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Assessment of vegetation regeneration after fire through multitemporal analysis of AVIRIS images in the Santa Monica Mountains

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Abstract

Spectral mixture analysis (SMA) from Airborne Visible/Infrared Imaging Spectrometer (AVIRIS) was used to understand regeneration patterns after fire in two semiarid shrub communities of the Santa Monica Mountains, California: northern mixed chaparral and coastal sage scrub. Two fires were analyzed: the Malibu Topanga fire (3 November 1993) and the Calabasas fire (21 October 1996). SMA was compared to the results of the Normalized Difference Vegetation Index (NDVI) to assess vegetation recovery. An unburned control plot (within the past 20 years), having similar environmental features, was used to generate two relative fire regeneration indices, Regeneration Index (RI) and Normalized Regeneration Index (NRI). Indices were calculated using the Green Vegetation (GV) endmember and the NDVI. These indices were determined to be largely independent of AVIRIS radiometric calibration uncertainty, minor errors in the atmospheric correction, topographic distortions, and differences in the phenological state of the vegetation because of interannual or seasonal differences. The temporal evolution of the two fires were combined to produce a longer observation period and used to fit a logarithmic regression model for each Mediterranean shrub community. The NRI developed from the GV endmember (NRI_{GV}) produced the closest estimate for the time of recovery in both communities based on recovery times in the literature. The use of NDVI worked very well for recovery in the northern mixed chaparral, but was less successful in the coastal sage scrub, mainly because of extensive herbaceous cover during the first years of the regeneration process. Endmembers generated from hyperspectral images were more accurate because they are tuned to capture the greenness of the shrub type of vegetation. Use of matching plots having similar environmental features, but which were burned in different years were demonstrated to improve estimates of the recovery within each community.

1. Background

Wildfires create profound changes in the structure and functioning of natural ecosystems. The semiarid shrub communities of Mediterranean climates are fire adapted, and California chaparral is one of the most susceptible to frequent fires (Hanes, 1988). In recent years, the fundamental role of fire in maintaining ecosystem function has been recognized, which has led to subsequent concern about the consequences of human impacts in altering the natural cycle of wildfire disturbance. Monitoring postfire regeneration is important to understand the need for future prescribed burns, to establish postfire resource management, and to design revegetation programs to reduce soil erosion (Keeley, 2000).

The development of high spatial resolution remote sensing instruments, both airborne and spaceborne, has provided an opportunity to evaluate patterns of vegetation recovery after wildfire. Several remote sensing studies have

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addressed the recovery of the vegetation after fire. The Normalized Difference Vegetation Index (NDVI) is the most widely used tool to assess the process of recovery after fire (Díaz-Delgado et al., 1998; Fiorella & Ripple, 1993; Henry & Hope, 1998; Jakubauskas, Lulla, & Mausel, 1990; Kushla & Ripple, 1998; Ricotta, Avena, Olsen, Ramsey, & Winn, 1998; Viedma, Meliá, Segarra, & Garcia-Haro, 1997; White, Ryan, Key, & Running, 1996). Other indices that have been tested include the normalized difference between Landsat Thematic Mapper bands TM4 and TM5 (Marchetti, Ricotta, & Volpe, 1995), the Structural Index (TM4/TM5) (Fiorella & Ripple, 1993; Kushla & Ripple, 1998), the Soil Adjusted Vegetation Index (SAVI; Henry & Hope, 1998), and the Tasseled Cap transformation (Fiorella & Ripple, 1993; Kushla & Ripple, 1998).

Marchetti et al. (1995) analyzed vegetation recovery by visual assessment. Other authors have assessed not only changes in vegetation indices after the fire (Fiorella & Ripple, 1993), but differences in the indices before and after the fire (Kushla & Ripple, 1998; Viedma et al., 1997; White et al., 1996). Kushla and Ripple (1998) also considered the quotient and the normalized difference in the vegetation index before and after fire.

Spatial analysis has been used to understand the recovery after a fire. Ricotta et al. (1998) used a fractal algorithm (textural analysis of NDVI) to assess recovery in terms of changes in landscape stability. Viedma, Meliá, and Chica-Olmo (1999) used a geostatistical approach and analyzed the semivariogram of TM5 within the burned site to measure changes in homogeneity.

The study of recovery after fire using multitemporal analysis requires atmospheric normalization of the image data, a step that has been included in the image analysis by almost every author. Viedma et al. (1997) also applied a topographic normalization. But these corrections may still be insufficient in accounting for measurement and environmental effects that are external to the changes due to the wildfire. Henry and Hope (1998) even questioned whether remote sensing can be used to study ecosystem recovery after fire. Many authors have described a wide range of noise factors that reduce the detection of regeneration patterns, including radiometric calibration uncertainty, errors in the atmospheric correction, topographic effects and shifts in the phenological state of the vegetation between data acquisitions due to interannual or seasonal climate differences. Díaz-Delgado et al. (1998) use control sites located in the same images, but not affected by fire to solve this problem. Their criteria for the control sites include similar environmental conditions and vegetation, ideally located adjacent or close to the burned sites. They used the following Regeneration Index (RI) to correct for external influences (Eq. (1)):

$$\mathrm{RI}_{\mathrm{NDVI}} = \frac{\mathrm{NDVI}_{\mathrm{fire}}}{\mathrm{NDVI}_{\mathrm{control}}} \qquad (1)$$

The temporal evolution of vegetation recovery interpreted from remote sensing data has been validated with aerial photography and field studies (Kushla & Ripple, 1998), in which the values of different indices produced from the images were correlated to increased vegetation cover due to regeneration. Shaw, Malthus, and Kupiec (1998) also correlated hyperspectral field measurements to increased vegetation cover. Other authors have searched for a relationship between the remotely sensed indices and the time elapsed since the fire to estimate the period of recovery, principally by using a logarithmic regression model (Díaz-Delgado et al., 1998; Fiorella & Ripple, 1993; Viedma et al., 1997). If the time since the wildfire is known from other sources, the remotely sensed estimation of vegetation recovery can be validated. Availability of GPS to map fire scars has increased knowledge of locations of specific wildfires.

