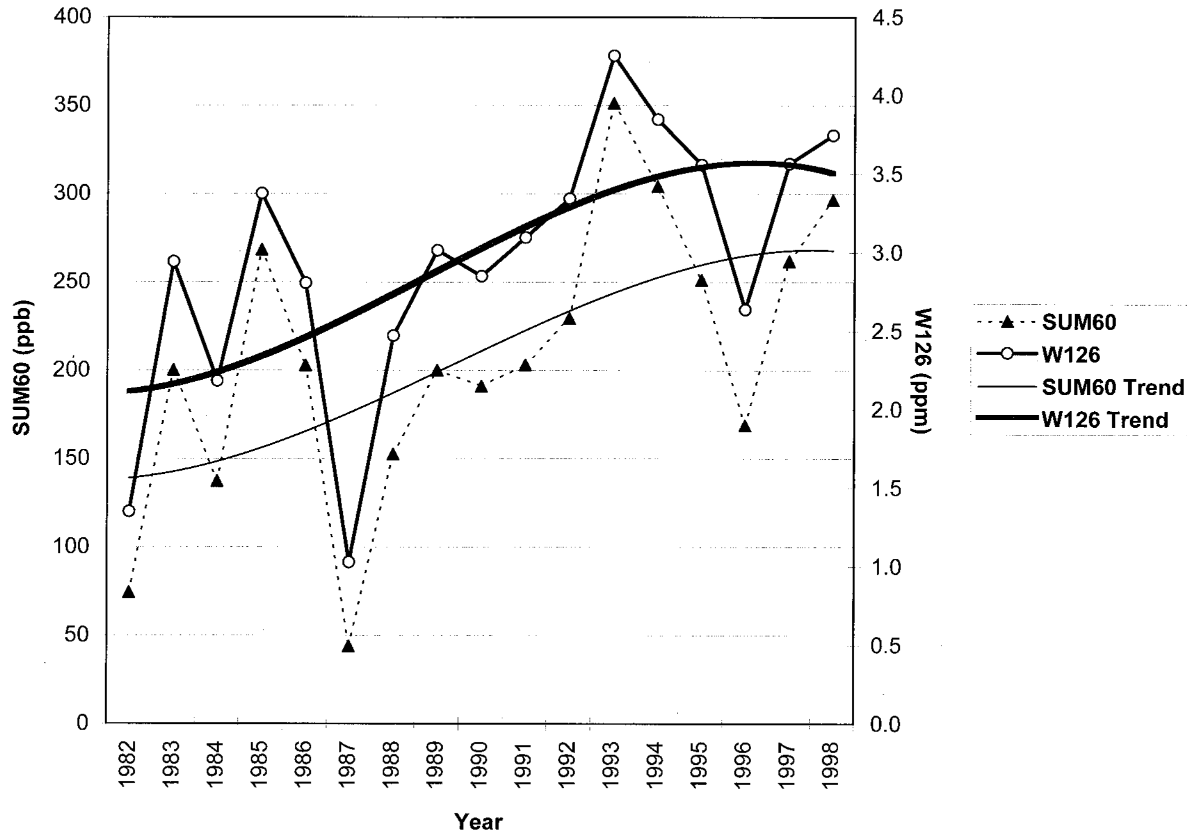

Figure 4. Time series of season-specific, average daily ozone exposure levels (SUM60 and W126) from 1982 to 1998 at Saguaro National Park East's continuous ozone monitor.

ppb and 3.6 ppm for SUM60 and W126, respectively. By applying this logic, the average daily SUM60 and W126 values at Mica Mountain might approach 500 ppb and 7.2 ppm, respectively. Levels of this magnitude should damage sensitive species such as ponderosa pine. In fact, ozone exposure levels in the Rincon Mountains during the mid-1980s were high enough to cause noticeable damage to the needles of ponderosa pines (Duriscoe and Selph 1985).

Atmospheric Correction and Masking

Although the MSS scenes contained negligible atmospheric path radiance based on results from the iterative band ratioing procedure and thus were not atmospherically corrected, an extensive amount of masking resulted in two optimal change detection areas (Figure 1). These areas presumably contain pixels that are unburned, highly vegetated, and dominated by ponderosa pine. The two areas are as follows.

(1) Tanque Verde Ridge and the western side of Mica Mountain (TV/WMica); the mean elevation is ~2200 m a.s.l.

(2) The eastern side of Mica Mountain (EMica); the mean elevation is ~1900 m a.s.l.

