Journal of Ecosystem & Ecography

Potter C, J Ecosys Ecograph 2016, 6:3
DOI: 10.4172/2157-7625.1000199

Research Article · Open Access

Thirty Year Analysis of Forest and Scrub Canopy Cover on the Big Sur Coast of California using Landsat Imagery

Christopher Potter*

NASA Ames Research Center, Moffett Field, CA, USA

***Corresponding author:** Christopher Potter, NASA Ames Research Center, Moffett Field, CA, USA, Tel: +09603180159; E-mail: chris.potter@nasa.gov

Received date: May 23, 2016; **Accepted date:** July 28, 2016; **Published date:** August 01, 2016

Copyright: © 2016 Potter C. This is an open-access article distributed under the terms of the Creative Commons Attribution License, which permits unrestricted use, distribution, and reproduction in any medium, provided the original author and source are credited.

Abstract

The potential for negative effects such as habitat loss and high severity wildfires on endemic and threatened biological resources on the United States Pacific coast from recent climate warming has received increasing attention. This study was designed to quantify, for the first time, variations in forest and coastal bluff scrub canopy density and related growth rates using 30 consecutive years of April-to-June Landsat satellite image data for the central California coast around Big Sur. A trend model was fit to multi-year Landsat NDVI time series using least squares non-linear regression on time. Analysis showed that annual growth rates for coast redwood stands in the Big Sur area, the southern-most range for *Sequoia sempervirens* on the Pacific coast, have been depressed by periods of drought that exceeded -1.2 standard deviations of long-term annual precipitation. There was no evidence from the Landsat record that recent large wildfires have affected region-wide coast redwood stand structure or growth rates. Nonetheless, extensive wildfires of 2008 did have a marked (albeit temporary) impact on canopy density of the region's mixed hardwood and Coulter pine forest zones, equivalent to the extreme drought effects of 1990-1991 and 2013-2014 on these higher elevation forest zones.

Keywords: Central coast; California; Forest; Coast redwood; Coulter pine; Landsat

Introduction

The Pacific coastal region of California has been found to be a narrow but coherent climatologic zone, typically less than 30 km wide and much narrower in Central California near Big Sur (Monterey County) where the steepest coastal elevations gradients in North America are found [1]. The highest peaks in the Santa Lucia Mountains form a wall behind steep coastal bluffs, which effectively traps cooler marine air and lead to the formation of steep elevation gradients in air temperature regimes, humidity and other climate factors.

It is common to observe temperature inversions on the Central Coast that frequently result from the persistent marine layer, and which remains very stable between May and October [2]. Summer fog is common below about 600 m (2000 ft) elevation [3]. Nonetheless, diurnal heating and cooling of ecological habitats along the Big Sur coast and higher into the Santa Lucia range involves a complex series of elevation gradients and topographic variations. The nearly vertical slopes of coastal scrub vegetation on ocean-facing bluffs starting just above sea level give way to mixed hardwood (predominantly oaks) and pine (*Pinus ponderosa*) forests at around 100 m elevation, which in turn transition to Coulter pine (*Pinus coulteri*) woodlands at around 850 m (3000 ft) elevation [4]. Along the riparian canyon bottoms and on the moist lower parts of north-facing slopes below about 60 m elevation, coast redwood (*Sequoia sempervirens*) stands are able to grow [5].

The study approach was to quantify and characterize variations in forest canopy density and elevation gradients using 30 consecutive years of Landsat satellite image data for the central California coast around Big Sur. The setting for this analysis is arguably located at the nexus of modern climate change geography in the western United States. The Central Coast is constantly subjected to extreme winter storm events [3], frequent droughts and wildfires, and human development impacts, together affecting wildlife populations, native plant communities, soil conservation, riparian zones, and water quality.

The numerous unique microclimates of Big Sur make it an important region in western United States to monitor impacts on natural biodiversity [6], including many endemic rare and endangered species, such as the wild orchid *Piperia yadonii*, the Santa Lucia fir (*Abies bracteata*), California condor (*Gymnogyps californianus*), California southern sea otter (*Enhydra lutris nereis*), and the southern-most habitat of the coast redwood. The Pacific redwood ecoregion has been identified by the World Wildlife Fund as being in the highest conservation priority class among ecoregions in the United States, based on biological uniqueness, conservation status, and impending threats [7].

