Monitoring post-burn recovery of chaparral vegetation in southern California using multi-temporal satellite data

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Abstract. Monitoring the post-burn recovery condition of chaparral vegetation in southern California is important for managers to determine the appropriate time to conduct controlled burns. Due to the difficulty of monitoring post-fire recovery over large areas and the absence of detailed fire records in many areas, we examined the possibility of using satellite observations to establish the post-fire recovery stage of chamise chaparral stands in this region. SPOT XS data collected on three dates between 1986 and 1992 were analysed to determine if temporal changes in a spectral vegetation index tracked the expected post-fire recovery trajectory of the above-ground biomass of chamise chaparral stands of varying post-fire ages. Results of the study indicated that neither the normalized difference vegetation index nor the soil adjusted vegetation index followed the expected post-fire recovery patterns in these stands. These findings are explained by interannual variations in precipitation having a larger than expected effect on the growth of this drought-resistant evergreen community, with changes in green leaf area dominating the temporal variations in the spectral vegetation indices.

1. Introduction

Five distinct regions of the world are characterized by climatic regimes where most of the annual precipitation is delivered during the winter season, resulting in drought conditions during the summer months. These areas of Mediterranean-type climate are transitional zones between temperate climates and the tropics, tending to occur on the west coasts of continents between approximately 30° and 40° latitude in both hemispheres. Portions of the Mediterranean Basin, South Africa, Chile, south-western Australia and California all share this climate type and consequently have all evolved structurally similar shrub-dominated sclerophyllous vegetation. Although climate is considered an integral factor in the evolution of these shrub-dominated formations, constraints imposed by soil nutrient conditions and fire regimes are also considered to be forcing variables in the development of Mediterranean shrublands (Bond and van Wilgen 1996). Broadleaf forests and woodlands occur in less fire-prone areas of this climate.

All Mediterranean-type ecosystems (MTEs) contain fire-adapted and fire-dependent plant species, as well as species that are merely fire-tolerant. Excluding Chile, fire is considered a natural phenomenon in MTEs, so the fire adaptations of the plant species are considered evolutionary and have resulted in great species
richness (Bond and van Wilgen 1996). The depth of this convergent evolution has been the centre of debate, but it is generally accepted that all five MTEs have vegetation similar in structure and appearance (Di Castri 1981). Terms for these shrublands vary regionally, and they are called *matorral* in Chile, *garrigue* in France and Italy, *fynbos* in South Africa, *mallee scrub* in Australia and *chaparral* in California. Similarities have also been found in post-fire response between different Mediterranean-type shrublands. Traditional theories regarding vegetation succession and climax vegetation do not apply to fire-prone vegetation communities. Instead, the dominant plant species of the mature or climax community appear the first year after a fire.

In general, the chaparral vegetation of California consists almost exclusively of deep-rooted, woody shrubs that usually form a dense canopy in mature stands. This dense cover shades out most perennial and annual herbs (Mooney and Miller 1985). Chaparral is located at elevations lower than approximately 2000 m on rocky, nutrient-poor soils and steep slopes, often forming a mosaic pattern between grassland and woodland areas. Chaparral has a great latitudinal range, being found in Baja California, Mexico and also located as far north as south-western Oregon. At higher latitudes it is restricted to relatively xeric areas (Keeley and Keeley 1988). The most abundant chaparral shrub species is chamise (*Adenostoma fasciculatum*). This evergreen shrub has small needle-like leaves and often grows in nearly pure stands. Chamise-dominated chaparral tends to be less dense and to have less green leaf biomass than other chaparral types that occur on more mesic, north-facing slopes or high elevation sites.

As in other MTEs, prescribed fire has been used to reduce fuel loads in chaparral. These controlled burns are practiced with the goal of avoiding large catastrophic fires (that may occur following decades of fire suppression) while maintaining a burn cycle that will accommodate the native vegetation. In order to plan controlled burns, it is important to determine when a stand of chaparral has reached an appropriate level of maturity. However, determination of stand maturity may be difficult to assess in the absence of accurate fire history maps and it may be necessary to conduct field surveys in order to estimate when the vegetation last burned. The dense character of chaparral vegetation is a major hindrance to field work, particularly when large areas need to be surveyed.

