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Changes in Vegetation Cover and Productivity in Yosemite National Park (California) Detected Using Landsat Satellite Image Analysis

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Abstract

The Sierra Nevada of California is a landscape where large forest fires have been suppressed for over a century and future climate warming has the potential to alter vegetation cover and surface water runoff. Remote sensing over the past 25 years can add new data and insights to this climate impact study. To determine if vegetation cover density and productivity had changed significantly across Yosemite National Park (NP) in California (USA) since the mid-1980s, a time-series of Landsat satellite imagery was analyzed. The study design controlled for annual precipitation amounts, elevation gradients, and vegetation age since the last stand-replacing (wildfire) disturbance in a comparison of Landsat data. Landsat image analysis over the past 20+ years showed that consistent increases in the satellite normalized difference vegetation index (NDVI) during relatively dry years were confined to large wildfire areas that burned in the late 1980s and 1990s. Unburned areas of the NP above 2900 m elevation on the Sierra Crest showed extensive decreases of more than -100 units in NDVI between relatively dry years. Several relatively small wildfires that burned in the early 1980s (prior to 1987) were the only areas of the NP that showed notable increases in NDVI (more than +200 units) between relatively wet years. These findings conflict with any hypotheses that NDVI-controlled plant evapotranspiration fluxes and river flows downstream could be markedly altered solely by vegetation cover change over most of the Yosemite NP in coming decades.

Keywords

Landsat; Yosemite; National Park; Climate change; Precipitation; Sierra Nevada; California; Wildfire; Evapotranspiration; NDVI

Introduction

Changes in subalpine vegetation growth and species distribution with elevation have been reported in association with recent climate trends in the mountainous areas of California and in other mountain ecosystems elsewhere in the world [1,2]. Evidence from montane and high-elevation field studies around the world has indicated that more cold-adapted plant species have experienced growth declines, whereas the more warm-adapted species have had increased growth responses [3].

Precipitation time series analysis of Sierra Nevada forest greenness has shown a transition from water limitation at low-to-mid elevations (lower than 2000 m) to cold temperature limitation at higher elevations [4]. On a California statewide basis, surface air temperatures have been warming in certain regions between 1950 and 2005 [5]. Warming detected in the Sierra Nevada mountain region has been due to mainly to changes in minimum daily air temperature, which has increased by 3.8°C over the 20th century and accelerated primarily in two multi-decadal periods, from 1920 to 1940 and from 1976 to 2000 [6].

Projections of continued regional warming over the next 50-100 years have been associated with predictions for Yosemite National Park and other protected wilderness areas of the central Sierra Nevada of a higher number of lightning-ignited fires, larger annual area burned at high severity, earlier snowmelt, more frequent flood events, higher basin-wide evapotranspiration (ET) fluxes from vegetation, and decreased river water flows into the Central Valley [7,8].

Recent vegetation field surveys shown that whitebark pine (*Pinus albicaulis*) in subalpine zones of just east of Yosemite NP experienced significant mortality from 2007 to 2010 and were extensively infested by mountain pine beetles [9]. It was reported that subalpine forests sampled between 1934 and 2007 in the Sierra Nevada (the majority within Yosemite NP) experienced a 20% decrease in large trees (greater than 60 cm diameter) due to mortality [10]. Daily minimum temperature increased by +1.2°C over the same time period. These findings have led to the conclusion that future shifts in vegetation composition and structure in the region are likely to depend on interactions between water balance and disturbance factors like fire, insects, and disease.

Annual vegetation ET flux in Sierra montane and sub-alpine vegetation communities has been closely correlated with the satellite normalized difference vegetation index (NDVI) in the analysis by Goulden and Bales [8]. This study predicted future increases in ET due to thicker forest canopies (i.e., higher NDVI) and reduced surface-water supply in large rivers of the central Sierra Nevada. Water supplies in Yosemite NP likewise depend on snow- or glacier-fed surface runoff into the Toulumne and Merced Rivers, such that increases in vegetation ET may lead to lower flows downstream in these rivers. Nonetheless, in a water balance modeling study, Shupe and Potter (2013) reported that average elevation and snowpack accumulation were the most important explanatory variables to understand historical sub-basin contributions to monthly discharge rates in Yosemite NP [11,12]. Upper subalpine areas were found to make a large contribution to peak discharge rates in relatively dry years because of the importance of the high-elevation snow packs. Dettinger and Cayan reported that the fraction of the annual runoff from the central Sierra that occurs in late spring has been decreasing for approximately the past 50 years [13]. This evidence suggests that relatively more of the annual runoff has been occurring outside of the vegetation growing season as a result of warmer winter and spring temperatures in the central Sierra.

