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Shifts of Vegetation Cover on Southern California Mountains in Response to Recent Climate Variations

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Abstract

In the Peninsular Range mountains of southern California, air temperatures have been rising and precipitation variability has been increasing over the past several decades. Plants growing at the lower-elevation range in these mountains may be vulnerable to growth declines and mortality. This study was designed to quantify and characterize variations in vegetation canopy density using more than 30 consecutive years of Landsat satellite image data across the San Jacinto Mountains National Monument (SJMNM) area. Mapping of the normalized difference vegetation index (NDVI) from Landsat images (1985 to 2017), which has been closely correlated with percent cover measurements of green vegetation canopies in a variety of arid ecosystems, was used to detect periodic upslope and downslope shifts in plant cover. The change in Landsat NDVI between 1985 and 2017 within the 12-km transect surveyed in the northern San Jacinto Mountains by Fellows and Goulden [1] in the years 2002 and 2007-08 showed that vegetation green cover dropped notably in below-average precipitation periods, whereas green cover increased sharply in above-average precipitation years. This same temporal pattern of shifting in NDVI was detected along elevation gradients across the larger SJMNM. Although mortality of the predominant tree species may have increased in the mid-montane zone of the northern San Jacinto Mountains between 1700 and 2300 m elevation over several decades (prior to 2008), we found no evidence that such shifts in percent plant cover have yet become a wide-spread and permanent pattern across the larger SJMNM area.

Keywords: Forest; Landsat; Precipitation; Shrub land San Jacinto Mountains; Vegetation cover; NDVI

Introduction

Recent changes in woody plant species distribution have been reported in response to climate change in ecosystems worldwide, including species shifts up or down in elevation with relatively rapid, localized variations in precipitation and air temperature [2-8]. The Southern Interior Region of California has warmed on average by 0.02° C yr^{-1} from 1949 to 2009, and precipitation variability has increased from 1949 to the 1980s [1], climate patterns which have been associated with more recent forest growth decline and mortality in the San Jacinto Mountains.

Related studies of ecosystems in the Santa Rosa Mountains of southern California spanning 30 years by Kelly and Goulden [5] discerned that regional air temperatures have been rising and precipitation variability has been increasing (including declines in annual snowpack) over an elevation gradient of 2300 meters. These authors related vegetation mortality events to two extreme droughts recorded between 1977 and 2007, and further documented the upslope movement of the dominant shrub and tree species by approximately 65 meters' vertical distance. These types of relatively rapid upslope shift in plant cover have been linked to an observed increase in precipitation variability, a lower proportion of precipitation falling as snow, and surface warming. It was construed that plant species redistribution along arid mountain gradients has occurred episodically, with accelerated mortality in the lower elevations of all species ranges during relatively dry periods (e.g., 2002 and 2007) and infilling slowly during relatively wet periods. Specifically, Fellows and Goulden [1] reported that conifer tree mortality has occurred in the past 20 years in the mid-montane zone (between 1700 and 2300 m elevation) of the San Jacinto Mountains, driving the conifer distribution upslope.

The vast expanse of the southern California mountain ranges with their extremely rugged topography make field studies such as those of Fellows and Goulden [1] and Kelly and Goulden [5] difficult to replicate and then to extend into future years. Moreover, single-transect sampling designs cannot capture all the variability in steep mountain areas covering several hundred square kilometres. Satellite remote sensing can be used to fill this gap in vegetation change monitoring for these expansive montane regions. Accordingly, the objective of this study was to quantify and characterize variations forest and shrub canopy density and related growth rates across the SJMNM area using more than 30 consecutive years of Landsat satellite image data.

The Normalized Difference Vegetation Index (NDVI) from Landsat has been closely correlated with percent cover measurements of green vegetation canopies in arid ecosystems, as reported in numerous published studies [9-14]. More specifically, Ramsey et al. [15] found that NDVI from Landsat was closely correlated ($r = 0.88$; $p < 0.05$) with total percent cover of live vegetation in a semi-arid sage-brush ecosystem in south-central Utah. Montandon and Small [15] reported similar results for NDVI correlations with fractional cover in creosote-dominated shrubland sites of New Mexico.