The most widely used high spatial resolution sensor to study the regeneration after fire has been Landsat TM. Some studies have used SPOT-XS (Henry & Hope, 1998) and SPOT-multispectral (French et al., 1996). Hyperspectral sensors have not been extensively used for this purpose; however, for example, Shaw et al. (1998) studied regeneration in Scots pines with a high-resolution field spectroradiometer and Ustin and Xiao (2001) studied forest communities in central Alaska using NASA's Advanced Visible/Infrared Imaging Spectrometer (AVIRIS). Hyperspectral sensors have been demonstrated to be useful in change detection and have been shown to detect temporal changes in vegetation (Elvidge & Portigal, 1990; Gamon et al., 1995; Roberts, Green, & Adams, 1997; Roberts et al., 1998; Roberts, Green, Sabol, & Adams, 1993; Ustin, Roberts, & Hart, 1999; Ustin et al., 1998).

Most remote sensing fire recovery studies have been conducted in environments with Mediterranean climates (Díaz-Delgado et al., 1998; Henry & Hope, 1998; Jakubauskas et al., 1990; Marchetti et al., 1995; Ricotta et al., 1998; Viedma et al., 1997, 1999). Wildfires are an essential component of the ecology of semiarid shrub and savanna communities, which are adapted to frequent burning.

2. Objectives

The objectives of this study were the following.

(1) To assess the usefulness of hyperspectral remote sensing data to characterize the regeneration process.

(2) To compare the effectiveness of hyperspectral endmembers versus NDVI to detect changes in vegetation due to the recovery process.

(3) To understand regeneration after fire in two chaparral shrub communities, coastal sage scrub, and northern mixed chaparral, which are well adapted to fire events.

(4) To study the evolution of plant community regeneration over a longer period of time than the period covered by

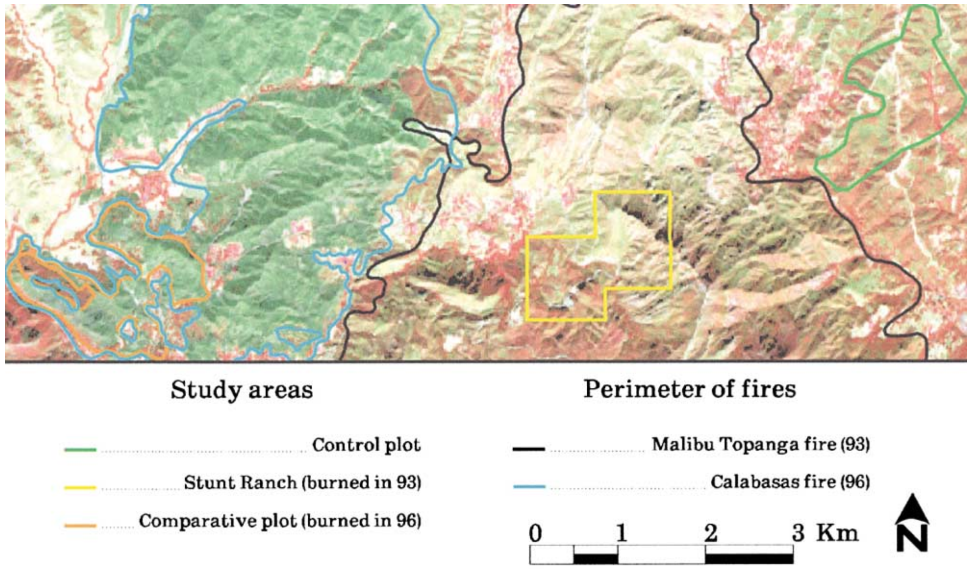

Fig. 1. AVIRIS image, 23 October 1996. Color composition (894, 1464, 675 nm displayed as red, green, blue, respectively). Overlaying the image are the perimeters of the Calabasas and Malibu-Topanga fires, and the perimeters of the three study areas: Stunt Ranch, burned in 1993, the comparative plot burned in 1996, and the control site, unburned at least in the last 20 years.

the remote sensing images, we substituted space for time. This was done by comparing two fires of different ages with control sites (places not burned in the past 20 years). The two fires (Stunt Ranch and comparative site) originated in different years but are in the same plant community and have similar environmental features.

3. Methodology

3.1. Study area

The sclerophyllous California chaparral communities are maintained by the Mediterranean climate, in which precip-

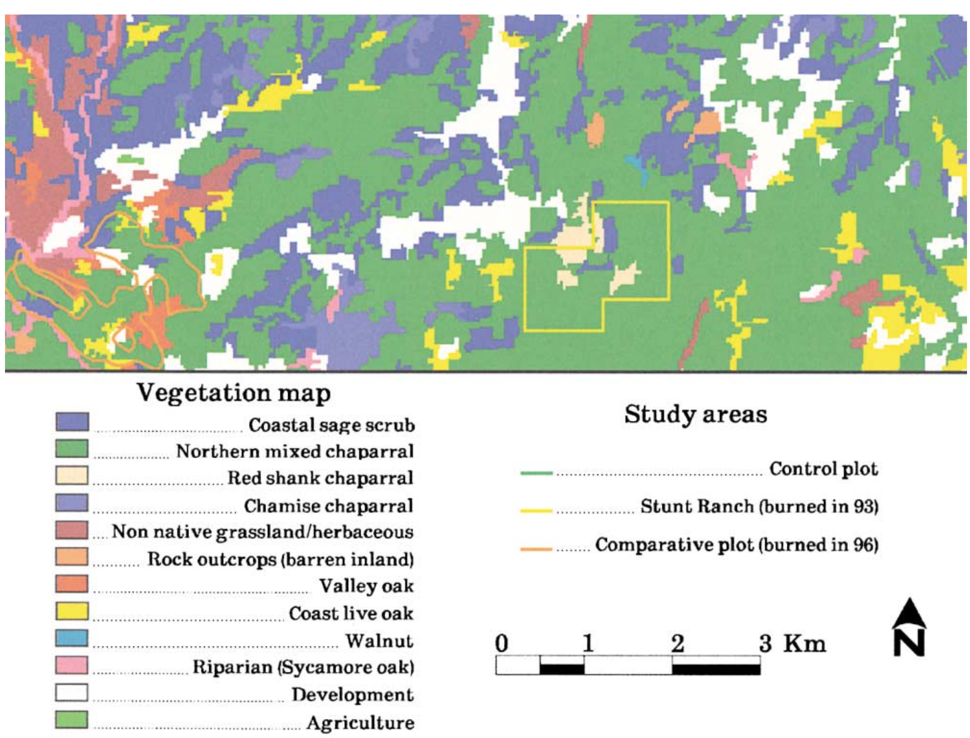

Fig. 2. Vegetation map and study areas.

itation is restricted to the winter months of plant dormancy and the active growing season continues throughout the long, hot, and dry summers (May–November). During summer drought, vegetation flammability is very high, providing a ready source for ignition. The total precipitation and timing of rainfall in moderate winters can even be more important in contributing to fire occurrence, because periods of higher rainfall contribute to greater biomass accumulation for fuel and denser scrub cover to carry fires over extensive areas (Keeley, Keeley, Hutchinson, & Johnson, 1981).