The Landsat satellite NDVI has been shown to be an effective tool to monitor large-scale change in green vegetation cover and forest productivity, especially following disturbance in remote mountain

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areas of the western U. S. [14-21]. Advantages of NDVI for the purpose of vegetation monitoring have been cited in its mathematical simplicity and ease of comparability across numerous multi-spectral remote sensing platforms [22]. Results from Landsat image analyses have shown that canopy green cover typically increases rapidly over the first five years following a stand-replacing disturbance, doubling in value by about 10 years after the disturbance, and then leveling off to approach pre- disturbance (mature) stand values by about 25-30 years after the disturbance event [23].

In the present study, 20+ years of Landsat satellite imagery at 30 m ground resolution was analyzed for the first time for Yosemite National Park (NP) to determine if NDVI had changed significantly across the NP landscape since the mid-1980s. The study design controlled for annual precipitation amounts, elevation gradients, and vegetation age since the last stand-replacing (wildfire) disturbance. The purpose of the analysis was to determine if changes in NDVI between burned and unburned areas suggested major alterations in patterns of vegetation productivity, water use (as a surrogate for ET fluxes), canopy density in protected areas of the NP. Comparison of relatively wet-to-wet and dry-to-dry year NDVI maps allowed the results to control for the high levels of interannual variation in snow accumulations and precipitation amounts observed over the study period, and to focus on the potential impacts of air temperature warming and insect damage.

Yosemite NP is managed as a wilderness area, such that changes in vegetation cover would have been little affected by directs human activities, mainly logging or residential developments. Climate change, wildfire, and pest and insect outbreaks are the main remaining drivers of vegetation cover change in the NP, making it a logical choice for studies of natural moisture availability and NDVI trends in the region over the previous three decades.

Study Area Description

Yosemite NP is located on the western slope of the Sierra Nevada Mountains in central California (Figure 1). The NP extends from lower elevations of 900 m along the Merced River bottoms on the western side, to the Sierra Crest at over 3600 m elevation on the eastern side, with total area coverage of about 3018 km^2. The predominant vegetation cover types in Yosemite NP are: evergreen forest between 1000 m and 3000 m, barren outcrops above 3000 m, riparian woodlands and scrublands along the river bottoms above 1000 m, and herbaceous grasslands in the lower basin below 1000 m and in alpine meadows (Figure 2).

Surface water in Yosemite NP is drained mainly by the upper Merced and Tuolumne Rivers, with a range of snowmelt-contributing elevations from 1200 to 3700 m. The majority of total snowmelt (50 - 60%) into these rivers is derived from the 2100–3000 m elevation range [24]. After June, the main sources of snowmelt are from elevations above 3000 m.

The climate of Yosemite NP is characterized by warm, dry summers and cool, wet winters, with precipitation falling primarily between November and April. Yearly precipitation has been highly variable in Yosemite NP since the early 1990s (Figure 3). Over the past 25 years of precipitation records, the relatively wet years of 1986, 1995, 2005, and 2010 and the relatively dry years of 1990, 2001, 2007, and 2013 have been confirmed as extremes by peak annual snow water equivalents across the Sierra Nevada [4].

Methods

Landsat image data

Near cloud-free imagery from the Landsat Thematic Mapper (TM) sensor was selected from the years 1986 to 2013 from the US Geological Survey Earth Explorer data portal (http://earthexplorer.usgs.gov/). TM image data from path/row 42/34 were consistently acquired for a anniversary window between June 20 and July 15 each year, around the peak of the Sierra Nevada growing season to

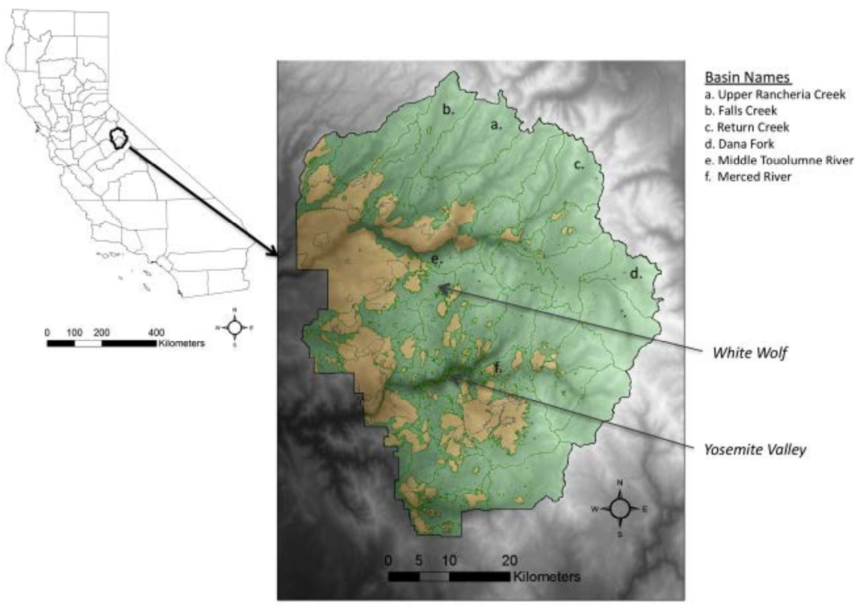

Figure 1: Map of the Yosemite NP study area in California with shaded elevation and wildfire perimeters (1930 - 2012) outlined in yellow , unburned areas (since 1930) outlined in green, with HU12 drainage basins delineated from US Geologic Survey.

