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Changes in Meadow Vegetation Cover in Yosemite National Park (California) Based on Three Decades of Landsat Image Analysis

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Abstract

Meadow ecosystems can serve as sensitive indicators of climate change impacts on the Sierra Nevada region. Landsat 30-m resolution image data over the past 25 years in Yosemite National Park was analyzed to track changes in the normalized difference vegetation index (NDVI) in all meadow units of Yosemite National Park. Results showed that NDVI values from the wet year of 2010 were significantly lower than NDVI values from the comparatively dry year of 2013 in the majority of meadow areas in the National Park. This finding implied that higher surface water levels could be detected in wet years using Landsat imagery. A sequence of NDVI changes in consistently dry years over the past three decades (1990, 2001, 2007 and 2013) showed progressively higher green plant cover in the majority of meadow areas, suggesting that some encroachment of woody vegetation since the early 1990s was detectable, especially at sub-alpine meadow elevations.

Keywords

Landsat; Meadows; Climate change; Wildfire; Sierra Nevada; California

Introduction

Meadows are found throughout practically every landscape of the montane and subalpine zones of the Sierra Nevada region of California [1]. A water table generally at a depth of less than 1 m and fine-textured soils are required to support wet meadows [2]. These are valley-bottom alluvial landforms on slopes commonly less than 6% [3]. An open meadow type is composed predominately of perennial sedges, rushes, and grasses, although wet meadows in the lodgepole pine montane zone may also support fringes of low ericaceous shrubs and willows, or stands of pine and aspen on the margins, particularly in the absence of wildfire.

Mountain meadows have been characterized as "sponges," storing snowmelt runoff within alluvium, and as "valves," regulating the discharge of groundwater from hillslope and bedrock flow systems [4]. During high stream flows, healthy meadows will slow channel runoff and allow for sediment deposition on the meadow floodplain, thus reducing bank erosion. During dry months in the Sierra Nevada, meadows sequester nutrients, trace metals, and organic materials in shallow pools and oxbows. Sierra Nevada meadows provide habitat for many invertebrates, as well as for threatened vertebrate species such as the willow fly-catcher (*Empidonax traillii*), great gray owl (*Strix nebulosa*), and the Yosemite toad (*Bufo canorus*) [5].

Degradation of montane meadows can occur along a number of pathways. Compaction of meadow soils by roads, intensive trampling, or overgrazing by livestock can reduce infiltration and promote lowering of the water table and stream channel bottoms (incision) [6]. As channels become more incised, water passes through a meadow more quickly and the filtering effects meadows can have on down-slope water quantity and quality are reduced [7]. In contrast, healthy meadows maintain high water tables, reduce erosion to downstream areas, and act as natural filters that improve downstream water quality.

Meadows in the Sierra Nevada may burn when vegetation cover is tall and dry, especially during drought periods. A fire crossing a meadow with high surface moisture usually consumes only current growth and some mulch [2]. Under extreme drought conditions, fire may damage the meadow, notably from subsequent gully erosion around meadow stream channels [8]. Ratliff [2] described a wildfire event in Kings Canyon National Park that started at 2680 m in early August 1977 and burned 60% of a 12 ha meadow area. Intensity of burning and depth of burning varied from place-to-place in the meadow. Areas with wide-leaf sedges burned most intensively, and the ash layer reached a depth of 38 cm in some places. One year after the fire, grass species made up only 8% of the ground cover, but three years later, grass cover had increased to about 75%.

Annual herbaceous forage production on Sierra Nevada meadows ranges from less than 340 kg ha^{-1} to over 4000 kg ha^{-1} [2]. Cole et al. [9] reported that meadows in wilderness areas can be maintained in a relatively undisturbed condition where pack stock use is low, but that substantial loss of vegetation cover is likely wherever meadows in the Sierra Nevada receive even moderate levels of repeated grazing.