We selected two chaparral shrub communities for our study, coastal sage scrub, and northern mixed chaparral. These types are commonly present in the Santa Monica Mountains, California, an east–west trending range located on the southern California coast and forming a northern boundary for the city of Los Angeles. These communities are widespread in the Mediterranean climate of California and both recover rapidly after fire. An important characteristic of these types of Mediterranean communities is that the shrub cover increases annually until it reaches the density of mature stands. Ultimately, given sufficient time for recovery, plant density and cover is limited by available soil water (Hanes, 1988). Herbaceous cover is sparse, and only abundant during a brief period after fire before shrubs become reestablished (Keeley & Keeley, 1981; Keeley et al., 1981; Rundel & Parsons, 1979; Trabaud, 1987). Therefore, these communities do not follow clearly defined successional stages. Frequent wildfires maintain shrub dominance in these communities. If fires are too frequent, type conversion can occur by depletion of the seed bank and plant stress.

Several distinct communities of chaparral are found in the Santa Monica Mountains that differ in biomass accumulation, flammability, and recovery patterns (Hanes, 1988). However, all chaparral have a high susceptibility to fire and fire plays a major role in ecosystem functioning. Wildfire return frequencies have been estimated to be 10–40 years (Muller, Hanawalt, & McPherson, 1968; Keeley, Fotheringham, & Morais, 1999). Within the past few years, a large number of fires have occurred within the Santa Monica Mountains due to an active policy of fire suppression, nonremoval of accumulated dead fuels, and the extended drought of 1987–1993. Also, prescribed burns can be conducted on only a few days each year (Radtke, Arndt, & Wakimoto, 1982), limiting the potential to control wildfires using this strategy.

The regeneration process in this habitat was studied through the analysis of three test sites located in the University of California Los Angeles' Stunt Ranch Santa Monica Mountains Reserve, a Natural Reserve of the University of California (http://nrs.ucop.edu/reserves/stunt. html). Paired plots between Stunt Ranch and another recently burned plot (comparative plot) provided a comparison to the control (unburned) site, adjacent to the Stunt Ranch (see Fig. 1). These plots were selected to provide a time series for change detection. The Stunt Ranch area was burned by the Malibu-Topanga fire (6890 ha, 3 November 1993). The Calabasas fire (5270 ha), used for the comparative plot was burned 3 years later (21 October 1996), and a control plot free of wildfire, for at least the last 20 years were selected.

The coastal sage scrub and northern mixed chaparral communities that grow at the Stunt Ranch were analyzed (see Fig. 2). Coastal sage scrub is a drought deciduous community in which 33% species are evergreen (Mooney, 1988). It occupies drier sites and has sparser shrub density and lower total plant cover than northern mixed chaparral. The common species present are sages (*Salvia apiana*, *S. leucophylla*, and *S. mellifera*), Californian sagebrush (*Artemisia californica*), eriogonum (*Eriogonum cinereum*, *E. elongatum*, and *E. fasciculatum*), bush sunflower (*Encelia californica*), and herbs (e.g., *Lotus*, *Lupinus*, and *Mimulus*) (Sawyer & Keeler-Wolf, 1995). Sage species have relatively shallow roots, active growth is shifted to winter and spring, and plants remain inactive during the dry periods. Most woody sage species regenerate quickly after the fire because of root-crown-sprouting (McAuley, 1996). During the first years after fire herbaceous cover appears, coastal sage scrub reaches its maximum vegetation cover about 5 years after fire (O'Leary & Westman, 1988).

The northern mixed chaparral community, interior to coastal sage shrub, grows in more moist sites than coastal sage scrub. Species such as chamise (*Adenostoma fasciculatum*), various California lilacs (*Ceanothus* sp.), manzanita (*Artostophylos* sp.), scrub oak (*Quercus dumosa*), sugar bush (*Rhus ovata*), and toyon (*Heteromeles arbutifolia*) are common. This community is also well adapted to drought and fire and many species of shrub have the ability to crown-sprout (McAuley, 1996). Of the two most dominant species in northern mixed chaparral in the Santa Monica Mountains, *A. fasciculatum* sprouts and produces seedlings after fire (facultative seeder) (Moreno & Oechel, 1991) and *C. megacarpus* does not sprout after fire but germination is stimulated by fire (Montygierd-Loyba & Keeley, 1987). The regeneration process is slower in mixed chaparral than coastal sage scrub since the total amount of vegetation to be recovered is higher. In a first stage after fire, chaparral is colonized by many wind-dispersed sage species and some herbaceous species (Barro & Conard, 1991; McAuley, 1996). Northern mixed chaparral generally requires about 10–20 years to recover, but can withstand fire intervals as short as 10 years (Horton & Kraebel, 1955; Minnich & Bahre, 1995). More frequent fires can lead to type conversion.

3.2. Data set

The information layers used in this study were the following.

• NASA's hyperspectral instrument, the AVIRIS acquired scenes on five different dates (three in the fall and two in the spring):

19 October 1994: almost 1 year after the Malibu Topanga fire.

17 October 1996: immediately before the 3 November Calabasas fire.
23 October 1996: immediately after the 3 November Calabasas fire.
7 April 1997: a period of spring growth.
18 May 1998: a period of spring growth.

AVIRIS is an imaging spectrometer that collects spectra with a nominal wavelength sensitive range of 10 nm, over 224 spectral bands between 380 and 2500 nm. It is flown at an elevation of 20 km, collecting a cross track swath of 12.3 km, to give a ground instantaneous field of view of 20 m. A typical AVIRIS scene consists of 614 samples, and 512 lines, covering a 12.3 × 10.2 km area (http://makalu.jpl.nasa.gov/aviris.html). Two or three AVIRIS scenes of the same flight line were fused on each date in order to cover the entire study area of 206 × 550 pixels (4.1 × 11.0 km). Two scenes were fused for the 1996 and 1997 images and three for the 1994 and 1998 images.

• A spectral library was generated from field and laboratory measured spectra collected at the site and others in the Santa Monica Mountains region. For further details about data collection, see Roberts et al. (1998) and Ustin et al. (1998). Some of the endmembers used were reference endmembers extracted directly from AVIRIS image data.