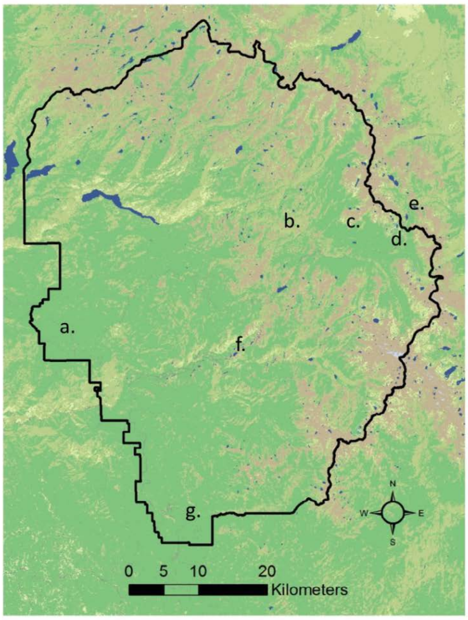

Figure 2: Vegetatation cover types in the Yosemite NP from the USDA 2012 CLD. Color key: Green – Evergreen forest, Tan – Shrubland, Yellow-Grassland.

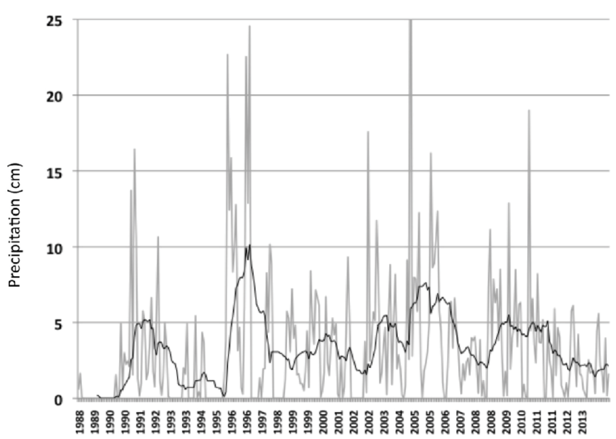

Figure 3: Monthly precipitation recorded at the White Wolf weather station (37.58° N, -119.65° W; 2670 m elevation). The 12 month running mean precipitation is shown as the dark solid line. Missing values are noted for the years 1989-90 and 1995-96.

minimize variation caused by seasonal vegetation fluxes and sun angle differences. Snow cover on tree canopies was absent in these images [23]. Any residual snow cover under forest canopies was considered part of the soil background reflectance.

All images used in this study were acquired by Landsat TM sensors, geometrically registered (UTM Zone 10) using terrain correction algorithms (Level 1T) applied by the U. S. Geological Survey EROS Data Center, and then converted to at-sensor reflectance following the algorithms from [24,25]. No further corrections for atmospheric scattering were applied, since the reflectance indices used in this study employed the NIR wavelengths that are minimally affected by atmospheric scattering, especially during the summer months for the Sierra Nevada study area [26,27].

Landsat data sets from the relatively wet years of 1986, 1995, 2005, and 2010 and the relatively dry years of 1990, 2001, 2007, and 2013 were processed for comparison. NDVI (scaled from 0 to 1000) was computed for all Landsat images as the differential reflectance between the red and near-infrared (NIR) portions of the spectrum by the equation:

$$NDVI = (NIR – Red) / (NIR + Red)$$

Where NIR is the reflectance of wavelengths from 0.76 to 0.9 µm and Red is the reflectance from 0.63 to 0.69 µm. Low values of NDVI (near 0) indicate barren land cover whereas high values of NDVI (near 1000) indicate dense canopy vegetation cover.

Additional spatial data sets

Areas burned by wildfire between 1930 and 2012 and the years since wildfire within the NP were delineated from the Yosemite Fire History database [28]. These fire perimeters were compiled in part from the California Department of Forestry, Fire and Resource Assessment Program (FRAP; data available at http://frap.cdf.ca.gov/), with additions from the National Park Service.