Study Area Descriptions

The SJMNM covers 76,250 ha (Figure 1) in the Peninsular Range system, east of the Los Angeles Basin in southern California. Dominant tree species were described by Fellows and Goulden [1] within two broad conifer groups: mid-montane (1400 to 2750 m) and sub-alpine (2600 to 3000 m). The mid-montane conifer group includes *Abies concolor* (white fir), *Pinus lambertiana* (sugar pine), *P. coulteri*, (Coulter pine), *P. jeffreyi* (Jeffrey pine), *P. ponderosa* (Ponderosa pine), and *Calocedrus decurrens* (incense cedar). The sub-alpine conifer group includes *P. contorta* (lodgepole pine) and *P. flexilis* (limber pine). Shrub species common in the SJMNM include chamise (*Adenostoma fasciculatum*), California juniper (*Juniperus californica*), and desert ceanthous (*Ceanothus greggii*) [16].

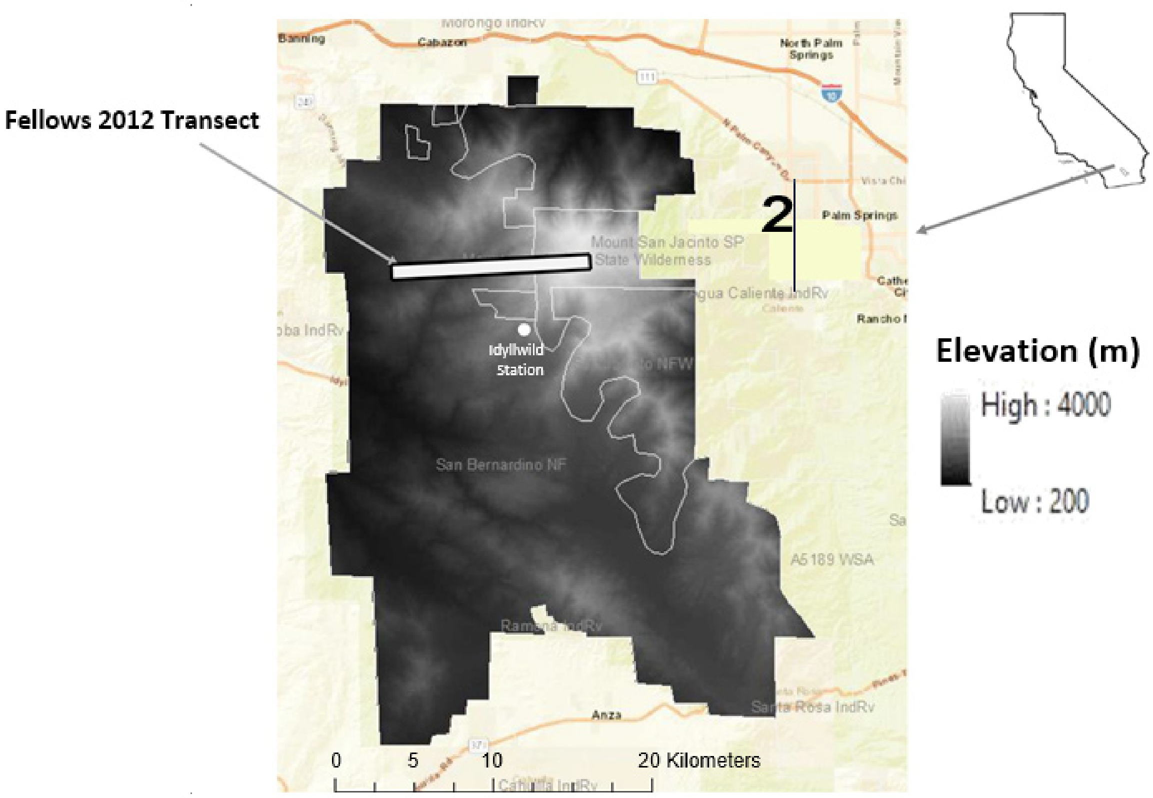

Figure 1: Study area location in the San Jacinto Mountains of southern California.

Annual precipitation at 1640 m elevation (Idyllwild station, 33° 45' N, 116° 43' W) has averaged 605 mm over the past 30 years (ranging from 270 to 1145 mm yr^{-1}), with mean monthly air temperatures from winter to summer ranging from 5.4° to 20.8°C. Air temperature decreases in the San Jacinto Mountains with elevation at an average lapse of 5° C km^{-1} [17], whereas mean precipitation increases with elevation to around 1500 m [18].