• A regional vegetation map with a spatial resolution of 30 m that was generated in 1993, just prior to the Topanga Malibu fire, was used for validation. Dr. Janet Franklin (San Diego State University) produced the vegetation map using a spring 1993 Landsat TM image and high spatial resolution aerial photography, in cooperation with the National Park Service (http://www.nps.gov/gis/apps/samo/samo fmo.html) (see Fig. 2).

• A fire history GIS layer with the perimeters delineated for fires since 1925. These fires were originally mapped by the Los Angeles and Ventura County Fire Departments on USGS 7.5′ topographic quadrangles. Any area smaller than 40 ha was not mapped (http://atlas.sdc.ucsb.edu).

• A georeferenced 1993 SPOT-Pan image with a spatial resolution of 10 m.

• A Digital Elevation Model (DEM) with a horizontal spatial resolution of 30 × 30 m.

3.3. Selection of the test sites

The comparative burned plot and a control site at Stunt Ranch along with the Stunt Ranch burn site were selected to understand the regeneration process and took into account the following.

• The same communities exist in all plots. This was determined using the 1993 vegetation map resampled to 20 m to match the AVIRIS pixel resolution. Only pixels identified as composed of one of these two communities were selected within each plot.

• Plots are large enough to include the range of spectral variability within each community. All three coastal sage scrub plots (comparative plot, control site, and Stunt Ranch) were about 20 ha (500 pixels) in extent, while the three northern mixed chaparral plots were about 110 ha (2750 pixels).

• The regeneration process depends on interval of fire recurrence because some species will be eliminated from the site if the fire-free interval is less than the age to reach maturity (Pausas & Vallejo, 1999). Stunt Ranch was completely burned in 1993. The fire history data layer confirmed that this area had not been burned in the previous 20 years and has not burned since 1993. We verified that the comparative plot, burned in 1996, had not been burned in either the 20 years before or since 1996. Finally, the control plot was not burned during the past 20-year interval.

• Similar climatic conditions were assured, mainly in terms of precipitation, based on NOAA weather station records. Plots were at a similar elevation and distance from the Pacific Ocean. The distance between the plots ranged from 2 to 6 km. Average elevation was about 420 m at the Stunt Ranch and the unburned control plot, but 320 m for the plot burned in the Calabasas fire.

• Plots were at a similar distance to the Pacific Ocean and have some maritime haze distortion. All plots were located approximately 6 km from the Pacific Ocean.

• Plots have a similar slope and aspect to reduce topographic distortion in the AVIRIS images. This was calculated using the DEM resampled to 20 m. The average slope for the all plots and both communities was about 18°, and the aspect was predominantly west facing, especially for the coastal sage scrub.

3.4. Atmospheric correction

The AVIRIS data were radiometrically corrected to reflectance using the MODTRAN3 radiative transfer code, in which the atmospheric water vapor bands of AVIRIS were used to fit the model. The surface reflectance was determined by (Green, Conel, & Roberts, 1993; Roberts et al., 1997) (Eq. (2)):

$$\rho_\lambda = \frac{\pi(L_{t,\lambda} - L_{\mathrm{path},\lambda})}{F_{0,\lambda} T_{d,\lambda} T_{0,\lambda}} \tag{2}$$

where ρ_λ is the reflectance at wavelength λ; $L_{t,\lambda}$ is the upwelling radiance at the sensor; $L_{\mathrm{path},\lambda}$ is the path radiance; $F_{0,\lambda}$ is the exoatmospheric solar irradiance; $T_{d,\lambda}$ is the downwelling atmospheric transmittance; and $T_{0,\lambda}$ is the upwelling atmospheric transmittance.

3.5. Geometric correction

The geometric correction of the AVIRIS images was accomplished using the SPOT-Pan image. The SPOT image had been previously georeferenced, and resampled to 20 m to match the spatial resolution of AVIRIS scences. At least 100 tie points were used per scene. The thin plate splines mathematical model was used to compute the warping transformation, which is calculated based on a set of tie points, but is always exactly fit at each of the tie points (PCI, 1997). The aircraft has a different displacement when each flightline is acquired so a polynomial approach can not be used, as the polynomical model computes a unique function for the entire scene. Nearest neighbor resampling was used in order to preserve the original spectral values.

3.6. Spectral mixture analysis (SMA)

SMA has been used to measure changes in vegetation cover (Garcia & Ustin, 2001; Roberts et al., 1993), and was used here to model the AVIRIS reflectance data. Each pixel spectrum is understood to be a mixture or a linear combination of pure spectra. These pure spectra, or endmembers, in different proportions can reproduce all or most of each pixel's spectrum (Adams et al., 1993). Eq. (3) was used to compute SMA (Shimabukuro & Smith, 1991):

$$\rho_{i,j,\lambda} = \sum_{k=1}^{N} F_{i,j,k}\rho_{k,\lambda} + \varepsilon_{i,j,\lambda} \tag{3}$$

where $\rho_{i,j,\lambda}$ is the reflectance at the locations i, j and wavelength λ; $F_{i,j,k}$ is the weight factor for each endmember k; $\rho_{k,\lambda}$ is the reflectance of each endmember k in the wavelength λ; $\varepsilon_{i,j,\lambda}$ is the residual term for each wavelength λ. The constraints used in the model were (Eq. (4)):

$$0 \leq F_{i,j,k} \leq 1 \text{ and } \sum_{k=1}^{N} F_{i,j,k} = 1 \tag{4}$$

This constraint produces two restrictions, where the weight of each endmember must be a value between 0 and 1, and all of them must add to 1. This creates endmember fractions and total cover that are physically realistic.

Different land cover types require a different number of endmembers to model the measured reflectance. A forested ecosystem might be best described as a mixture of two endmembers, green leaves and shade, while a shrubland may require four endmembers (Roberts et al., 1998). The endmembers used for this study were Green Vegetation (GV), Nonphotosynthetic Vegetation (NPV), Soil, and Shade. The specific endmembers (see Fig. 3) selected (using a threshold root mean squared [RMS] criteria) were:

- Spectrum of green leaves of *Ceanothus oliganthus* for GV.
- Spectrum of stems of *Erigonum cinereum* for NPV.
- Bare soil spectrum extracted from an AVIRIS pixel.
- Shadow was simulated to be spectrally flat, equal to zero reflectance across the spectrum.

The same endmembers were used in all images to ensure spatial and multitemporal comparability among AVIRIS images.