Elevation at 1 arc-second resolution was derived from the United States Geological Survey (USGS) National Elevation Dataset (NED). For each 30-m grid cell, slope (in percent) was calculated as the maximum rate of change in elevation value from that cell to its neighbors to determine the steepest downhill descent from the cell. Aspect was calculated and expressed in degrees, moving clockwise from 0 (due north) to 360 (again due north).

Vegetation cover types within the NP were determined from the U. S. Department of Agriculture's National Agricultural Statistics Service (NASS), California Cropland Data Layer (CDL) from 2012 (available at http://nassgeodata.gmu.edu/CropScape). The CDL is a raster, geo-referenced land cover data layer with a ground resolution of 30 m. The CDL is produced using Landsat satellite imagery collected during the current growing season.

NDVI difference calculations

NDVI images were overlaid and the differences between date values were computed using raster mathematics. The relatively wet years of 1986, 1995, 2005, and 2010 and the relatively dry years of 1990, 2001, 2007, and 2013 were compared for changes over time across the entire study area. This overall methodology controlled for annual precipitation amounts, as well as elevation gradients, and vegetation age since the last stand-replacing (wildfire) disturbance.

Within burned areas, the mean yearly NDVI was computed for time series comparisons by years since fire. Within unburned (since 1930) areas of the NP, which covered a great portion of the study area as a whole, 2000 point locations were randomly selected to test the differences between cumulative distributions of NDVI as a function of elevation, slope, aspect, and vegetation cover types. This sub-sampling method provided an appropriate number of points for statistical comparison of the yearly NDVI values.

Tests of statistical significance between NDVI dates were carried out using the two-sample Kolmogorov-Smirnov (K-S) test, a non-parametric method that compares the cumulative distributions of two data sets [29]. The K-S 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 *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

NDVI differences over time

Differences in Landsat NDVI over more than 20 years across the Yosemite NP showed that changes in vegetation cover greenness were strongly dependent on both annual precipitation and the history of wildfires (Figures 4a and 4b). Comparison of the relatively wet years of 2010 and 1986 (Figure 4a) indicated that most areas of the NP showed declines in NDVI, except along the Merced and Toulumne River bottoms where riparian vegetation would have had ready access to stream water into the summer months. Unburned areas in the Yosemite Wilderness northeast of Mount Gibson (around 38.00° N, -119.70° W; 2540 m elevation) and from Toulumne Meadows (37.87° N, -119.36° W; 2650 m elevation) north into the McCabe Lakes area (38.03° N, -119.34° W; 2770 m elevation) showed extensive declines in NDVI (more than -200 units) between these relatively wet years.

Based on FRAP data, a total of 77,652 ha (26%) of the NP area were delineated as burned since 1930. Most wildfire areas throughout the NP that burned during the late 1980s and 1990s stood out with declines in mean NDVI for each burned area of more than -100 units between these relatively wet years (Figure 5a), most notably within the Ackerson, A-Rock, Alaska, Frog, and Steamboat fire perimeters. Several relatively small wildfires that burned in the early 1980s (prior to 1987), namely the Bartlett, Pate Valley, and Glacier Point fires, were the only areas of the NP that showed notable increases in NDVI (more than +200 units) between these relatively wet years, along with the forested areas surrounding Edison Lake (at 37.63° N, -119.52° W; 2490 m elevation).

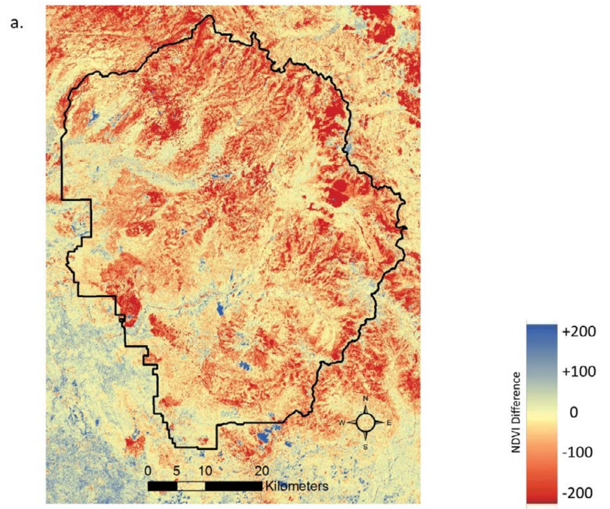

Figure 4(a): Difference in Landsat NDVI across Yosemite NP for (a) comparison of relatively wet years of 2010 and 1986, (b) comparison of relatively dry years of 2013 and 1990.