In the absence of extreme weather events, chaparral follows a well defined recovery process after fire (e.g., Hanes 1971, Hubbard 1986, Thomas and Davis 1989). For the first few years, herb cover is high, dominated largely by annual herbs that require fire to stimulate germination (fire annuals). Meanwhile, shrubs re-establish from seedlings, as well as re-sprouting from below-ground biomass reserves not killed by fire. Shrub cover increases steadily until approximately 20 years after burning (Horton and Kraebel 1955), while living above-ground biomass increases (figure 1) at a high rate for the first 10 years (Black 1987). Biomass accumulation continues for nearly 40 years after a fire (Rundel and Parsons 1979, Mooney 1981). This recovery sequence suggests that chaparral vegetation should not be deliberately burned until some level of stabilization is reached in the recovery sequence (i.e. canopy closure or decrease in living biomass accumulation).

Relationships between spectral vegetation indices (SVIs) and biophysical quantities, such as above-ground biomass and per cent cover have been examined in a wide variety of environments (see e.g., Hope *et al.* 1986, Clevers 1988, Dymond *et al.* 1992, Gamon *et al.* 1995). SVIs are intended to reduce multi-spectral data to a single value
that is sensitive to changes in vegetation quantities but insensitive to different view angles and variations in illumination conditions and soil background. The normalized difference vegetation index (NDVI) is a widely used SVI obtained by dividing the difference between near-infrared and red reflectances by the sum of these reflectances. Because variations in soil background can affect the NDVI, Huete (1989) suggests using the soil adjusted vegetation index (SAVI) to minimize index sensitivity to soil background differences. The SAVI is calculated by adding an adjustment factor (0.5 is considered appropriate for most soils) to the denominator of the NDVI and multiplying the full expression by one plus the adjustment factor (1.5 total in this case). This multiplication is introduced to maintain the same bounded conditions of the NDVI, a range of $-1.0$ to $1.0$ (Huete 1989).

Most research into the relationship between SVIs and biophysical quantities has not focused on landscapes dominated by shrub cover. Marchetti et al. (1995) found that changes in a SVI (the Infrared Index) corresponded to post-fire recovery phases of garrigue vegetation in Italy. Shrub cover in the Jornada Basin of New Mexico has been shown by Duncan et al. (1993) to correlate with changes in the NDVI and the SAVI. Gamon et al. (1995) collected spectral reflectance data over chaparral vegetation in central California using a hand-held radiometer and found significant relationships between biomass (green and total) and NDVI. These results suggest that SVIs such as the NDVI and SAVI can be used to monitor the increase in above-ground biomass after fires in shrubland vegetation communities. This should make it possible to track the post-fire recovery status of chaparral stands using SVIs derived from satellite data.

2. Research goals

It is apparent from the preceding discussion that the accumulation of living biomass in post-burn chaparral tends to follow a well defined pattern over time.
(figure 1) and SVIs may indicate the above-ground biomass in shrubland communities (e.g., Dymond et al. 1992, Duncan et al. 1993, Gamon et al. 1995). Therefore, it was hypothesized that changes in a SVI over time would track green biomass accumulation and therefore provide an indicator of relative stand maturity in chamise chaparral. Varying atmospheric and illumination conditions may affect the relationship between SVIs and biomass. However, satellite imagery can be radiometrically registered (e.g., Schott et al. 1988, Caselles and Garcia 1989, Hall et al. 1991) so that temporal changes in the SVI indicate the rate of biomass accumulation which would be expected to vary according to the recovery phase of the vegetation.