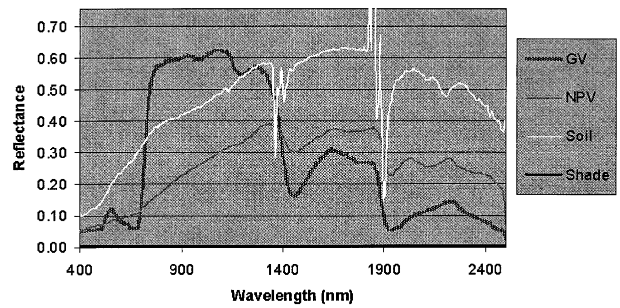

Fig. 3. Reflectance spectral of the endmembers, GV, NPV, Soil, and Shade used in this study. Note that the soil spectrum was extracted from an AVIRIS image. The sharp spikes are due to noisy bands in atmospheric water absorption windows (~ 1400 and 1900 nm).

SMA was performed, using the four endmembers: GV, NPV, Soil, and Shade, on 180 AVIRIS bands, once noisy bands and those in atmospheric water absorption windows were eliminated. RMS residuals were obtained to determine how well the endmembers modeled the AVIRIS spectra data. The RMS represents the extent to which the reflectance contributed by all endmember fractions match the measured spectrum for each pixel. The RMS for all images averaged 0.014 in our study areas, with a S.D. of 0.005. The largest errors were for the 23 October 1996 image (RMS = 0.019, S.D. = 0.007).

3.7. NDVI

The NDVI has been widely used in vegetation studies to assess regeneration and change detection processes. It was computed to provide a comparison to the results using SMA endmembers. The NDVI was calculated from Eq. (5) (Roberts et al., 1997):

$$\text{NDVI} = \frac{\rho_{793} - \rho_{677}}{\rho_{793} + \rho_{677}} \tag{5}$$

where ρ_{793} and ρ_{677} are the reflectance values for bands centered at 793 and 677 nm, respectively.

3.8. Regeneration measurements

Once the endmembers and NDVI were produced, two indices were utilized to assess the recovery after fire, a RI and a Normalized Regeneration Index (NRI) (Eqs. (6) and (7)):

$$\text{RI}_{\text{VI}} = \frac{\text{VI}_{\text{fire}}}{\text{VI}_{\text{control}}} \tag{6}$$

$$\text{NRI}_{\text{VI}} = 1 + \frac{\text{VI}_{\text{fire}} - \text{VI}_{\text{control}}}{\text{VI}_{\text{fire}} + \text{VI}_{\text{control}}} = \frac{2\text{VI}_{\text{fire}}}{\text{VI}_{\text{fire}} + \text{VI}_{\text{control}}} \tag{7}$$

Where VI_{fire} is a measure of the vigor of the vegetation (GV or NDVI) for a burned plot. $\text{VI}_{\text{control}}$ is the GV or the NDVI for an unburned control plot. RI and NRI provide values >0 and ≤ 1; a value of 1 indicates 100% recovery, i.e., a completely recovered plot. The normalization index (Normalized Recovery Index, NRI) takes into account possible microsite differences between plots in terms of the total recovery time differences.

The average VI per plot and community were calculated to define the mean value of recovery for each community and site. The RI and NRI were obtained for the two burned sites, so VI_{fire} values were from either the Stunt Ranch or the comparative plot, whereas the $VI_{control}$ was always obtained from the control site. Therefore, the RI and NRI values for the comparative site (burned in 1996) were 100% before the fire. However, we cannot independently know the original state before the fire at Stunt Ranch, since there are no images before 1993, when the fire occurred. Nonetheless, vegetation studies at Stunt Ranch that preceded the fire indicate these communities were present within the site.

For a valid comparison, the control site must have characteristics closely similar to the fire sites: same vegetation communities, patch sizes, climatic conditions, distance to the sea, and topographic position. These relationships were found to be true based on the GIS database layers, so the variation between control and burned plots were interpreted to be solely due to the regeneration process. Therefore, the recovery was independent of spectral differences between image dates caused by other effects, e.g.:

- possible AVIRIS radiometric calibration uncertainty,
- possible minor error(s) in the atmospheric correction,
- topographic effects, and
- phenological state of the vegetation due to interannual or seasonal differences.

The evolution of the comparative 1996 burn site was combined with the evolution of the Stunt Ranch, using the beginning of the 1993 fire as the reference date, to compare these data. This was possible since both fires were ignited at the same time of the year, in late October and early November, and both were high intensity fires. This timing is important since the season and intensity of fires have great impact on chaparral in terms of germination success (Barro & Conard, 1991), phenological stage and dormancy, and other factors that influence regrowth potential.

Once the data from the two fires were processed, a logarithmic regression model was applied to determine the regeneration time for each community (Fiorella & Ripple, 1993):

$$RI_{VI} = \alpha + \beta \log t \tag{8}$$

Where t is the time (days) elapsed since the fire event. α and β are the regression coefficients. This model was applied for RI and NRI, for both VI: the GV and the NDVI models.

4. Results

Figs. 4 (northern mixed chaparral) and 5 (coastal sage scrub) show the average values and standard deviation of GV fraction and NDVI for the Stunt Ranch and control plot. NDVI and GV are primarily influenced by the phenological state of the vegetation. As expected, spring images have higher values of GV and NDVI, while fall images have the lower ones. Therefore, no trends in regeneration can be established for the Stunt Ranch 1993 burn area. Variation is also high within the control plot, which should be stable in terms of regeneration, because of the extended period since the last wildfire. However, the phenologial state is apparent. In GV and NDVI values, which are somewhat higher for the northern mixed chaparral due to its greater vegetation cover S.D. of GV and NDVI within each plot is high. This does not imply error, but demonstrates variability at the microsite scale, which is high due to the presence of different species or bare soil within each community. Hereafter, the focus will