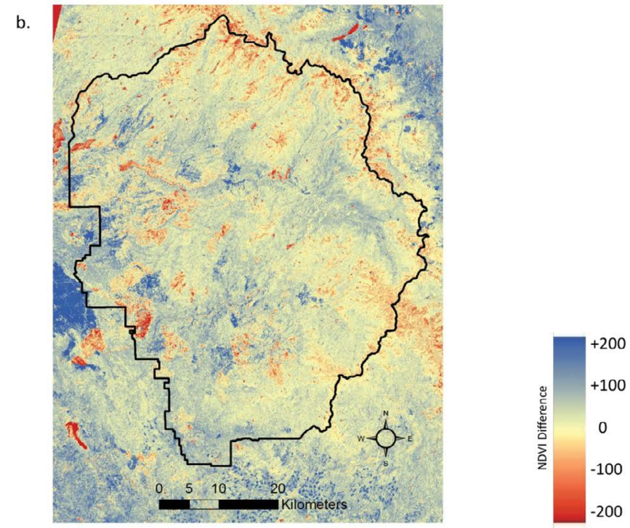

Figure 4(b): Comparison of relatively dry years of 2013 and 1990.

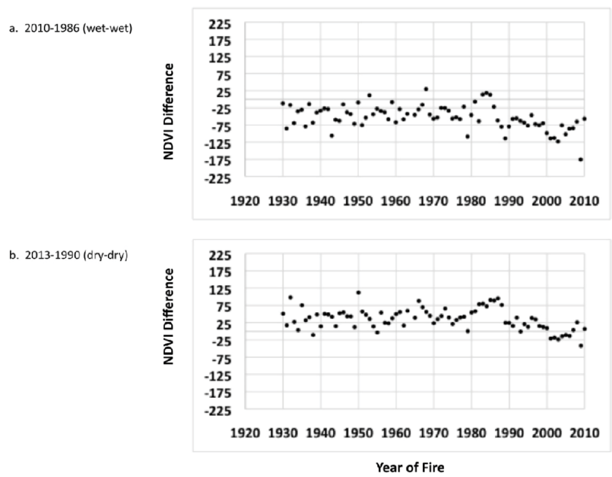

Figure 5: Mean NDVI difference computed for each burned area of Yosemite NP by year of the fire for (a) comparison of relatively wet years of 2010 and 1986, (b) comparison of relatively dry years of 2013 and 1990.

The comparison of the relatively dry years of 2013 and 1990 (Figure 4b) indicated that increases in mean NDVI for each burned area of more than +100 units were confined largely to Leconte Fire area of 1999, the Walker Fire area of 1988, the Glacier Point Fire area of 1986, the Pate Valley fire area of 1985, and unburned areas northwest of Aspen Valley (37.84° N, -119.79° W; 1744 m elevation). All other areas of the NP showed almost no change in NDVI (less than plus or minus 50 units) between the dry years of 2013 and 1990. Notable areas of decrease (more than -100 units) in NDVI between these relatively dry years were within the large burned area perimeters (Figure 5b), particularly the Ackerson and Eleanor fires, the Hoover fire, and the Big Meadow and Wildcat fires, both of which burned in 2009.

Unburned northeastern areas of the NP above 2900 m elevation on the Sierra Crest also showed extensive decreases of more than -100 units in NDVI between these relatively dry years. These areas were representative of a widespread regional pattern of NDVI that has declined in nearly all alpine (herbaceous cover) zones of the central Sierra Nevada, while the unburned subalpine (forest-shrub) transition zones have been greening up as the growing seasons have gotten longer and drier. This was a marked and consistent deviation of green cover trends along the treeline boundaries of Yosemite NP.

Statistical analysis of changes in green vegetation cover was carried out for the 224,165 unburned (since 1930) ha of Yosemite NP. Comparison of the NDVI differences among HU12 basins showed a area-weighted mean change of -60 units between the wet years of 2010 and 1986, versus a basin area-weighted mean change of +13 units between the dry years of 2013 and 1990 (Figure 6). The cumulative distributions of these two (wet versus dry year) NDVI difference group were significantly different (K-S test, $p < 0.001$), with a maximal difference of 88 units. The HU12 basin areas that showed the largest average decreases in NDVI between 1986 and 2010 were the Upper Rancheria Creek, Falls Creek, Return Creek, and Dana Fork (Table 1) [30].

The statistical comparison of the yearly NDVI values sampled from 2000 randomly selected unburned locations across Yosemite NP confirmed that mean NDVI decreased consistently in the wet years after 1986 (Table 2) [31]. Mean NDVI did not change significantly between the wet years of 2005 and 2010. Conversely, mean NDVI increased by a small (but statistically significantly, $p < 0.05$) increment between the relatively dry years of 1990 and 2013. Three of the four dry years (the exception being 1986) showed significantly higher mean NDVI ($p < 0.05$) than was estimated for the relatively wet years of 1995, 2005, and 2010.

NDVI change with vegetation type and elevation

Mean NDVI in unburned areas was highest for evergreen forest cover types, with maximum values detected above 700 units in every year. Mean NDVI in unburned areas was lowest (less than 300 units) for herbaceous grassland and wetland meadow cover types sampled in wet years.