Methods

Satellite Image Data Processing

Cloud-free imagery from Landsat sensors was selected from the United States Geological Survey (USGS) Earth Explorer data portal (available online at earthexplorer.usgs.gov) for every year from 1986 to 2017. Landsat scenes from path/row 40/37 were acquired between May 1 and June 30 each year. All images used in this study were geometrically registered (UTM Zone 10) using terrain correction algorithms (Level 1T) applied by the USGS EROS Data Centre.

For the Landsat 4-5 Thematic Mapper (TM) images acquired between 1985 and 2011, 30-m resolution surface reflectance data were generated from the Landsat Ecosystem Disturbance Adaptive Processing System [19]. Moderate Resolution Imaging Spectroradiometer (MODIS) atmospheric correction routines were applied to Level-1 TM data products. Water vapor, ozone, geopotential height, aerosol optical thickness, and digital elevation are input with Landsat data to the Second Simulation of a Satellite Signal in the Solar Spectrum (6S) radiative transfer models to generate top of atmosphere (TOA) reflectance, surface reflectance, brightness temperature, and masks for clouds, cloud shadows, adjacent clouds, land, snow, ice, and water. Landsat 8 (after 2012) surface reflectance products were generated from the L8SR algorithm, a method that uses the scene center for the sun angle calculation and then hard-codes the view zenith angle to 0. The solar zenith and view zenith angles are used for calculations as part of the atmospheric correction.

NDVI was computed for this study using Landsat bands by the equation:

$$NDVI = (NIR – Red) / (NIR + Red)$$

where Red is the reflectance band from 0.63 to 0.69 µm and NIR is the near-infrared reflectance band from 0.77 to 0.90 µm [20]. NDVI was scaled by the USGS Earth Explorer source from 0 to 10000, with low values of (near 0) indicating barren land cover and high values of NDVI (above 7000) indicating dense canopy vegetation cover [21].

Statistical Analysis

All 30-m Landsat NDVI values within a 0.5 km wide x 12 km long transect covering the sampling gradient locations of Fellows and Goulden [1] were extracted for time-series analysis over an elevation range from 1297 m to 3150 m (Figure 1, hereafter referred to as the “Fellows [17]” transect). Within the larger SJMNM boundary areas shown in Figure 1, 5000 points were randomly selected for extraction of yearly Landsat NDVI values, spanning all elevation zones from 400 m to 3200 m consistently. Tests of statistical significance between years of NDVI were carried out using the two-sample Kolmogorov-Smirnov (K-S) test, a nonparametric method that compares the cumulative distributions of two data sets [22]. The K-S Difference test does not assume that data were sampled from Gaussian distributions (nor any other defined distributions), nor can its results be affected by changing data ranks or by numerical (e.g., logarithm) transformations. The K-S test reports the maximum difference between the two cumulative distributions, and calculates a probability (p) value from that difference and the group sample sizes. It tests the null hypothesis that both groups were sampled from populations with identical distributions according to different medians, variances, or outliers. If the K-S p value is small (i.e., < 0.05), it can be concluded that the two groups were sampled from populations with significantly different distributions.

Results

Climate Data Summaries

Comparisons of water-year (WY, October to September) precipitation totals at the Idyllwild weather station showed that the years 1993, 1995, 1998, 2005, 2011, and 2017 were all above-average precipitation periods (Figure 2). Each of these WYs totals was more than 50% higher than the long-term WY average. The WYs of 1999-2002, 2007, and 2014 were all below-average precipitation periods in the study area, commonly with 40% lower precipitation than the long-term WY average. Trends in average annual air temperature records showed a significant warming pattern ($p < 0.01$) in the 30-year climate record at the Idyllwild station (Figure 3).

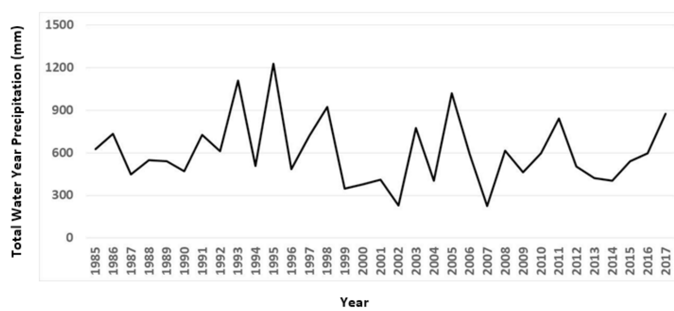

Figure 2: Water-year precipitation totals from 1985 to 2017 at the Idyllwild weather station.