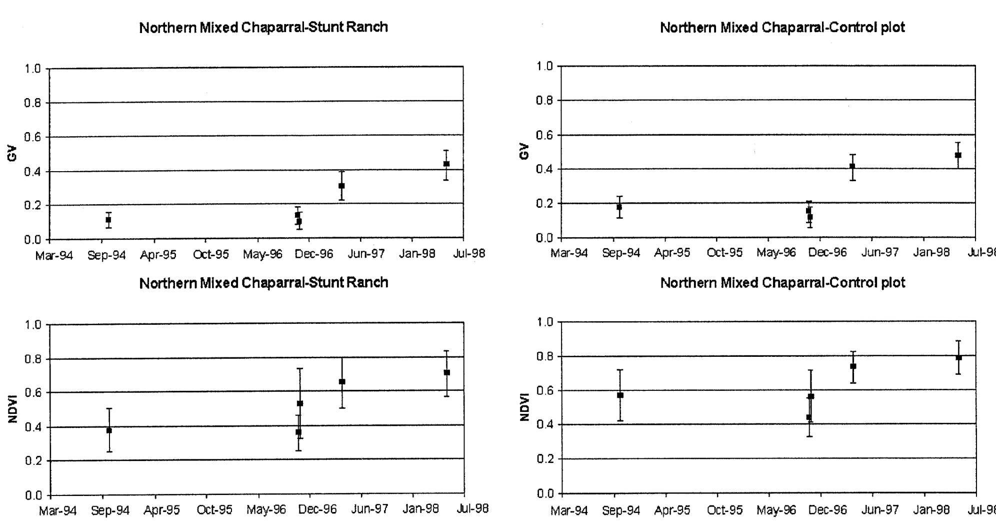

Fig. 4. Evolution through time (in months) of average values (±1 S.D.) of GV and NDVI for two plots, the Stunt Ranch and the control plot. Community: northern mixed chaparral.

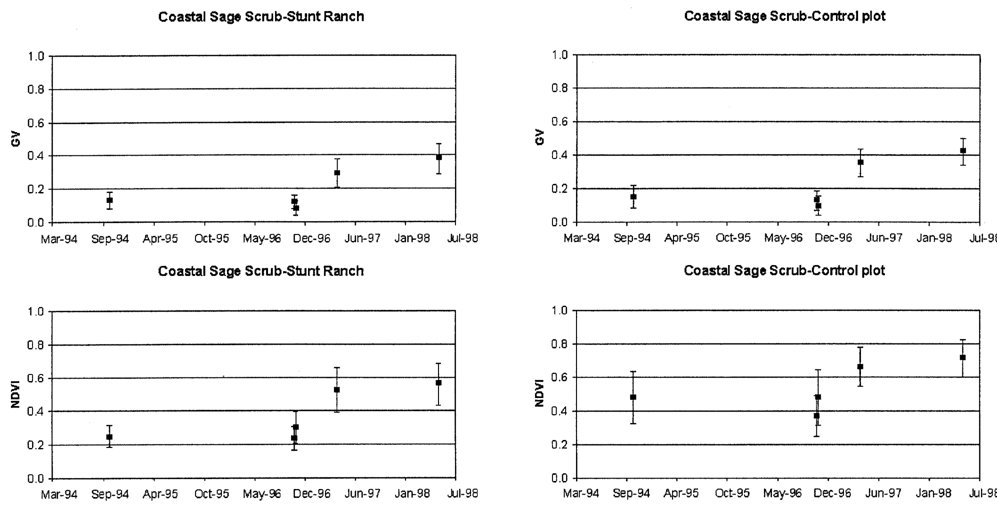

Fig. 5. Evolution through time (in months) of average values of GV and NDVI for two plots, the Stunt Ranch and the control plot. Community: coastal sage scrub.

be on the trends within the communities, so we only consider the average values of GV and NDVI.

Figs. 6 (northern mixed chaparral) and 7 (coastal sage scrub) show the results for both fires, at Stunt Ranch and the comparative plot, after taking into account the control plot in the calculation of the RI. After obtaining this index, the recovery process can be better understood. There is an increase in the RI_{GV} and RI_{NDVI} after the fire, this is particularly clear for the comparative plot where we had data from the beginning of the recovery. Both indices worked well for the northern mixed chaparral, but RI_{NDVI} did not work as well for the coastal sage scrub. As previously stated, the situation of the RI_{NDVI} before the fire should be equal to 100% (total recovery, no fire). Yet, the results were inconsistent for the coastal sage scrub, indicating that there were NDVI differences between these communities before the fire.

The results of the RI and NRI analyses for the two communities are shown in Figs. 7 and 8. The evolution of the comparative site was evaluated against the evolution of the Stunt Ranch, taking the beginning of the fire as the reference date to further understand the recovery process.

The evolution of the northern mixed chaparral is presented in Fig. 8, which shows that the indices did demonstrate changes in vegetation recovery over a 5-year period. On the other hand, the results are less clear for the coastal sage scrub (Fig. 9) in terms of RI_{NDVI} and NRI_{NDVI}. These indices seem to be more influenced by phenological differences within these communities making interpretations difficult. The spring values for the 1997 and 1998 images (the last two values shown in each figure) are much higher than expected based on the relative regeneration process, whereas the fall images have values that are much lower than expected. A similar result was also observed by Viedma et al. (1997), who used an NDVI time series but found they could not fit a good regeneration model for sparse shrub communities. Their study was also conducted

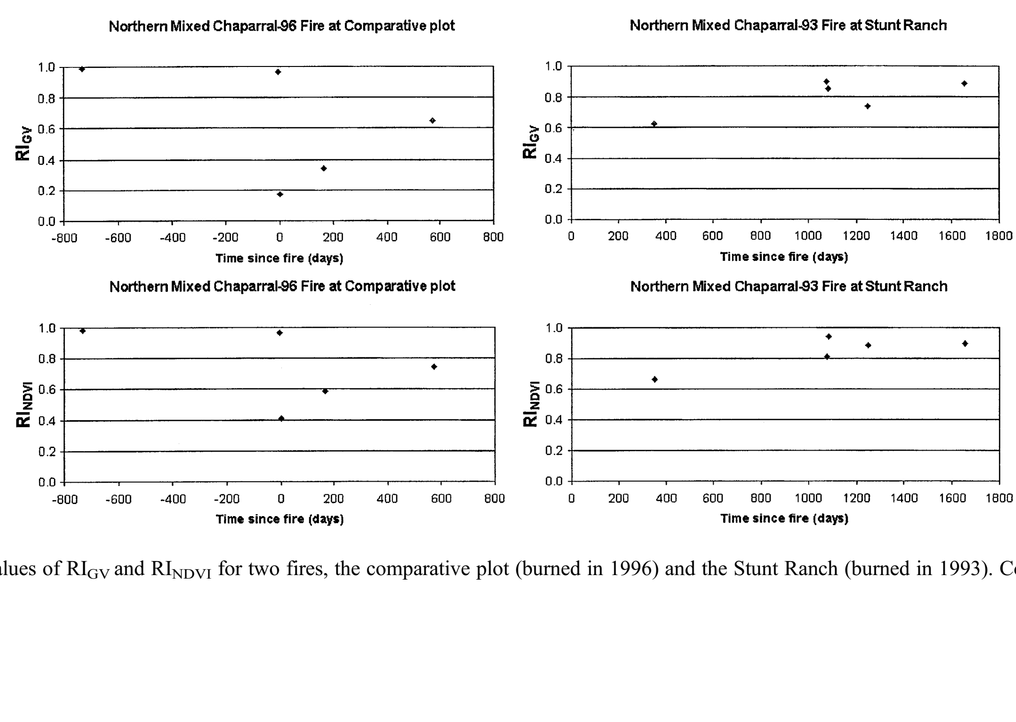

Fig. 6. Average values of RI_{GV} and RI_{NDVI} for two fires, the comparative plot (burned in 1996) and the Stunt Ranch (burned in 1993). Community: northern mixed chaparral.