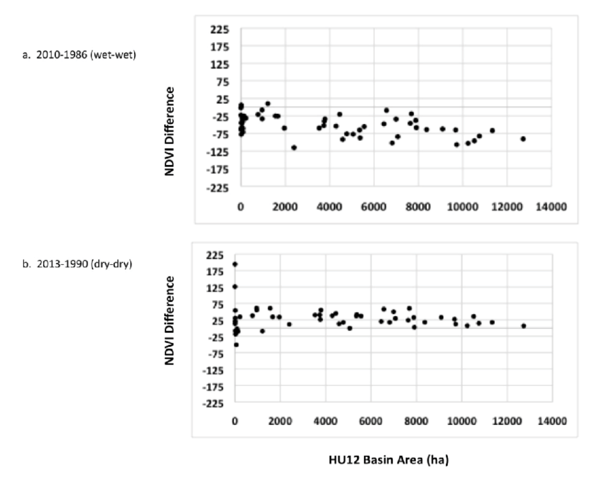

Figure 6: NDVI differences in unburdened areas of Yosemite NP by the size of HU12 basins for (a) comparison of relatively wet years of 2010 and 1986, (b) comparison of relatively dry years of 2013 and 1990.

Table 1: Mean change in NDVI between 1986 and 2010 for all unburned (30-m resolution) areas of the largest HU12 basins (> 6000 ha) within Yosemite NP [30].

HU12 Basin Name	Area (ha)	Mean	2 SE
Upper Rancheria Creek	12,725	-91	0.44
Lyell Fork	11,335	-67	0.48
Piute Creek	10,750	-83	0.46
Delaney Creek-Tuolumne River	10,524	-96	0.68
Falls Creek	10,241	-103	0.60
Return Creek	9,730	-107	0.77
Upper South Fork Merced River	9,680	-65	0.40
Yosemite Creek	9,092	-62	0.47
Kendrick Creek	8,370	-64	0.53
Lyell Fork Merced River	7,908	-58	0.57
Tenaya Creek	7,881	-38	0.45
Middle South Fork Merced River	7,687	-19	0.35
Illilouette Creek	7,636	-46	0.51
Register Creek-Tuolumne River	7,073	-84	0.67
Upper South Fork Tuolumne River	6,994	-34	0.30
Dana Fork	6,819	-102	0.76
Indian Canyon Creek-Merced River	6,565	-9	0.42
Gray Peak Fork-Merced River	6,449	-48	0.43

Table 2: Yearly NDVI sampled from 2000 randomly selected point locations in all unburned (since 1930 based on the Yosemite Fire History database; van Wagtendonk and Davis, 2008) areas of Yosemite NP.

	Wet years				Dry Years					
	1986	1995	2005	2010	1990	2001	2007	2013	2010 - 1986	2013 - 1990
Mean	298	161	233	232	296	308	329	-66	26	303
St. Dev	198	191	203	197	175	179	205	90	50	180
2 SE	9	9	9	9	8	8	9	4	2	8
Minimum	-341	-215	-286	-188	-272	-172	-448	-524	-225	-298
Maximum	785	741	750	719	728	750	784	329	396	754

A 95% confidence interval for a sample mean difference is greater than (plus or minus) 2 standard errors (SE) [31].

Regression results for NDVI versus elevation (Figure 7) showed a consistent non-linear decrease in NDVI ($R^2 > 0.3$ for all years) above 2000 m elevation in all years. The correlations of NDVI values with elevation were higher overall in wet years compared to dry years, but correlation of the NDVI difference with elevation was weaker in the wet years compared to the dry years. The NDVI difference in both the wet years and the dry years changed from positive levels to predominantly negative levels at elevations above 2500 m. Regression results for NDVI versus slope or aspect showed no significant relationship for any of the years.

Validation of these NDVI results in this study for sub-alpine forest areas comes from a comparison of the field measurements made by Millar et al. (2012) of whitebark pine (*Pinus albicaulis*) stands located from 3 km to 60 km east of Yosemite NP [9]. All the study plots of Millar et al. (2012) were observed to have declined in green canopy cover (NDVI) over the past 25 years, at between -10% to -36%, in either a comparison of relatively dry years or relatively wet years since 1990 [9]. These results were consistent with the documented 50-80% increases in whitebark pine mortality within the treeline transition zone (above 2850 m elevation) from 2007 to 2010 in forests extensively infested by mountain pine beetles.