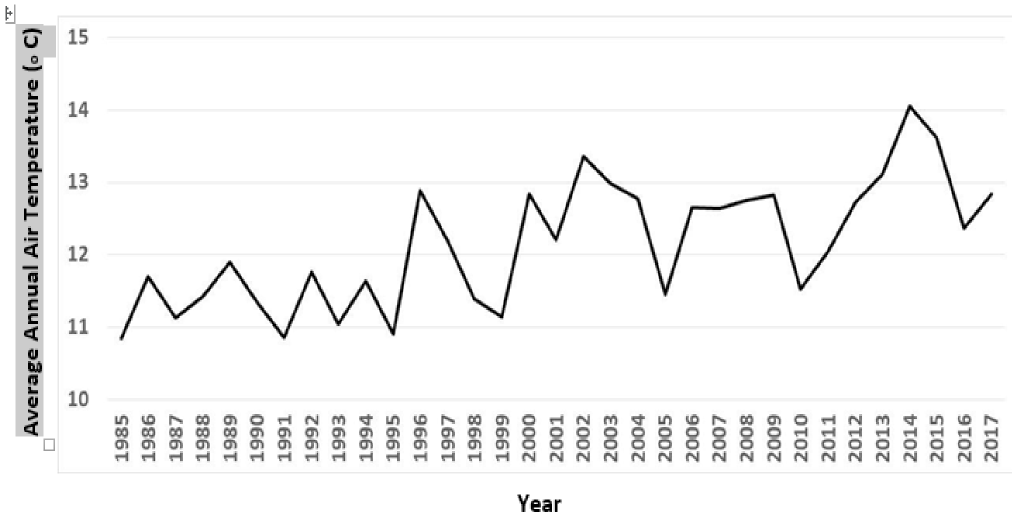

Figure 3: Trends in average annual air temperature records from 1985 to 2017 at the Idyllwild weather station.

Landsat NDVI Changes with Elevation

The change in Landsat NDVI between 1985 and 2017 across the Fellows [17] sampling transect from low to high elevation (1297 m to 3150 m) showed that vegetation green cover was significantly lower ($p < 0.01$, K-S test) in below-average precipitation periods of 2002, 2007, and 2014, compared to green cover in the above-average precipitation years of 2011 and 2017 (Figure 4). These differences between dry-to-wet year green cover was most pronounced in the mid-montane zone between 1600 m and 2300 m elevation, and to a lesser degree in lower montane elevation zone of 1300 m to 1600 m.