The goal of this research was to determine if temporal changes in a SVI would follow the expected post-burn recovery trajectory of chamise chaparral in southern California. Chamise chaparral is a community dominated by evergreen shrubs, so interannual variations in precipitation are not expected to cause significant changes in SVIs, even in late summer. The shrub species are well adapted to yearly drought periods, except in years when rainfall is substantially below normal. Since biomass accumulation in this vegetation community typically slows after 10 years and stops after 40 years, SVI values for mature stands are not expected to change significantly over short time intervals of a few years (figure 2). In contrast, because biomass accumulation is high for the first 10 years following a fire, SVI values for young stands (less than 10 years old) would be expected to change significantly over the same time period.

The SVI chosen to test these hypotheses was the NDVI due to its wide use and strongly established relationships with above-ground biomass amount in different landscapes, including shrublands. We also examined the relationship of the SAVI instead of the NDVI because this index could be expected to be more stable than the NDVI across varying soil backgrounds (Huete 1989). Chamise chaparral landscapes, particularly in the early years of post-fire recovery, are dominated by bare soil.

3. Methodology

The general approach adapted in this study was to identify stands of chamise chaparral which were at different phases in the post-fire recovery cycle (including

![Figure 2. Hypothetical NDVI curve for post-burn chamise chaparral.](image-url)
mature stands) and then compare changes in their mean NDVI (or SAVI) values over periods ranging from 2 to 6 years. These SVI values were calculated using multi-spectral satellite data for August 1986, 1988 and 1992. Thus, we were able to examine changes in SVI values over a 2-year period, a 4-year period and a 6-year period. We expected these intervals to be sufficiently long to minimize effects of interannual variations in rainfall.

3.1. Study area and data

Data for the current study were collected over Naval Air Station (NAS) Miramar, which is located approximately 15 km north of San Diego, California (32°45'N, 117°00'W) and covers an area of 96 km² (figure 3). This area was chosen for study since much of the station has not been developed, chaparral stands with different fire histories are abundant and a detailed geographic information system (GIS) exists for the station. The study focused on the eastern portion of NAS Miramar where there is an abundance of undisturbed natural vegetation along with detailed fire history maps.

The vegetation and land cover of NAS Miramar have been mapped in detail by O'Leary et al. (1994). Approximately 36 land cover classes were identified and entered into a GIS. Locations of all chamise chaparral stands were identified using this database.

Locations and dates of both wildfires and prescribed burns were obtained from the Environmental Protection Division of the Staff Civil Engineer Department at NAS Miramar. The earliest burn shown on the map occurred in 1980 and the most recent fire was in 1990. Mature stands of chamise chaparral (>20 years) were identified on the GIS and then field checked and photographed.

SPOT XS data, acquired on 5 August 1986, 7 August 1988, and 25 August 1992

Figure 3. Location of Naval Air Station Miramar.
were used in this study. Since the images were taken at the same time of year, differences between them should be largely attributable to changes over time and not phenological differences or seasonal illumination changes. Late summer is an appropriate time for studying evergreen shrub cover because nearly all annual herbs are dead following the summer drought, and many perennial herbs and drought-deciduous shrubs are dormant. By using imagery acquired in August, potential for cloud cover is also reduced. The comparison of images acquired 2, 4, and 6 years apart (as opposed to only 1 year) was chosen to allow sufficient time for significant changes to occur in the composition (shrubs versus herbs) and per cent cover of recently burned areas of chamise chaparral.

3.2. Analytical procedures

The digital numbers (DNs) in each band of each SPOT image were converted to radiances using sensor calibration coefficients provided by SPOT Image Corporation. Each scene was geometrically registered and georeferenced to State Plane coordinates. To normalize for atmospheric differences between dates, radiometric registration was performed using a technique similar to those described by Schott et al. (1988), Caselles and Garcia (1989) and Hall et al. (1991). These methods assume that each scene contains areas that are invariant from date to date, so that they should have constant radiances values between dates. We considered the 1986 scene to be the reference image and radiometrically registered the 1988 and 1992 scenes to match it. Pseudoinvariant features (or PIFs) were identified in the images and the radiances values observed in the 1988 and 1992 scenes were plotted against the 1986 reference values. Regression equations were determined for each band of each image and then used to ‘normalize’ radiances values of each date. To test the accuracy of the normalization process, ten additional (independent) PIFs were identified and the corrected scenes were plotted against the reference image. Each of the test regressions plotted close to the 1:1 line (perfect agreement) and did not indicate any systematic error. The corrected SPOT data were used to calculate NDVI and SAVI.