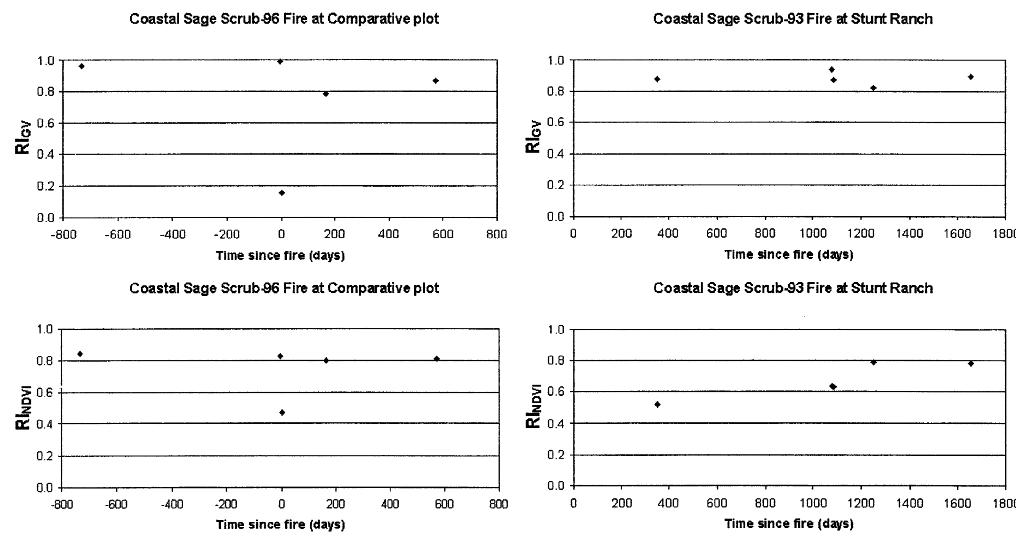

Fig. 7. Average values of RI_{GV} and RI_{NDVI} for two fires, the comparative plot (burned in 1996) and the Stunt Ranch (burned in 1993). Community: coastal sage scrub.

in a Mediterranean environment with similar conditions to the coastal sage scrub community here.

This pattern can be explained by the evolution of this community after fire. Both shrub communities have inhibitors to limit herbaceous growth. After the fire, herbaceous cover appears during the first few years, being greater for the coastal sage scrub than the northern mixed chaparral because of more open space and greater solar insolation. During the spring, the coastal sage scrub community appears to be greener or to have more complete recovery relative to the control plot where only the shrubs are green. (See Fig. 9 for graphs of RI_{NDVI} and NRI_{NDVI}. Values of RI_{NDVI} and NRI_{NDVI} with days since fire are equal to day number: 167, 573, 1251, and 1657. These are spring images.) Therefore, the seasonal phenology and abundance of the herbaceous cover masks the evolution of the shrubs. On the other hand, during the fall data acquisition, the herbaceous plants have dried and the NDVI shows greater decline than does in the control plot. (See Fig. 9 for graphs of RI_{NDVI} and NRI_{NDVI}. Values of RI_{NDVI} and NRI_{NDVI} with days since fire are equal to 1, 350, 1079, and 1085 and they are fall images.) The NDVI is less influenced by the effect of masking of the regeneration process in the northern mixed chaparral because the community is primarily composed of shrubs, which have a less pronounced seasonal phenology (see Fig. 8 for graphs of RI_{NDVI} and NRI_{NDVI}). Garcia and Ustin (2001) report similar seasonal differences in community responses when vegetation types have a large component of annual grasses and herbs.

The GV provided good results for both communities. The GV endmember used in this study was from green leaves of

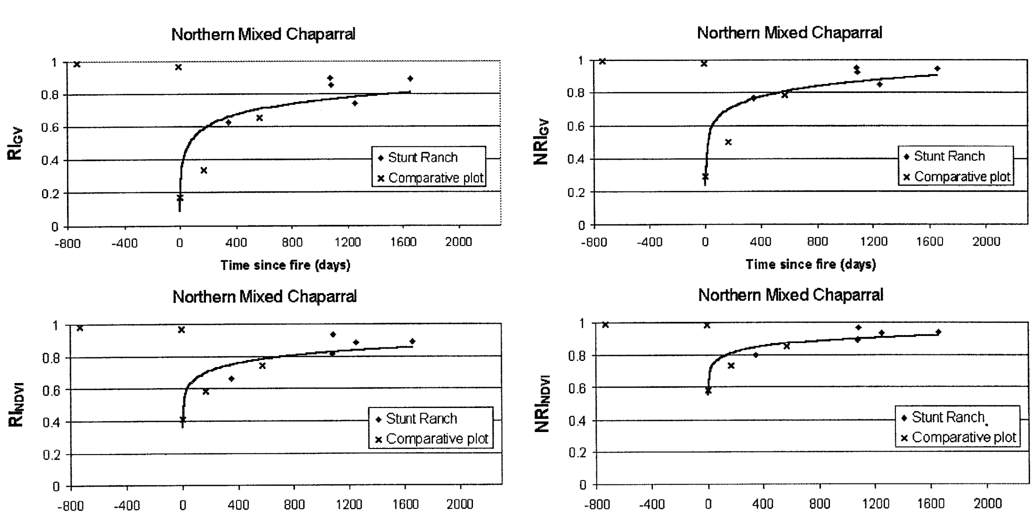

Fig. 8. Average values of RI_{GV}, RI_{NDVI}, NRI_{GV}, and NRI_{NDVI} with the logarithmic adjusted combined model for the two wildfire areas. Community: northern mixed chaparral.