Berlow et al. [10] reported that montane meadows in the Sierra Nevada have experienced expansion of shrubs (and reduction in herbaceous plant cover) since the introduction of livestock grazing and fire suppression efforts that began in the late 1800s. Shrub expansion has been commonly attributed to increased meadow aridity due to historic changes in stream hydrology [11]. Experimental results from Berlow et al. [10] also implied that small (1 m^2) soil disturbances by pocket gophers can promote the germination and growth of sagebrush seedlings in ungrazed herbaceous meadow areas. More frequent flooding and/or wildfires in the past also could have inhibited gopher activity in wet meadow areas, and thus restricted opportunities for shrub establishment. Such large-scale disturbances (flooding and wildfire) in Sierra Nevada meadows may have been essential to maintaining stable forest-meadow boundaries [8].

The objective of the present study was, for the first time, to analyze 25 years of Landsat satellite imagery at 30-m ground resolution in Yosemite National Park to determine if meadow vegetation cover had changed significantly since the early 1990s. Comparisons of Landsat vegetation index values between relatively wet and dry years were

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evaluated for detection of higher water tables in meadow units. The study design controlled for annual precipitation amounts, elevation gradients, and years since the last major wildfire.

Satellite remote sensing has been shown to be an effective method to measure large-scale patterns of vegetation biomass and productivity in remote mountain areas [12]. Van Wagtendonk and Root [13] reported that the satellite normalized difference vegetation index (NDVI) can provide information necessary to distinguish fuel model types when analyzed over a summer growing season in the Sierra Nevada. Similar studies have found that NDVI is sensitive to early (herbaceous) post-fire recovery and subsequent woody (tree and shrub) regrowth trajectories [14,15].

Study Area Description

The study area was the Yosemite National Park (NP) on the western slope of the Sierra Nevada mountains in central California (Figure 1). 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 shrub lands along the river bottoms above 1000 m, and herbaceous grasslands in the lower basin below 1000 m. Yearly precipitation has been highly variable in Yosemite NP since the early 1990s (Figure 2). Over the past 25 years of precipitation records, the relatively wet years of 1995, 2002, 2005, 2009, 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 [16].

The boundaries of meadow units within the National Park (NP) study area were mapped for the Sierra Nevada Multi-Source Meadow Polygons Compilation (SNMP v1.0; available online at http://meadows.ucdavis.edu/products/data) by Fryjoff-Hung and Viers [3]. Meadow attribute data were collected by the SNMP from various agencies, individuals, and organizations. A confidence rank (1=low, 10=high) was assigned to determine the best quality layers, which were filtered and rasterized at a 10m resolution before conversion to the polygon boundary file.

A total of 2389 meadow polygons were identified within the NP study area from the SNMP database, covering a total area of 8043 ha. The mean area coverage of these meadows was 3.4 ha (with a minimum of 0.27 ha and a maximum of 175.2 ha), ranging in elevation from 980 m to 3610 m. As image examples, two meadow units were selected (Table 1) to represent montane (1500-2500 m) and subalpine (2500–3000 m) ecosystem types [1].