The NDVI and SAVI images were co-registered with NAS Miramar GIS layers containing vegetation and age classes. Chamise chaparral stands in four different age classes were studied: mature stands (23 sites), 1980 burns (5 sites), 1981 burns (17 sites) and 1982 burns (12 sites). Sizes of the individual vegetation stands ranged from 12,000 m² (30 pixels) to over 400,000 m² (1000 pixels). Mean SVI values were calculated for all stands and compared using a difference of means *t*-test. A separate test was used for each age class over each interval (e.g. the 1980 burns between 1986 and 1988).

4. Results and discussion

Changes in NDVI values between the three observation dates (1986, 1988 and 1992) for each stand of chamise chaparral in the four age categories are plotted in figure 4. A notable feature of these plots is the low NDVI values that were obtained for each age class and on each observation date (NDVI < 0.14). While these low NDVI values could be expected for the recently burned stands, the values for the mature stands were unexpected. These low NDVI values suggest that the soil background is a dominant component in the three scenes regardless of stand age. It could be expected therefore, that an adjustment for variations in the soil background might produce different SVI trends in these shrub communities. However, the results
Figure 4. Mean NDVI for individual stands in each age class, 1986 to 1992.
Table 1. Correlation coefficients of mean NDVI values between observation dates for each burn class.

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<tr>
<td>Mature</td>
<td>0.745</td>
<td>0.796</td>
<td>0.872</td>
<td>23</td>
</tr>
<tr>
<td>1980</td>
<td>0.559</td>
<td>0.014</td>
<td>0.646</td>
<td>5</td>
</tr>
<tr>
<td>1981</td>
<td>0.599</td>
<td>0.730</td>
<td>0.443</td>
<td>17</td>
</tr>
<tr>
<td>1982</td>
<td>0.743</td>
<td>0.382</td>
<td>0.663</td>
<td>12</td>
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obtained using SAVI virtually replicated those obtained using the NDVI. Correlations between the NDVI and SAVI for each observation date ranged between 0.91 and 0.918. Given the similarity in findings obtained using the two different indices, the remaining discussion will focus on the NDVI.

It is apparent from the plots in figure 4 that the variation in NDVI values was substantial for all age classes on each observation date. Standard deviations were all in the range of 0.1 to 0.2 NDVI units. The relative ordering of stand NDVI values is not well preserved across the three observation dates, as indicated by the crossing of lines in figure 4. Correlating the NDVI values between successive observation dates confirms this observation since the correlation coefficients do not exceed 0.872 (table 1). The correlation coefficients listed in table 1 also indicate that the relative ordering of NDVI for the mature stands (0.745 < r < 0.872) is more stable than the ordering observed for the other age classes (0.014 < r < 0.743). This is to be expected since mature stands have greater canopy closure and are less prone to temporal variations in cover conditions.

While there is considerable variability in NDVI trends across the period of investigation, each age class does appear to follow a similar NDVI trajectory from 1986 to 1992. The maximum NDVI values generally occurred in 1986 and then decreased in 1988, followed by a slight increase in 1992 (figure 4). These trends are particularly apparent when the mean NDVI is plotted over time (figure 5). The

![Figure 5. Mean NDVI by age class (symbols) shown with twelve-month rainfall totals (bars).](image-url)
sharp reductions in mean NDVI values between 1986 and 1988 are all statistically significant at the 0.05 confidence level when tested using a difference-of-means \( t \)-test. The mean NDVI values for the three burn classes are similar in each observation year, with the maximum spread being observed in 1992.