Based on results from a viewshed analysis using a DEM, most of the TV/WMica pixels are exposed to the Tucson metropolitan area and its air pollution plume. Even though not all pixels are exposed directly to the plume, upslope winds can transport pollutants deep within the forests (Miller and others 1986). EMica pixels are not exposed directly to the pollution plume. Therefore, ozone exposure levels should have been higher at TV/WMica than at EMica, and thus more ozone-induced foliar injury should have occurred at TV/WMica. TV/WMica was assumed to be the "symptomatic" (i.e., test) site, while EMica was assumed to be the "asymptomatic" (i.e., control) site.

Antecedent Climate Conditions

Antecedent moisture availability differs considerably among the three acquisition dates. Drought conditions during the growing season (April to September) varied from moderate drought-like conditions in 1972 to severely wet conditions in 1986 and 1992 (Figure 5). Both

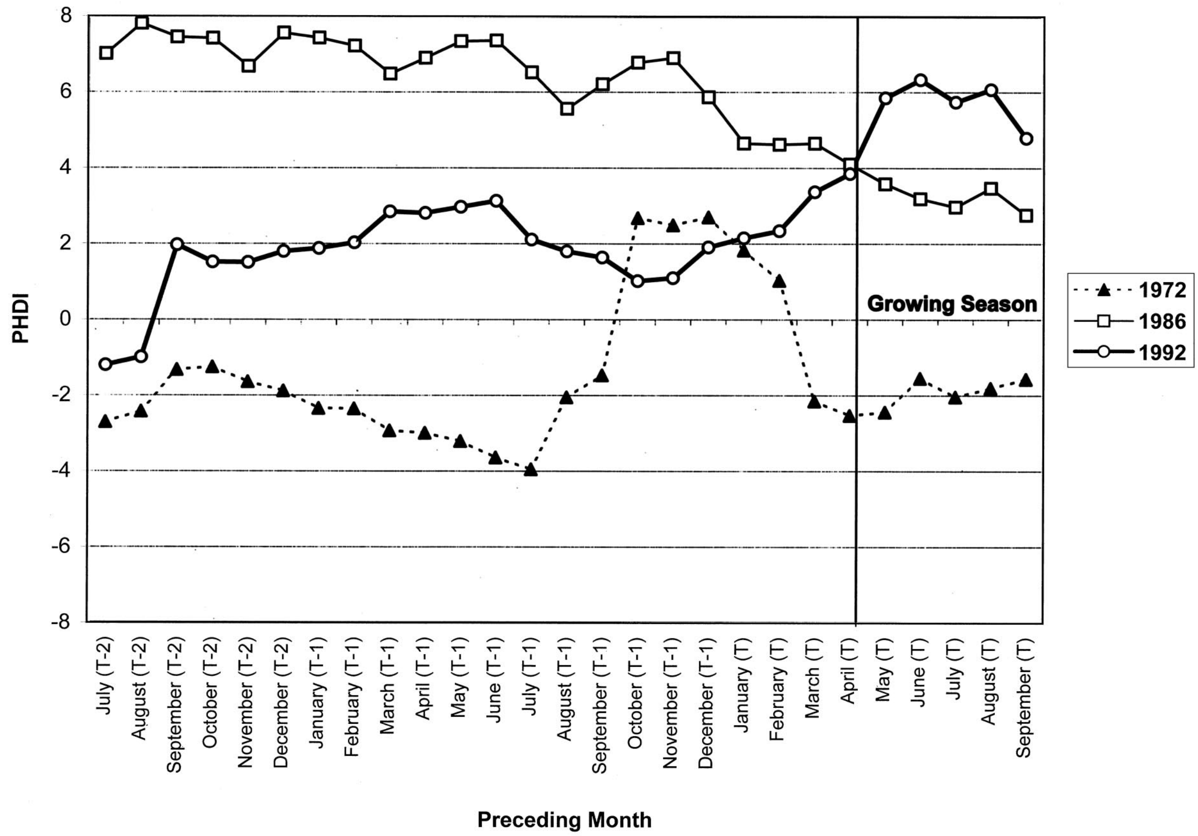

Figure 5. Time series of monthly PHDI values preceding late September/early October, the time of image acquisition.

Table 1. Summer PHDI values and winter precipitation totals (mm) preceding the image acquisition dates

Year	Summer PHDI	Winter precipitation[a]	
		T-1	T
1972	−2.0	35	64
1986	3.3	198	105
1992	5.4	152	176

[a]T is the winter directly preceding the image acquisition date; T-1 is the winter before the directly preceding winter.

1986 and 1992 were significantly ($\alpha = 0.05$) wetter than 1972, while 1992 was significantly wetter than 1986. Both 1986 and 1992 had substantially larger antecedent winter precipitation totals than did 1972 (Table 1). Comparisons of summer-season PHDI values and winter-season precipitation totals suggest that ponderosa pines in the Rincons had the most available moisture in 1992 and the least available moisture in 1972. Consequently, by assuming all other factors to be equal among the three time periods, the smallest and largest VI values for the ponderosa pine pixels should occur in 1972 and 1992, respectively.