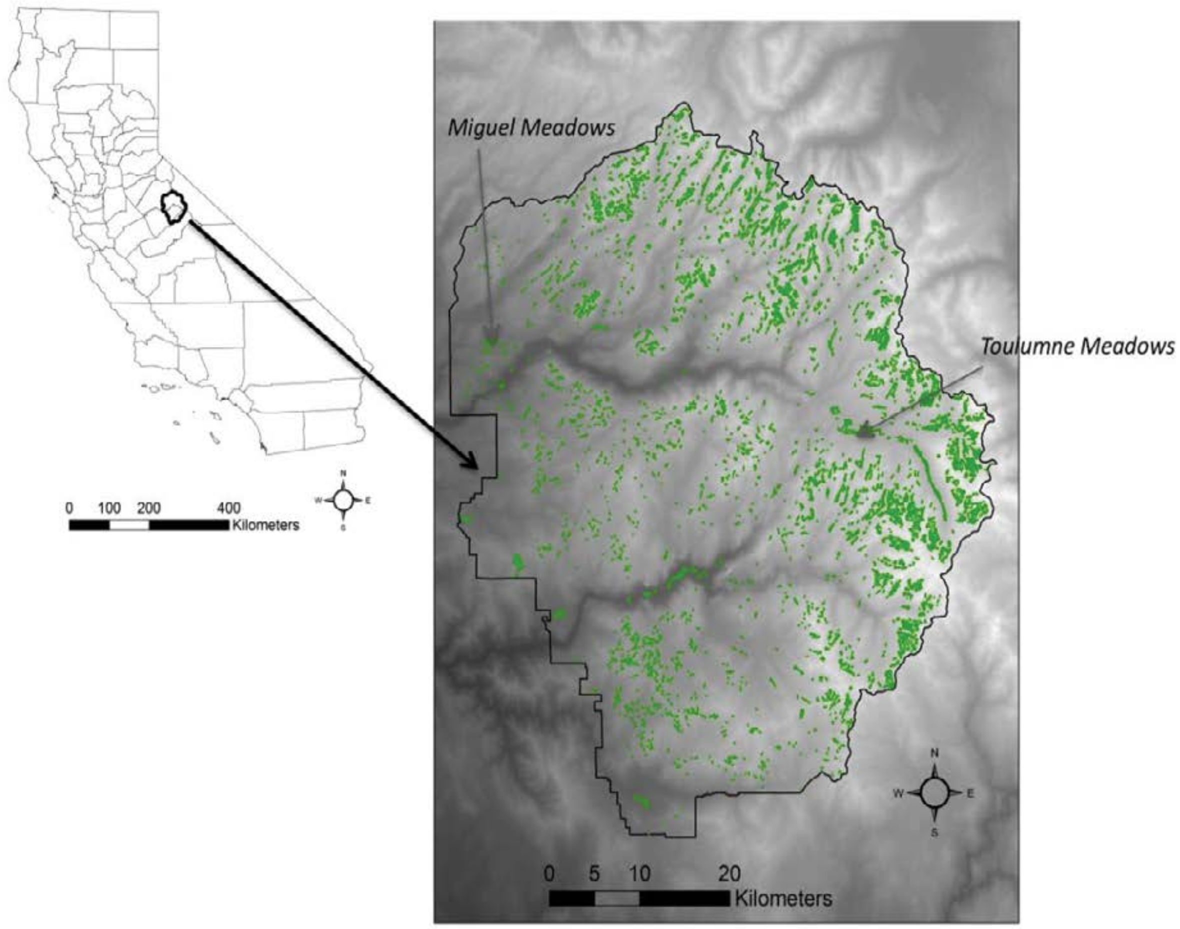

Figure 1: Map of the Yosemite NP study area (dark outline) in central California, with shaded elevation and meadow units overlaid (outlined in green) from the SNMP data base [3].

Methods

Landsat image processing

Near cloud-free imagery from the Landsat Thematic Mapper (TM) sensor was selected for the years 1990 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 an anniversary window between June 20 and August 20 each year, around the peak of the Sierra Nevada growing season [17], to minimize variation caused by seasonal vegetation phenology and sun angle differences.

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 Chander et al. [18]. 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 [19], especially during the summer months for the Sierra Nevada study area [20].

Calculation of NDVI

NDVI (scaled to maximum value of 1) 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. 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 [21]. Low values of NDVI (near 0) indicate barren land cover whereas high values of NDVI (near 1) indicate dense canopy vegetation cover in the Sierra Nevada region [13].