The proposed method of tracking the post-fire recovery status of drought-resistant chamise chaparral shrub communities using satellite-based NDVI observations was not supported by the results of this study. While the mean NDVI values for mature stands were higher than those of the recently burned age classes, the NDVI values for these younger stands were very similar over time regardless of the time since fire. The consistent patterns of NDVI over time for both mature and recently burned stands suggest that some regional factor controls the variations in NDVI. The most obvious variable to consider was precipitation, so the 12-month rainfall totals for the period preceding each satellite acquisition were plotted in the from of a bar chart on figure 5. Despite the drought-tolerant characteristics of shrubs found in chamise chaparral communities, severe drought conditions (e.g. in 1987) are likely to cause a marked decrease in green leaf area. The NDVI would respond directly to this change in green leaf area rather than to the change in overall above-ground biomass. While the 12-month precipitation (367 mm) prior to the 1988 satellite overpass was slightly higher than the long-term average for this location (approximately 300 mm), the mean NDVI values for all age classes are still significantly less than those in 1986. The recovery of green leaf area to pre-drought levels appears to require more than a single season of adequate precipitation, even in mature stands.

The change in mean NDVI values between 1988 and 1992 illustrated in figure 5 also points to the role of precipitation in controlling the green leaf area of the vegetation and hence the NDVI. The region studied experienced particularly dry years in 1989 and 1990, while precipitation in 1991 was just below the long-term average. In 1992 precipitation was just above the average and these two consecutive non-drought years allowed the vegetation in the three burn classes to recover to a condition that produced slightly higher NDVI values than those observed in 1988. In contrast, the mature class showed no change in NDVI over this period.

Two possible explanations for this trend are suggested by previous research. First, the 1986 peak in NDVI values for the recently burned stands may reflect post-fire growth of suffrutescent sub-shrubs such as *Lotus scoparius* (deer weed). These sub-shrubs are usually very abundant during the first 2 to 4 years following fire, after which chamise returns to being dominant (Westman and O’Leary 1986). Despite the fact that *Lotus scoparius* is drought-deciduous, it has less woody stems than chamise and this may boost NDVI values in early post-fire years. However, it is more likely that the stability of NDVI values in mature stands after 1988 is due to depletion of soil nutrients in older chaparral stands. Black (1987) found that nutrient uptake in stands older than 10 years is reduced, since more nutrients are locked up in standing biomass and litter. The additional nutrients supplied by ash deposition contribute to higher growth rates in young chaparral, whereas older stands do not experience this benefit (Christensen and Muller 1975, Black 1987). Rundel and Parsons (1979) also found that productivity in older stands is much lower than that in young stands and that leaf area index (LAI) consistently decreases in stands over 20 years old. This research was conducted at high elevations in the Sierra Nevada which receive approximately 700 mm of precipitation annually. Since significant decreases in LAI were observed in a region where rainfall is not as much a limiting factor, it is likely that LAI reductions in dry areas (i.e. San Diego County) may be
even more pronounced, particularly following drought. All of these studies suggest that the decrease in NDVI observed for mature stands between 1986 and 1988 may have been partially caused by nutrient depletion, further accentuated by below average precipitation.

5. Conclusions

The biomass accumulation curve for chamise chaparral may follow a regular progression when total above-ground biomass is considered. However, the red and particularly the near-infrared reflected radiances (which are used to calculate the NDVI) respond more directly to changes in green leaf area index. Although these vegetation communities are well adapted to drought and are dominated by evergreen species, short-term fluctuations (a few years) in green leaf area are likely and lead to similar variations in the NDVI. If observations are integrated over periods that filter out interannual fluctuations, then there may be a more direct correlation between green leaf area (and NDVI) and total above-ground biomass. However, it seems unlikely that we could use single anniversary date satellite imagery to assess the recovery stage of chamise chaparral with any certainty. Furthermore, the low absolute NDVI values of this vegetation community present a major constraint to multi-temporal comparisons of the index for evaluating changes in vegetation condition since variations in illumination and atmospheric conditions, scene background and sensor calibration are likely to produce sufficient ‘noise’ to mask the NDVI signal corresponding to changes in vegetation condition. The apparent sensitivity of the NDVI to changing green leaf area in chamise chaparral suggests that further investigations to quantify this relationship are justified.

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References