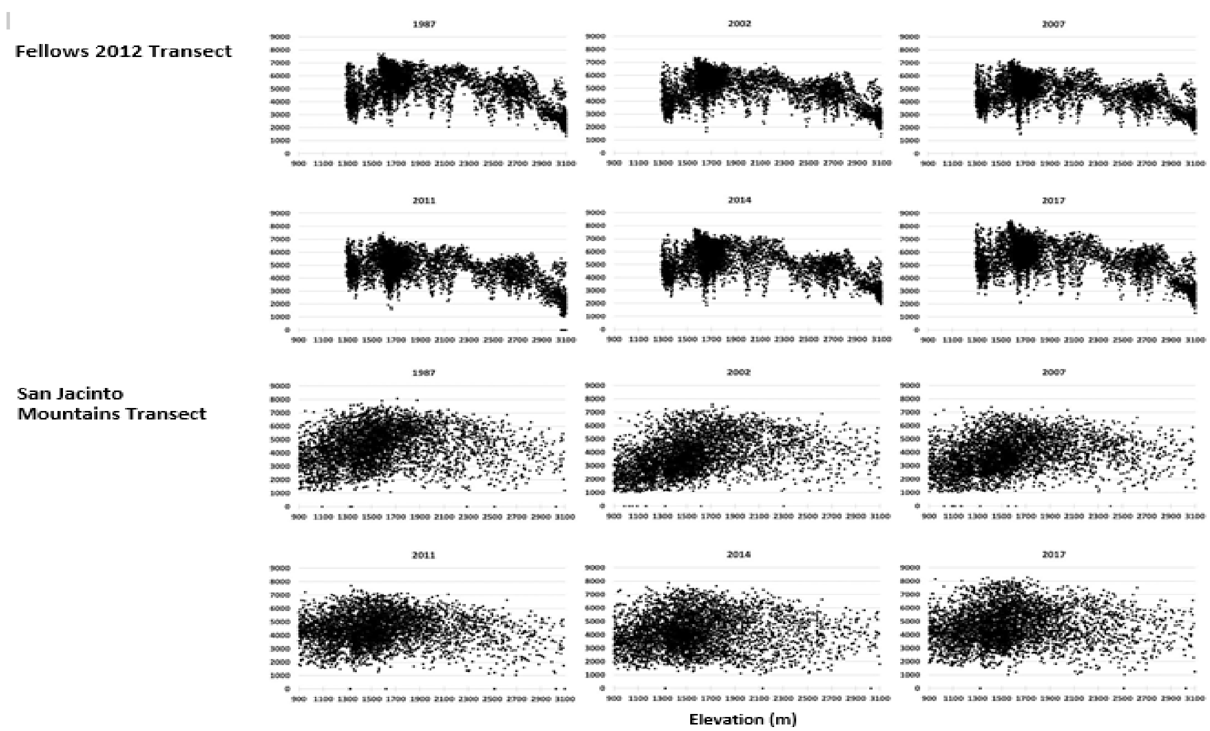

Figure 4: Change in NDVI with elevation across the Fellows 2012 transect and the larger SJMNM area for selected dry and wet years since 1986.

Comparisons of NDVI with elevation along the Fellows 2012 sampling transect were also made to the year 1987, which was a slightly below-average precipitation period, compared to the long-term average. This early year from the time-series showed significantly higher ($p < 0.01$, K-S test) overall NDVI than in the years 2002, 2007, 2017. This difference was due mainly to the higher green cover observed in 1987 within the sub-alpine zone of 2600 m to 2800 m elevation, compared to more recent years.

Comparison of NDVI change with the 2007 measurements of the fraction of conifer cover reported over the Fellows [17] sampling transect by Fellows and Goulden [1] showed numerous differences, which were most pronounced at all elevations below 2100 m (Figure 5). Specifically, the total green cover of perennial plants measured by NDVI in 2007 below 2200 m elevation showed a maximum level of 7300 and an average of 5056 NDVI units, whereas the fraction of conifer cover reported by Fellows and Goulden [1] below 2200 m elevation was consistently below 0.3 and only reached 0.5 (roughly comparable to 5000 NDVI units) at around 2100 m elevation. This implied that at sampling locations below 2100 m elevation conifers were not numerous in the overall vegetation cover, and the higher relative NDVI detected at these locations was contributed by non-conifer trees and shrubs. Nonetheless, the peak fractions of conifer cover reported by Fellows and Goulden [1] at 2200 m and 2500 m along their sampling transect corresponded to peaks in the NDVI elevation profile as well. NDVI showed another peak around 2800 m elevation that was not measured as high fraction of conifer cover by Fellows and Goulden [1], implying again that non-conifer trees and shrubs made up a substantial fraction of the total perennial plant green cover at this elevation zone.