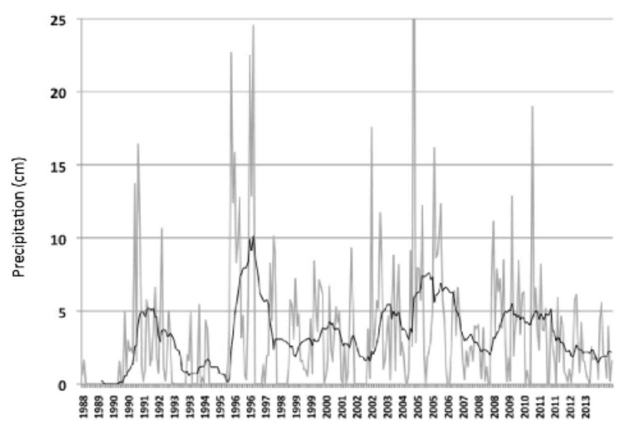

Figure 2: Monthly precipitation recorded at the White Wolf weather station (37.85° N, -119.65° W; 2670 m elevation) downloaded from www.raws.dri.edu in October 2014. The 12-month running mean precipitation is shown as the dark solid line. Missing values were noted for the years 1989-90 and 1995-97.

Other spatial data sets

Areas burned by wildfire were delineated from the database compiled by the California Department of Forestry, Fire and Resource Assessment Program (FRAP), with contributions from the USDA Forest Service, the Bureau of Land Management, and the National Park Service (data available at http://frap.cdf.ca.gov/). Elevation at 1 arc-second resolution was derived from the United States Geological Survey (USGS) National Elevation Dataset (NED).

Vegetation cover types were determined from USDA 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 satellite imagery from the Indian Remote Sensing RESOURCESAT-1 (IRS-P6) Advanced Wide Field Sensor (AWiFS) collected during the current growing season.

Statistical methodology

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 [22]. 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

Comparison of Landsat NDVI values from 2010 (wet year) and 2013 (dry year) showed that meadow areas within the Yosemite NP study area had a more extensive coverage of high water tables and surface water (observed as more negative NDVI values) in the wet year (Figure 3a), and a more extensive coverage of emergent vegetation and lower water tables (observed as more positive NDVI values) in the dry year (Figure 3b). Statistical analysis showed that the cumulative distribution of meadow NDVI values in 2010 was significantly different (K-S $p<0.001$; Maximum Difference=0.40) from the distribution of meadow NDVI values in 2013, with mean NDVI values for all meadow polygons (N=2389) estimated at 0.231 and 0.443 for 2010 and 2013, respectively. The significant decline in meadow NDVI with elevation, starting at around 2500 m, was apparent in both wet and dry years (Figure 3).

The time-series of meadow NDVI values for the comparatively

Table 1: Meadow units delineated for the NP study area for visualizations of NDVI time-series trends.

Place Name	Latitude (N)	Longitude (W)	Elevation (m)	SNMP ID
Miguel Meadows	37.96°	-119.84°	1530	9929
Toulumne Meadows	37.88°	-119.38°	2625	9514

dry years of 1990, 2001, 2007, 2013 showed that, on average, green vegetation cover increased progressively between 2001 and 2013 (Table 2). Although mean NDVI of all meadows in 1990 was estimated to be higher on average than for mean NDVI of all meadows in 2001, the mean and cumulative distribution of meadow NDVI values in 2013 was still significantly higher (K-S $p<0.001$; Maximum Difference=0.1) than meadow NDVI values in 1990. The mean difference between meadow NDVI in 2013 and 1990 was 0.013 (Table 2), with a minimum of -0.184 and a maximum of 0.275.

The majority of high NDVI (2013-1990) difference values (at >0.05) were detected in the montane meadow elevations between 1500 m and 2500 m (Figure 3c). There were 56 meadow units in the NP study area detected with the positive difference between NDVI in 2013 and 1990 greater than 0.10, covering a total of 110 ha. The largest of these meadows was the 24 ha Big Meadow unit (37.71° N, -119.75° W) located at 1320 m elevation near Forest on the Yosemite NP western boundary.

The two meadow units selected for a closer examination of the trends and yearly differences between NDVI (as shown in Figure 3 and Table 2) were the Miguel Meadows (montane) and the Toulumne Meadows (sub-alpine) units. The continuous time-series of yearly NDVI from 1990 to 2013 (Figure 4), for these two locations, showed a marked increase in vegetation green cover after the year 2000 within both meadows. NDVI declines during the relatively wet years of 2002 and 2009 confirm higher surface water cover on the meadows during these periods, immediately followed by periods of NDVI increase implying lower surface water and higher vegetation green coverage.