Vegetation Index Changes at 1985 Ozone Damage Survey Plots

In 1985, researchers examined ponderosa pines in SNP East for air pollution injury. All of the 225 trees examined exhibited some form of chlorosis, which was interpreted as representing ozone-induced foliar injury (Duriscoe and Selph 1985). Comparisons of foliar injury data from 14 plots with plot-specific VI changes from 1972 to 1986 has revealed a significant ($\alpha = 0.1$) relationship between percentage foliar injury (i.e., percentage of total leaf affected) and change in VI. Larger foliar injury values were associated with a reduced increase in green leaf biomass from 1972 to 1986 (Figure 6). These survey-based results established a link between foliar injury and VI changes.

Multitemporal VI Values and Changes at the TV/WMica and EMica

VI values at the two sites increased from 1972 to 1986 and from 1986 to 1992 (Table 2). This increase appears to have been caused by an increase in moisture availability. If antecedent moisture conditions had been

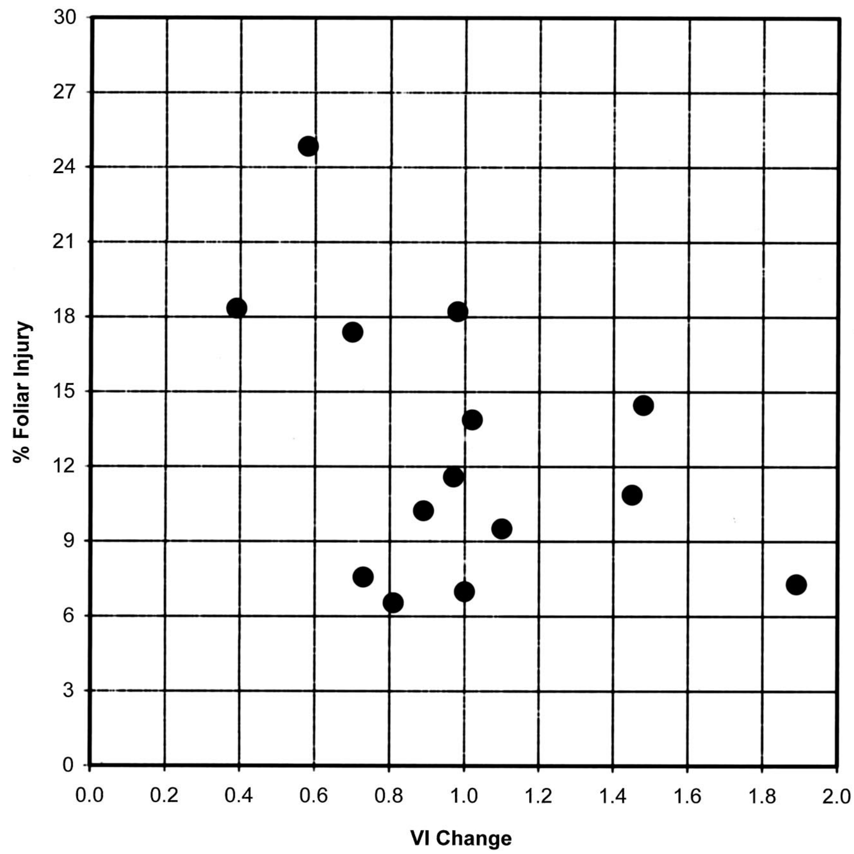

Figure 6. Plot of plot-specific changes in VI values from 1972 to 1986 versus 1985 foliar injury values.

Table 2. Average VI values, percentage changes in values between the years, and total number of pixels at TV/WMica and EMica[a]

	VI		% change		n	
Year	TV/WMica	EMica	TV/WMica	EMica	TV/WMica	EMica
1992	2.36	2.39	3.4	6.1	694	549
1986	2.28	2.25	44.2	57.2	596	525
1972	**1.58**	**1.43**			701	579

[a]Values in boldface are significantly ($\alpha = 0.05$) different from each other.

nearly identical for all three dates, an ozone-related decrease in VI values might have been expected, especially from 1972 to 1986.