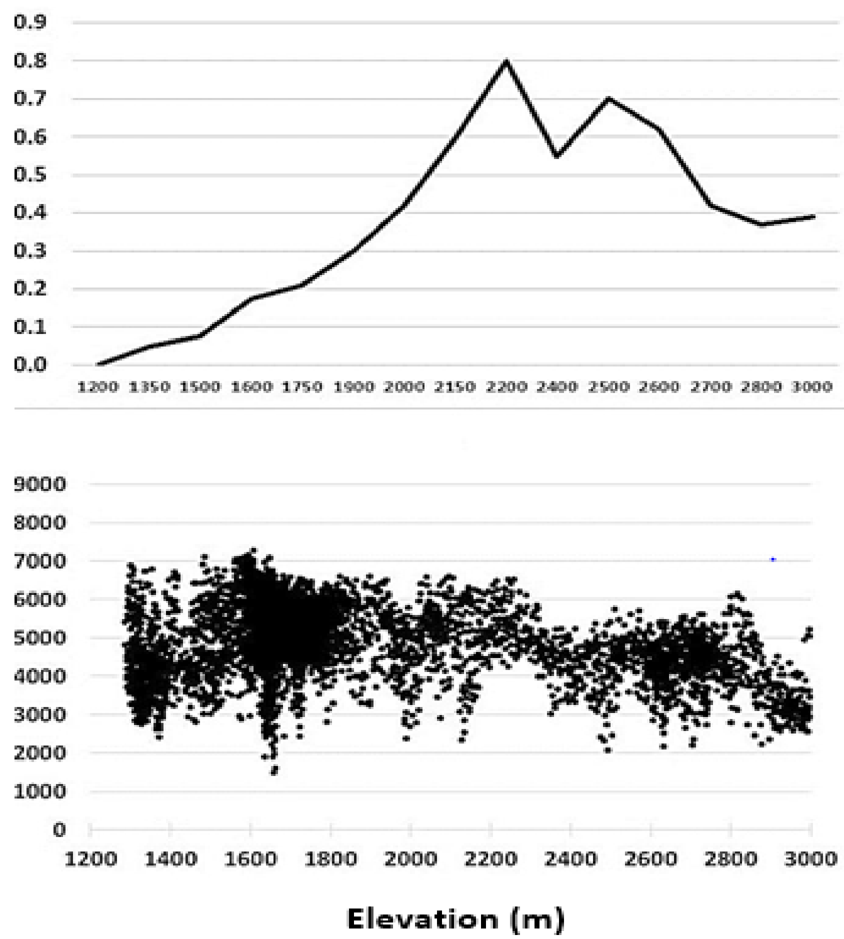

Figure 5: Comparison of the conifer fraction measured in 2007 by Fellows and Goulden [1] along their elevation transect and 2007 NDVI along the same 30-m transect.

Landsat 30-m pixels along the Fellows 2012 sampling transect were divided into south-facing and north-facing aspects for comparison of yearly NDVI along the full elevation transect measured by Fellows and Goulden [1]. Nearly 66% of all these pixels' locations were south-facing and the south-facing NDVI locations were significantly higher ($p < 0.01$, K-S test) by 500 to 1000 NDVI units than at north-facing locations along the entire Fellows 2012 sampling transect for each of the years shown in (Figure 4).

To assess whether the Fellows 2012 sampling transect was representative of the larger SJMNM cover area shown in Figure 1, land cover types from the USGS National Land Cover Dataset [23] were first plotted along the full elevation gradient from 900 m to 3100 m.

There were several notable differences found between the Fellows 2012 sampling transect and the larger SJMNM cover area (Figure 6) - namely a higher frequency of river canyons, grasslands, barren rock and open space (roads and cleared land) over the larger SJMNM area, especially at elevations below 2100 m. In addition, the Fellows 2012 sampling transect showed an absence of shrub land cover between about 2000 m and 2500 m elevation, whereas the larger SJMNM area showed continuous cover of shrub lands and evergreen forest over the full elevation gradient.