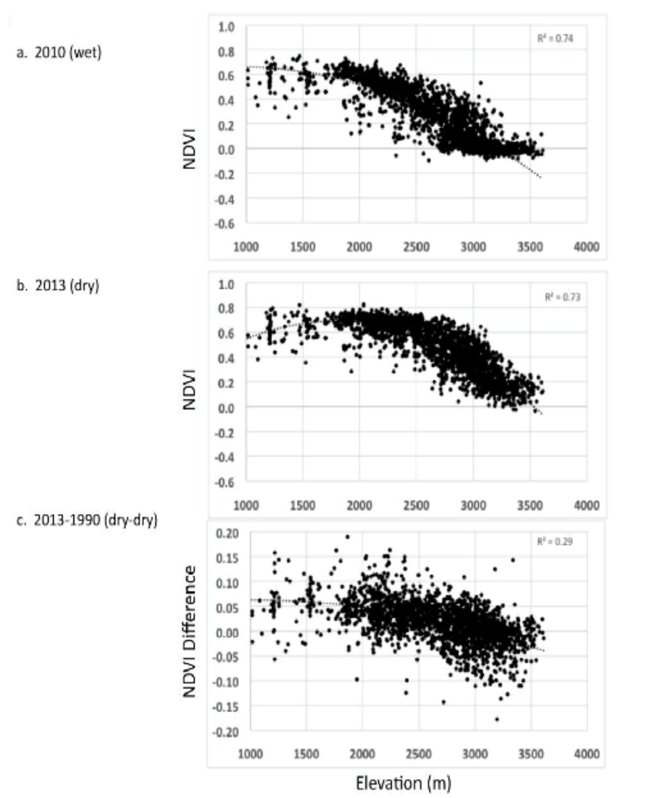

Figure 3: Mean Landsat NDVI in meadow areas of the Yosemite NP study area (*N* = 2389) plotted versus elevation for (a) the relatively wet year of 2010, (b) the relatively dry year of 2013, and (c) the difference between NDVI in 2013 and 1990. Best-fit non-linear regression lines are shown.

Table 2: Comparisons of mean NDVI in four consistently dry years within meadow areas in the Yosemite NP study area. *N* = 2389 NDVI values for all years.

	1990	2001	2007	2013	NDVI 2013 -1990
Mean	0.430	0.398 [a]	0.414 [a]	0.443	0.013 [b]
St. Dev.	0.177	0.177	0.177	0.202	0.045
2 SE	0.007	0.007	0.007	0.008	0.002

[a]Different from Mean 2013 NDVI at 95% confidence;
[b]Different from zero at 95% confidence;
A 95% confidence interval for a sample mean difference is greater than (plus or minus) 2 standard errors [23].

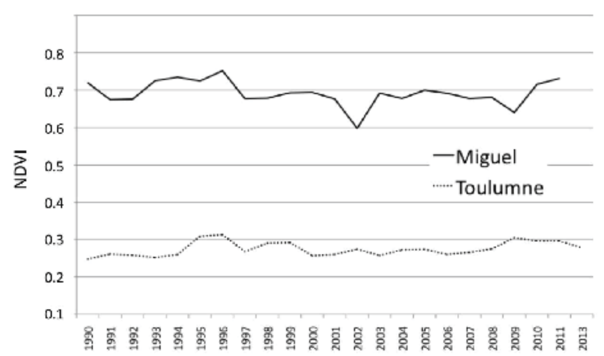

Figure 4: Time series of yearly summertime (between mid-June and August) NDVI sampled from 1990 to 2013 for Miguel Meadows and Toulumne Meadows.