There are, however, significant differences in VI changes between TV/WMica and EMica. In 1972, VI values at TV/WMica were significantly ($\alpha = 0.05$) larger than those at EMica. From 1972 to 1986 and from 1986 to 1992, TV/WMica had significantly ($\alpha = 0.05$) less "green-up" (i.e., smaller increase in VI values) compared to EMica (Table 3). As a result, in 1986 and 1992, VI values at the two sites were approximately equal. The "greenness" gap between TV/WMica and EMica that existed in the 1970s diminished and re-

Table 3. Average VI differences between 1972 and 1986 and 1986 and 1992 at TV/WMica and EMica, along with the total number of pixels involved in the differencing

	VI difference[a]		n	
Years	TV/WMica	EMica	TV/WMica	EMica
1972–1986	0.09	0.14	576	523
1986–1992	0.69	0.82	585	532

[a]Differences at TV/WMica and EMica are significantly (α=0.05) different from one another.

versed by the early 1990s. In 1992, EMica might have actually had, on average, more green leaf biomass than did TV/WMica.

Discussion and Conclusions

This paper has illustrated the benefits of integrating multitemporal satellite data, ozone exposure levels, and past field surveys to assess ozone-induced foliar injury in the Rincon Mountains of southern Arizona. Spatiotemporal variations in VI values have been examined with respect to climate variations and temporal trends in ozone levels to uncover evidence of injury in ponderosa pine areas. This research has uncovered significant changes in VI values from 1972, 1986, and 1992 and has associated those changes with measured foliar injury values and expected ozone exposure levels.

Several converging lines of evidence point toward the strong likelihood of increases in ozone-induced foliar injury from 1972 to 1992 at ponderosa pine areas in the Rincons, especially sites on Tanque Verde Ridge and western Mica Mountain. A 1985 survey of ponderosa pines, where all trees were found to have ozone-induced foliar injury (Duriscoe and Selph 1985), supports the view that presumed ozone levels in the Rincons are high enough to cause noticeable foliar injury to ponderosa pines. In addition, dendroclimatological research has shown that actual growth from 1951 to 1986 of 7 of 15 coniferous forest stands in southern Arizona mountains was significantly lower than the predicted growth for the 35-year time period (Graybill and Rose 1992). This anomalous growth may be related to ozone exposure levels resulting from the expansion of the Tucson area.

Examination of the 1985 field survey data also produced a plausible association between foliar injury and changes in VI values. Larger foliar injury values were associated with a smaller overall increase in VI values from 1972 to 1986. Using this relationship and the general rule that ozone levels in areas exposed to pollution plumes are usually higher than levels in nearby relatively protected areas (Williams and others 1977, Peterson and others 1987, Ray 1998), VI values at an exposed area (TV/WMica) were found to have increased at a slower rate compared to those at a protected area (EMica). The reduced increase in "green-up" may have been caused partially by ozone-induced foliar injury and subsequent decreases in green leaf biomass. However, one cannot overlook the strong possibility that spatial differences in VI values may also have been caused by a number of other factors including other forms of human disturbance, natural competition, fine-scale climate variations, insect infestation (e.g., western pine bark beetle), fungus, and chemical deficiencies or excesses.

This paper's results reveal the strong possibility of distinct, topographically based, spatial variations in ozone-induced foliar injury within the Rincons as well as a worsening of foliar injury from the early 1970s to the early 1990s. If the results are correct, substantial ozone precursor reduction measures are needed to protect and improve forest health in the region. This policy issue is related directly to the split between NO_x-sensitive (i.e., ozone concentrations increase with increasing ambient NO_x concentrations) rural areas and VOC-sensitive (i.e., ozone concentrations increase with increasing ambient VOC concentrations) urban areas, since evaluations of ozone policy based on human exposure, rather than forest exposure, are more likely to favor VOC controls (Sillman 1999). This is the case in the Tucson area, where most humans inhabit VOC-sensitive areas, while coniferous forests exist in NO_x-sensitive areas. In fact, the western boundary of SNP East is almost always NO_x-sensitive (Diem 2000). Therefore, reducing peak ozone concentrations in the Rincons involves NO_x controls. Paradoxically, those same controls might actually increase exposure levels in the populated, urban areas. As can be discerned from above, reducing ozone exposure levels is a complicated policy issue.

Air quality policy decisions in the Tucson area need to consider the protection of both human health and forest health. Unfortunately, ozone concentrations are not monitored in the Rincons and Santa Catalinas. Therefore, high ozone concentrations, which might actually exceed the federal standard, are not recognized. In addition, limited foliar injury data have been collected within these mountains. More research is required before any concrete conclusions can be made regarding the relationship between ozone pollution and ponderosa pine injury in the Rincons and the Santa Catalinas. Future work might involve the establishment of ozone passive sampling networks in ponderosa pine areas as well as multidate, image-based, change classifications (using higher spatial satellite imagery such as Landsat Thematic Mapper) and subsequent field surveys to quantify foliar injury and other forms of disturbance. Resulting information is needed to determine the magnitude and spatial patterns of ozone-induced foliar injury, information that could influence policy decisions regarding ozone reduction in the Tucson region.

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