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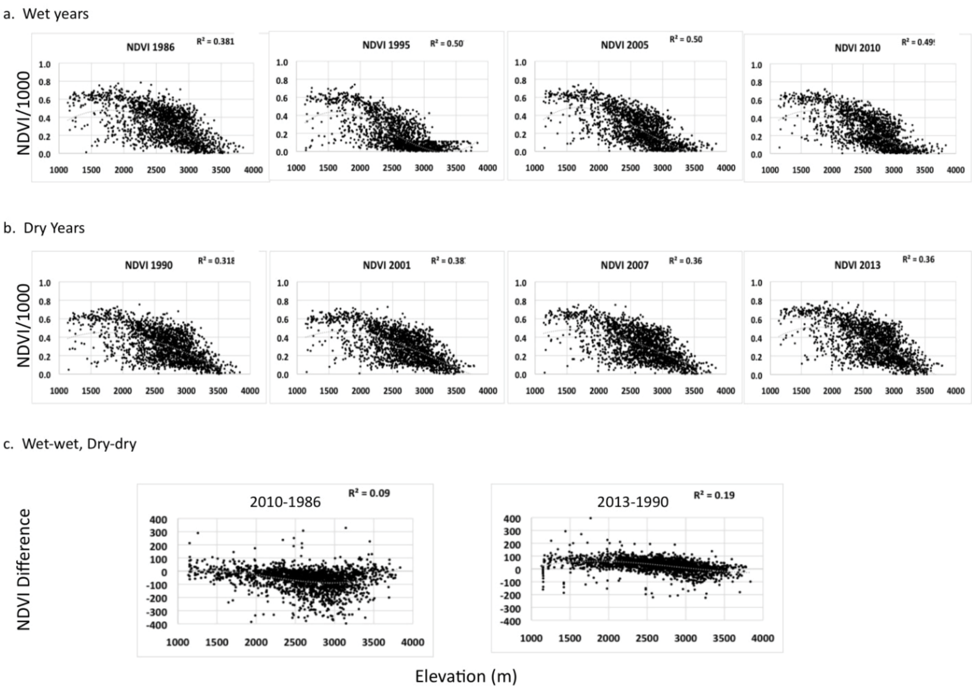

Figure 7: NDVI (sampled at 30 m resolution) versus elevation for N=2000 unburned locations Yosemite NP.

NDVI change in areas of special interest

Areas of special interest for ecological and cultural value in Yosemite NP (locations in Figure 2) were examined more closely for 27-year trends (1986 to 2013) in NDVI (Figure 8). At elevations lower than 2000 m, such as along the Mist Trail in Yosemite Valley and around the Toulumne Grove of Giant Sequoias (*Sequoiadendron giganteum*), NDVI has been relatively constant at between 600 and 700 units since 1986. In the Mariposa Grove of Giant Sequoias, where understory thinning and burning has been used to reduce fuel hazards, and heavy visitor use has been restricted to access by foot or through an interpretive tram system, NDVI has increased steadily, and most impressively between 1995 and 2005 [32]. At area elevations higher than 2000 m, changes in NDVI have been highly variable since 1986, following the pattern of increases in relatively dry years and decreases in relatively wet years. Meadow areas at elevations between 2700 and 3000 m gained the most vegetation green cover in dry years following wet years.

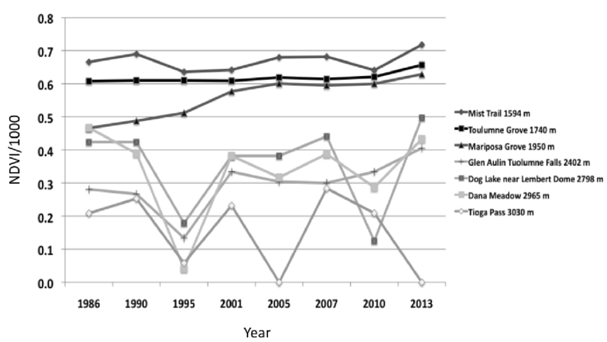

Figure 8: Trends in NDVI from 1986 to 2013 in selected areas of special interests for ecological and cultural value in Yosemite NP (with elevations listed).

Discussion

NDVI has increased significantly in Yosemite NP over the past 20+ years predominantly in large wildfire areas that burned in the late 1980s and 1990s. All other areas of the NP showed almost no change in NDVI (less than plus or minus 50 units) between the dry years since 1990, and NDVI more frequently decreased (rather than increased) at locations in the 20+ year time-series comparison of consistently wet periods. These results suggest that future changes in NDVI across the Sierra-Nevada region are likely to be more dependent on the frequency of severe drought events and the extent of stand-replacing wildfires, than upon region-wide temperature warming projections.

Winter precipitation and summer temperature of the same water year have been shown to be the most influential climatic variables for annual growth prediction for coniferous tree species of northern California [33]. This implies that lagged (multi-year) effects of extreme dry or wet years on NDVI changes would be minimal. The results of this study, derived from more than 20 years of Landsat image analysis, support the conclusion that the detectable changes in NDVI over time in Yosemite NP have been strongly dependent on elevation, annual precipitation (including snowpack accumulation), and wildfires.