The Miguel Meadow area showed slightly more NDVI values lower than 0.2 (indicating higher surface water cover) in the wet years of 2009 and 2010 than in the dry year of 2013 (Figure 5a), whereas the Toulumne Meadows area showed much higher overall coverage with NDVI values lower than 0.2 in the wet year of 2010 than in the dry year of 2013 (Figure 5c).

Nearly all of the Toulumne Meadows area was detected with NDVI values greater than 0.45 in the dry year of 2013 (Figure 5c). Most the stream channels within Toulumne Meadows had NDVI values greater than 0.5 in 2013 (indicating growth of emergent plant cover), whereas in the wet year of 2010, these channels had NDVI values less than zero (indicating open water with no emergent plant cover).

The difference between NDVI in 2013 and 1990 was greater than 0.12 for much of the Toulumne Meadows area (Figure 5d), indicating a major increase in emergent plant cover in this meadow unit since the early 1990s. The forested areas surrounding Toulumne Meadows showed a similar level of NDVI increase between 1990 and 2013. While herbaceous vegetation in the Sierra can grow with high NDVI in the early season months, during extreme dry years, grass cover NDVI will decrease even in meadows (compared to evergreen woody shrub and trees) by July-August, when most of these Landsat images were obtained. For this reason, higher NDVI would indicate more woody plant cover invasion, based on the dry year image comparisons.

For the entire in Yosemite NP study area, a total of 256 meadow units were detected as having area burned over the past 65 years (according to the FRAP 2012 database). Meadow area burned covered a total of 573 ha (Figure 6), which was 7% of the total meadow area in the NP study area. The majority of meadow areas that burned were from fire dates within the last 30 years. These estimates of meadow