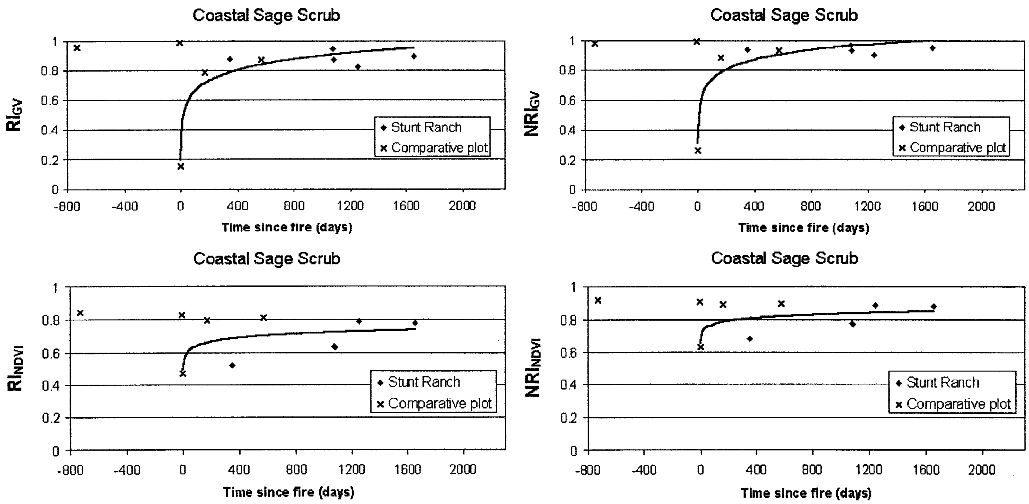

Fig. 9. Average values of RI_{GV}, RI_{NDVI}, NRI_{GV}, and NRI_{NDVI} with the logarithmic adjusted combined model for the two wildfire areas. Community: coastal sage scrub.

the shrub *C. oliganthus*. This suggests that GV may characterize the vigor and greenness of the shrub species more accurately than if NDVI was used. Additionally, the NPV captures the dried herbaceous plant material separately and therefore GV decreases less compared to the control plot.

The logarithmic regression model (see Eq. (8)) was applied to determine the regeneration time for each community. Figs. 8 and 9 show the trends in recovery for each community and index. The poorest fit is for the coastal sage scrub in the case of the RI_{NDVI} and NRI_{NDVI}. It can be seen in Table 1 that *R*-Pearson values are lowest, explained largely by the seasonal appearance of herbaceous cover. The initial state of the community in the plots before the fires occurred was considered to be the average of the values of RI and NRI before the fire. The regeneration time was estimated when the logarithmic model reached this initial state. RI_{NDVI} and NRI_{NDVI} estimations for coastal sage scrub disagree with the literature and appear to require too long a regeneration time relative to observations of burn frequency. RI_{GV} and NRI_{GV} provide more consistent values (P value <0.01) with the expected regeneration time of 5 years for this habitat (O'Leary & Westman, 1988).

The longest recovery estimations for northern mixed chaparral are for RI_{NDVI} and the lowest for NRI_{GV}. All relationships were found to be significant (P value <0.01). Horton and Kraebel (1955) and Minnich and Bahre (1995) estimates for this community are longer than for coastal sage scrub, indicating ages of 10–20 years for recovery. Therefore, both NRI_{GV} and NRI_{NDVI} provide good results. RI_{VI} seems to overestimate the time of recovery. The *R*-Pearson values were high except for the coastal sage scrub NDVI indices. NRI_{GV} indices produce values closer to the expected initial state of 1.0.

5. Conclusions

The main lessons to be emphasized from this study are the following.

1 Control plots with similar environmental features within the scenes were needed to generate regeneration indices. The control plots provide an analysis independent of possible AVIRIS radiometric calibration uncertainty, minor error in the atmospheric correction, topographic

Table 1
Equations of the logarithmic adjusted models for the different indices

		Equations $RI_{VI}=\alpha+\beta\log t$			$NRI_{VI}=\alpha+\beta\log t$		
		Slope	Intercept	*R*-Pearson	*P* value	Initial state	Regeneration time (years)
Northern mixed chaparral	RI_{GV}	0.097	0.091	0.89	0.0033	0.98	26.1
	NRI_{GV}	0.089	0.240	0.93	0.0008	0.99	11.9
	RI_{NDVI}	0.067	0.359	0.90	0.0022	0.97	28.0
	NRI_{NDVI}	0.050	0.552	0.94	0.0006	0.99	16.0
Coastal sage scrub	RI_{GV}	0.102	0.194	0.97	0.0001	0.98	6.0
	NRI_{GV}	0.093	0.311	0.96	0.0001	0.99	3.9
	RI_{NDVI}	0.034	0.486	0.61	0.1120	0.84	88.1
	NRI_{NDVI}	0.026	0.651	0.64	0.0882	0.91	52.2

Initial state and the regeneration time is estimated for each model.

distortions, and phenological differences in vegetation due to interannual or seasonal differences.

2 Normalization of the RI is able to minimize the external influences to the assessment of the recovery after fire.

3 RI_{VI} appears to overestimate regeneration developed by the logarithmic model of recovery more than the NRI_{VI}.

4 NRI_{GV} was best for estimating recovery in both communities, providing a better estimate for the recovery of the shrubs relative to the herbaceous vegetation.

5 The use of NDVI to obtain either RI or NRI worked very well for the northern mixed chaparral, but performed less well for the coastal sage scrub. This problem can be explained by the fact that during the first few years of the regeneration process the growth of herbaceous species is favored. Herbs/grasses are also present in the northern mixed chaparral, but cover is lower and they do not dry out as much as in the coastal sage scrub. This is why masking does not substantially affect the NDVI in the northern mixed chaparral community.

6 Endmembers generated from hyperspectral images were proven to be more accurate in following the regeneration process than the NDVI. The endmembers better capture the greenness for the type of vegetation required (semiarid shrubs) and are less influenced by herbaceous growth in the community than is the NDVI.

7 Matching plots with similar environmental features but burned in fires occurring in different years were demonstrated to be useful to understand the recovery within each community.

8 The estimates for regeneration after fire for both communities were extracted from the literature, but more detailed field work must be done to understand the trajectories of regeneration.

9 Remote sensing was shown to be an effective way to study the regeneration of plant communities over a longer time than the period covered by the remote sensing images by employing sites with comparative fires within the scene, control sites, and other data layers, e.g., fire location and history maps.

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