Previously published comparisons with field measurements have shown that remotely sensed NDVI from surface reflectance was significantly correlated with both stand-level leaf area index (LAI) and with annual growth increments in coniferous forests and woodlands stands, including those in the western United States [34-37]. Landsat

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NDVI values did not saturate until LAI levels were far greater than those commonly reported for subalpine forest stands of the Sierra Nevada [31].

An explanation for the increases in NDVI in unburned areas from the time-series analysis of consistently dry years (compared to consistently wet years) was offered by Goulden and Bales, citing the evidence from Trujillo et al., who reported denser vegetation canopies during lighter snowpack and earlier snowmelt years in the Sierra Nevada [8,4]. Comparatively wet years can result in heavier snowpacks in Yosemite NP and can delay the snow-free period in sub-alpine zones for vegetation growth late into the summer in some years [38]. Earlier snow-free dates in dry years allow for more herbaceous plant cover to develop in sparsely wooded areas, and for more invasion and growth of pine saplings and shrub cover in subalpine meadows to be facilitated in the driest years [39]. Deep rooting and access to moisture in the underlying fractured bedrock of the Sierra Nevada mountains may also buffer trees from extreme annual shifts in precipitation and evaporative demand [40].

Dolanc et al. speculated that a longer growing season in the Sierra Nevada is a likely explanation for the generalized increase measured in the density of small (10–30 cm bole diameter) subalpine trees over the past several decades [10]. The observed decrease in density of large bole diameter (> 61 cm) trees in Sierra Nevada subalpine zone over the past 75 years is also consistent with these observed changes in climate. Higher temperatures can shorten the time to drought-induced mortality of trees and can increase the susceptibility of conifers to insect attack [41,42].

Areas of recent decrease in NDVI stood out in the results within the perimeters of large wildfires in Yosemite NP across consistently dry or wet years. It is worth noting that recent field studies by Collins and Roller (2013) and Goforth and Minnich have implied that sustained re growth of mixed-conifer forests of the Sierra Nevada remains uncertain in areas affected by high severity, stand-replacing wildfires [43,44]. This is particularly the case for the pine component within mixed-conifer forests. Vigorous re growth response of shrubs, coupled with high frequencies of hardwood forest regeneration, suggest a long-term compositional shift of mixed-conifer forests of the Sierra Nevada.

Furthermore, years with larger wildfires and the largest areas burned have been commonly characterized by lower winter and spring precipitation than years dominated by smaller area fires (van Wagtendonk, and Fites-Kaufman, 2006), reinforcing again the critical dependencies between and vegetation green cover (detected by NDVI), inter-annual precipitation, and area burned by wildfire in the region [45]. The potential for larger and more severe burns in the Sierra Nevada over the next century makes the monitoring of changes in sub-alpine vegetation in National Parks of the area an important indicator of regional impacts of future climate change [46].

The NDVI time series for Giant Sequoia groves in Yosemite indicate that these areas have been well-protected from disturbances and continue to grow in canopy density. In contrast, prominent higher-elevation meadow areas in the NP showed increases in vegetation green cover mainly in dry years following wet years, which supports the hypothesis that woody shrub and pine sapling cover may be increasing as historically moist Sierra wetlands dry out due to extended periods of drought.

Based on the close relationship measured between NDVI and ET fluxes by vegetation, Goulden and Bales concluded that climate warming predicted for the year 2100 in would “thicken” vegetation cover in the Upper Kings River basin of the Sierra Nevada (about 50 km south of Yosemite NP), increase basin-wide ET fluxes by 28%, and decrease water flow downstream in the Kings River by 26%. The findings from Landsat image analysis that NDVI has decreased throughout the Yosemite NP over the past 20+ years conflict with any assumptions that ET fluxes and river flows downstream have been markedly altered by vegetation change over most of Yosemite in recent decades [8]. The current dynamics of NDVI change with elevation over most of the NP area would have to first reverse, and then accelerate notably, to begin to approach the year 2100 predictions reported by Goulden and Bales for altered ET fluxes and river flows in the Sierra Nevada [8].

Conclusions

Landsat image comparisons over the past 20+ years showed that consistent increases in the satellite NDVI during relatively dry years were confined to large wildfire areas that burned in the late 1980s and 1990s. Unburned areas of Yosemite NP above 2900 m elevation showed extensive decreases of more than -100 units in NDVI between relatively dry years. Ongoing monitoring of subalpine vegetation areas is needed to detect whether future changes in NDVI across the Sierra-Nevada region will be severely impacted by extreme drought events and larger stand-replacing wildfires.

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