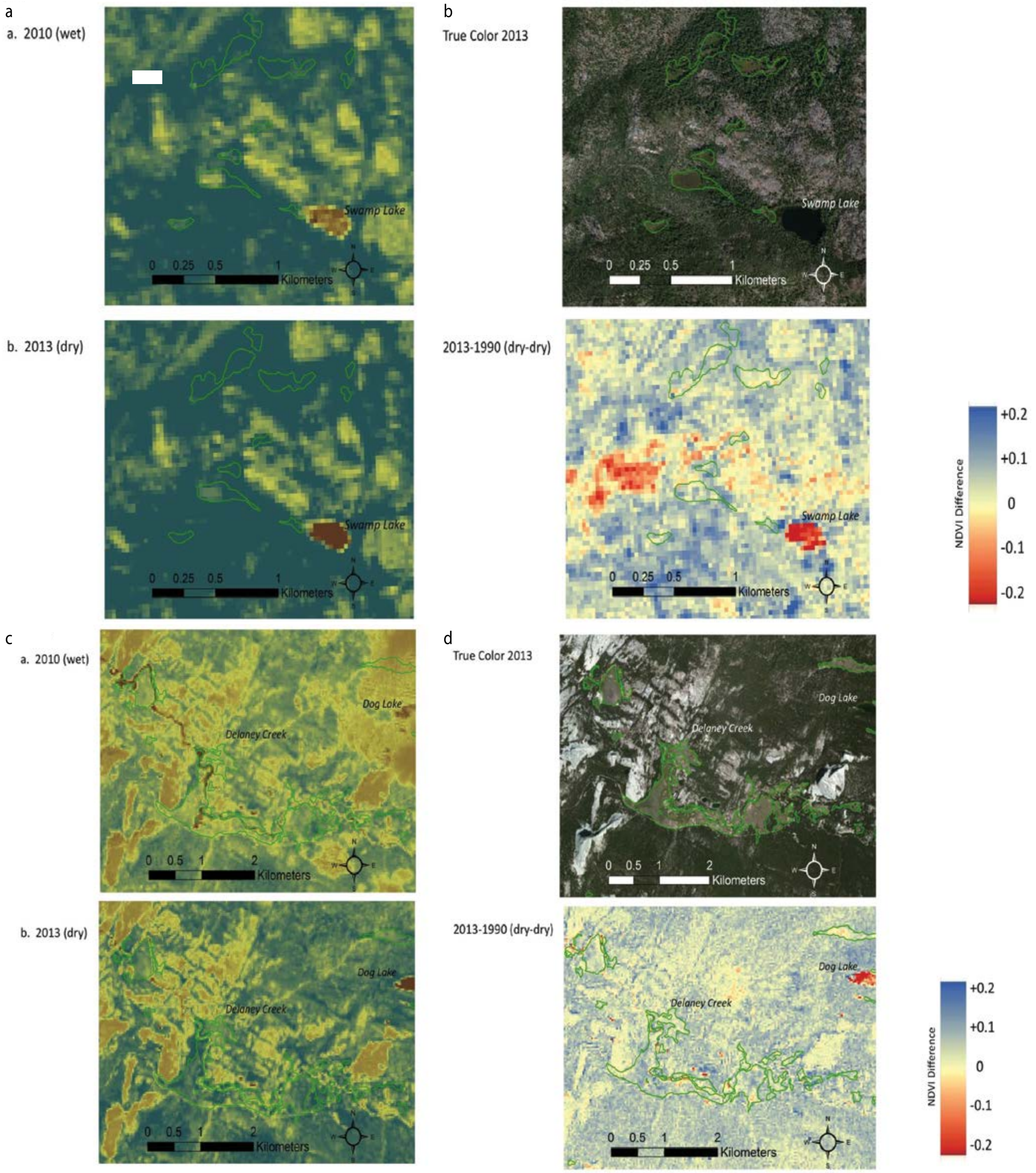

Figure 5: NDVI maps of (a) Miguel Meadows and (c) Toulumne Meadows for 2010 and 2013. (b and d) True color images and the difference between Landsat 30 m NDVI in 2013 and 1990 for the meadow areas. Green shaded lines delimit the perimeters of meadow units from the SNMP data base (Fryjoff-Hung and Viers, 2012).

area burned must be considered conservative however, since FPAP fire perimeter mapping has been shown to substantially underestimate burned areas in the southern California region [23,24]. Many more of the detections of a change in NDVI between consistently dry or wet periods could be a function of small wildfire impacts over the past three decades in the study area.

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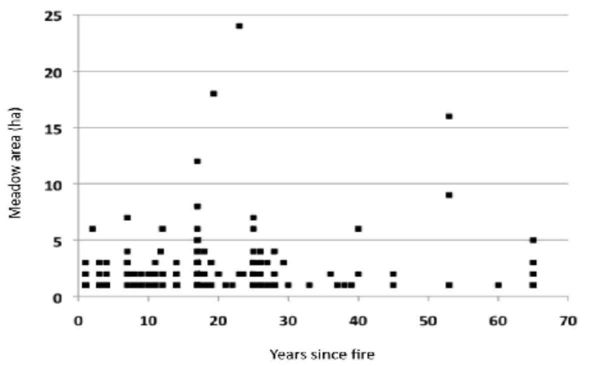

Figure 6: Meadow area versus the years since fire for 256 meadow units detected as having burned over the past 65 years in the Yosemite NP study area.

The mean meadow area burned was 2.2 ha. The maximum meadow area burned was 24 ha (at 37.56° N, -119.54° W), located 10 km northeast of the Yosemite NP south entrance near Wawona, within the 1983 Johnson Fire perimeter, which covered a larger area burned of 552 ha at 2285 m elevation. The change in NDVI between 2013 and 1990 over much of this meadow area burned in 1983 showed a decrease of around -0.08 NDVI units, which was the only location within the larger Johnson Fire perimeter where this magnitude of NDVI decrease was detected. In contrast, all regrowing forested areas within the Johnson Fire area showed a positive change in NDVI, at between 0.1 and 0.15 NDVI units of change since 1990.

For all 256 meadow units in the NP study area burned over the past 65 years, the mean difference between NDVI in 2013 and 1990 was 0.046 (with a maximum of 0.275 and a minimum of -0.099). This level of greening in burned meadow area since 1990 was higher (more positive) than the overall mean for all meadow units within the entire Yosemite NP study area.