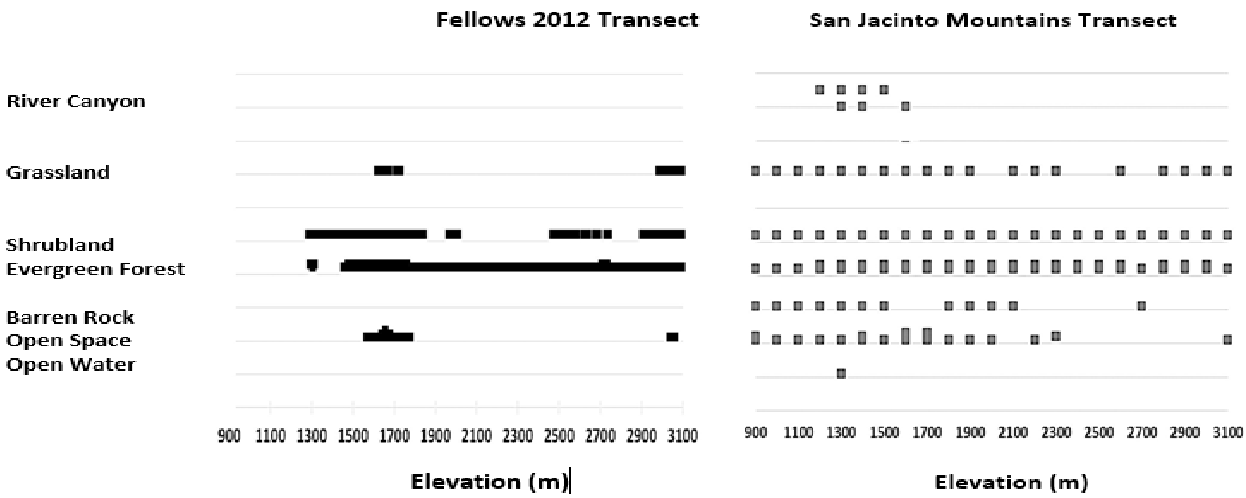

Figure 6: Comparison of 2011 NLCD land cover types along the Fellows 2012 elevation transect and across the larger SJMNM area.

Comparisons of NDVI time-series between the Fellows 2012 sampling transect and the larger SJMNM area showed notable differences as well (Figure 7). In all years since the mid-1980s, NDVI at elevations lower than 2200 m was significantly higher on average ($p < 0.05$) along the Fellows 2012 transect than in the larger SJMNM area. In above-average precipitation years (such as 1993, 2005, 2011, and 2017), NDVI at elevations between 2200 m and 2750 m was significantly higher on average ($p < 0.05$) along the Fellows 2012 transect than in the larger SJMNM area. Within the larger SJMNM area, average NDVI at elevations lower than 2200 was not consistently higher than average NDVI for elevations between 2200 m and 2750 m, whereas along the Fellows 2012 transect, NDVI was significantly higher on average ($p < 0.05$) in every year at elevations lower than 2200 m, compared to elevations between 2200 m and 2750m.

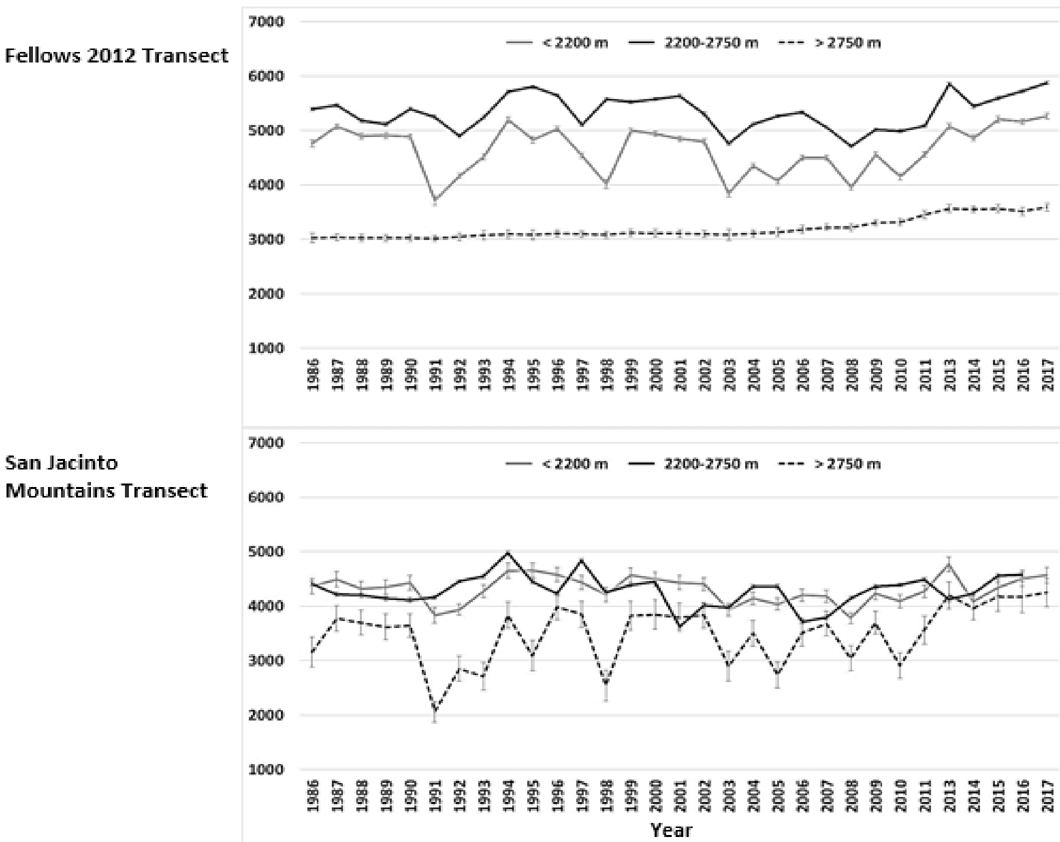

Figure 7: Comparisons of the change in average NDVI for three elevation zones across the Fellows 2012 transect and the larger SJMNM area for the years 1986 to 2017. Error bars represent two standard errors of the mean NDVI.