Discussion

The main findings from this study of 20+ years of Landsat image analysis for meadows of Yosemite National Park were twofold: (1) NDVI values from the wet year of 2010 were significantly lower than NDVI values from the dry year of 2013 in the majority of meadow areas, suggesting that higher surface water levels could be detected in wet years using Landsat imagery; and (2) the sequence of consistently dry years over the past decade (2001, 2007 and 2013) showed progressively higher NDVI in the majority of meadow areas, suggesting that some encroachment of woody vegetation was detectable, especially at sub-alpine elevations.

Toulumne Meadows presents a special case for studies of long-term change in Sierra Nevada meadows, due to its status as a popular tourist destination, as a major access point to the Yosemite high country, and the significant density of roads nearby. Cooper et al. [25] surveyed Toulumne Meadows vegetation communities and reported historic grazing impacts by sheep, current browsing effects by deer on willows, and pocket gopher disturbance to meadow soils. Vegetation has a discontinuous cover of perennial plants in most areas of the meadow, with broken sods and tussocks, an absence of grasses and sedges in many locations, and high cover of bare ground. Groundwater hydrology measurements showed that, while the high water tables can still occur in relatively wet years, vegetation in these areas has high levels of pocket gopher and vole activity, which creates bare ground that may be important to lodge pole pine (*Pinus contorta*) establishment and survival. This study also added that fire disturbance has been largely absent in this area of Yosemite NP since the mid 1800s, and this alteration of fire frequency may have resulted in large changes in the vegetation community as well as changes in lodge pole pine encroachment patterns. It was concluded that climatic warming impacts must be monitored for changes in Tuolumne Meadow's late-season water supply and vegetation growth.

Calendar year 2013 was the driest on record in California, with a total of just 30% of average statewide precipitation [26]. The previous statewide record low was 56% of average precipitation in 1976. This record drought period, which continued into 2014, may have promoted lower herbaceous plant production and more extensive drying of meadows in the Sierra Nevada than at any other time in recent history [27].

Debinski et al. [28] measured several significant changes in sub-alpine meadow plant communities during periods of extreme drought: (1) bare ground increased in dry meadows, (2) forbs decreased in both wet and dry meadows and (3) woody plant species increased in both wet and dry meadows. Based on reports such as this, and those of Berlow et al. [10], the sequence of drought-induced meadow effects for the Sierra Nevada can be outlined as follows: Thinner snowpacks in extreme drought years (e.g., 2013 and 2014) lead to lower soil insulation and less percolation of snow melt into the water table. Evapotranspiration fluxes start earlier and remain higher into the dry summer months. The extended grazing period for ungulates can lead to higher soil compaction and hardening. Lower herbaceous plant production leads to higher woody encroachment by shrubs and tree seedlings.

It is important to note however that the process of meadow degradation is not irreversible. A common restoration technique in the Sierra Nevada, known as 'pond and plug', has been used in degraded meadows where stream channels have been incised [29]. Using heavy machinery, the channel is plugged with excavated soils and aggregate, redirecting flows into historic meanders and reducing channel depth and slope. This increases the frequency of overbank flows, improves channel-floodplain connectivity, elevates groundwater levels, and starts to restore herbaceous plant production.

The effect of fire on changes in meadow vegetation cover were observed to be a slightly higher rate of NDVI increase starting about 10 years after the date of wildfires, compared to the overall mean rate of NDVI increase since 1990 for all meadow units within the NP study area. The extent of woody plant encroachment in meadows related to this observed effect of wildfires in the Landsat record has nevertheless yet to be verified by field measurements. Although the Yosemite NP study area had a relatively small number of meadow units that were affected by large wildfires over the past century, the potential for larger and more severe burns in the Sierra Nevada over the next century [30] makes the monitoring of changes in meadow vegetation an important indicator of regional impacts of future climate change.

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