The average NDVI for locations above 2750 m along the Fellows 2012 transect increased significantly ($p < 0.05$) from 2009 to 2017, and within the larger SJMNM area, average NDVI increased significantly ($p < 0.05$) from 2010 to 2015 (Figure 7). Prior to 2010, NDVI averaged for locations above 2750 m within the larger SJMNM area was highly variable between 2000 and 4000 NDVI units, whereas average NDVI above 2750 m elevation along the Fellows 2012 transect was stable for about 20 years at an average of 3000 NDVI units.

Discussion

Three decades of Landsat NDVI analysis generally supports the findings of Kelly and Goulden [5] and Fellows and Goulden [1] that surface temperature warming, and the occurrence of severe drought periods increase vegetation stress and perennial plant mortality in mountainous ecosystems of southern California. However, the updated (to 2017) satellite greenness index record indicated that these changes in live green tree and shrub cover have not been irreversible.

Although Fellows and Goulden [1] reported that conifer mortality from the years 2002 to 2007-2008 was focused in the lower portion of the mid-montane zone (from about 1800 m to 2500 m elevation) along their plot transect, which drove the conifer distribution upslope, we found no evidence that this upslope shift in percent tree greenness cover would be a permanent change. A 30-year time-series of NDVI along the Fellows 2012 transect was in agreement with the measurement results Fellows and Goulden [1], in that vegetation green cover was significantly lower in the below-average precipitation periods of 2002 and 2007 compared to green cover in the above-average precipitation years. Nonetheless, relatively wet years like 2017 allowed an extensive recovery and infilling of perennial vegetation cover, as measured by NDVI, even after several consecutive years of below-average precipitation across the SJMNM.

In spite of consistent temperature warming trends since the late 1970s in these California mountain landscapes, it is probable that a corrective downslope shift in plant (re)growth can be explained by dominant species tracking of changes in climatic water balance, rather than solely in response to surface temperature changes, as documented by Crimmins et al. [6]. Downslope shifts in vegetation cover density can be expected to occur in regions where future increases in precipitation and soil water availability will outpace evaporative demand, at least periodically. Based on the remote sensing results we presented, even vegetation decline during several consecutive years of warming and drought can be offset with infilling and regrowth during a single year of anomalously high rainfall in the San Jacinto Mountains.

Moreover, it was shown that the Fellows 2012 transect did not represent the larger SJMNM area in several important aspects. Land cover types are more diverse across the larger SJMNM area, particularly with representation of large river canyons and barren rock cover over longer and steeper elevation gradients. Changes in non-conifer forest cover was not represented in the Fellows 2012 transect, whereas these shrubland and grassland areas are prominent below 2000 m elevation across the larger SJMNM area. Prior to 2010, NDVI above 2750 m elevation along the Fellows 2012 transect was stable for about 20 years, while NDVI for locations above 2750 m within the larger SJMNM area was highly variable. The direction (positive or negative) of yearly NDVI change since 1986 in mid-montane zone of 2200 m to 2750 m elevation of the Fellows 2012 transect closely matched yearly NDVI direction changes in the sub-alpine zone above 2750 m elevation across the larger SJMNM area.

Conclusions

While mortality of predominant tree species may have increased in the mid-montane zone of the northern San Jacinto Mountains in the decades prior to 2008, remote sensing from the Landsat satellite detected no evidence that such shifts in percent plant cover have yet become a wide-spread and permanent pattern across the larger SJMNM area. The results from Landsat time-series analysis that the average NDVI for locations above 2750 m along the Fellows 2012 transect and within the larger SJMNM area has increased significantly from about 2009 to 2017 merits further investigations with field measurements and remote sensing in the San Jacinto Mountain range. This increase in sub-alpine vegetation green cover coincided with marked air temperature warming measurements (at the Idyllwild weather station) over at least the past 30 years.

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