Even minor shifts in climate and the frequency of extreme weather events have the potential to tip the balance in favor or against threatened biological resources that are susceptible to stress in the remote and rugged coastal environment of Big Sur. The potential for adverse effects of recent (since the 1950s) climate warming on Pacific coast redwood forests has received increasing attention from scientists and conservation organizations alike. Most notably, Carroll et al. [8] used tree-ring dating to show that California coast redwood has had a strong latitudinal gradient of climate sensitivities. Radial growth (i.e., annual wood production) increased with decreasing summer cloudiness in northern sections of the state, but the strongest dendro-climatic relationship occurred at the southernmost redwood location in Big Sur, where tree radial growth was correlated negatively with dry summer conditions and exhibited responses to historic fires. The main objective of the present study was to analyze the entire (30-yr) Landsat

Citation: Potter C (2016) Thirty Year Analysis of Forest and Scrub Canopy Cover on the Big Sur Coast of California using Landsat Imagery. J Ecosys Ecograph 6: 199. doi:10.4172/2157-7625.1000199

satellite image record in search of evidence of annual forest growth impacts from extreme climate and wildfires events, the interaction on which is largely unknown at this time.

The Landsat normalized difference vegetation index (NDVI) has been shown to be a reliable metric to monitor large-scale change in green vegetation cover and forest disturbance in remote mountainous areas [9-12]. Results from Landsat image studies have shown that canopy green leaf 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 [13].

Study Area

The study area was in the central Pacific coastal region near Big Sur, CA (Figure 1). Big Sur is generally delineated by the 140 km (90 miles) of coastline from the Carmel River in northern Monterey County, south to the San Carpoforo Creek in San Luis Obispo County, and extends about 30 km inland to the eastern foothills of the Santa Lucia Mountains. The terrain is rugged and undulating; with the steepest elevation gradients on the Pacific U.S. coast [14].

As many as fifty separate streams flow down the mountains to the ocean coastline. Several of these streams, including the Big Sur and Little Sur Rivers, Big Creek, Garrapata Creek, and Salmon Creek, have year-round flows and support endangered anadromous fish populations [15]. Steep ocean-facing bluffs rising up to 100 m above sea-level support sparse coverage of scrub vegetation, including the species California sagebrush (*Artemisia californica*), coyote brush (*Baccharis pilularis*), sage (*Salvia sp.*), and coast buckwheat (*Eriogonum fasciculatum*) [6]. Borchert et al. [5] reported that redwoods on the Big Sur coast are found most commonly on steep (>50%) lower slopes, at north to north-northwest aspects, and are densest at distances of 15 to 60 m from the nearest surface stream flow.

The region has a Mediterranean climate of warm, dry summers and cool, wet winters, with localized summer fog near the coast [3,16]. Annual rainfall is highly variable and ranges from 40 to 152 cm throughout the region, with highest event totals generally falling on the higher mountains in the northern extreme of the study area during winter storms [17]. Mean annual temperature ranges between 10°C and 15°C, from shaded canyon bottoms to exposed ridge tops, respectively [18].

Plant growth on the Central Coast can be highly variable from year-to-year and is generally limited by declines of soil moisture in the summer and by cool temperatures in the winter [18]. The annual production pattern for coastal plants is rapid growth in the late fall (November) after the first rains have returned, slow winter growth (December-February), and rapid growth again in spring (March-May).

Wildfires are a naturally occurring phenomenon in Mediterranean ecosystems of the California central coast. The Marble-Cone Fire in 1977, the Rat Creek Gorda Fire in 1985, the Ventana Wilderness Prewitt Creek Fire in 1996, and the Tassajara and Kirk Complex Fires in 1999 are all well-documented forest fire events on the Big Sur landscape [19]. In June and July of 2008, about 99,000 ha of the study area was burned by the third-largest forest fire in California's history, the Basin Complex and Indians Fire on the Monterey Ranger District of the Los Padres National Forest [20]. During the recent drought period of 2013 to 2014 [11], the Pfeiffer Ridge Fire burned more than 360 ha of forest over a five-day period starting on December 17, 2013.

Although old-growth redwoods have thick bark that allows the trees to survive moderately intense fires [21], logging removed the majority of mature coast redwood stands in California over the past 200 years [22]. The history of logging coast redwoods in the Big Sur region has rendered most present stands as secondary growth, aged between 100 and 150 years [8].

Forest soil moisture measurements used in this study were made at the Brazil Ranch (center coordinates: latitude 36.35°N, longitude 121.88°W) near Big Sur (Figure 1). Brazil Ranch serves as a primary research site for the U.S. Forest Service to monitor and manage vegetation, wildlife, water quality, and sensitive coastal habitats on the Los Padres National Forest of Monterey County.

Methods

Climate data

Monthly climate summaries from a period 1985 to 2015 were obtained from the Western Regional Climate Center (WRCC) California Climate Tracker [1] data portal (www.wrcc.dri.edu/monitor/) for the Big Sur State Park (BSP, NWS ID# 040790; Elevation 320 m) station BSP represents the longest, complete rainfall record on the Monterey County coast south of Carmel, dating back to 1950 for rainfall measurements. The station is situated 3.5 km due east from the ocean coastline.

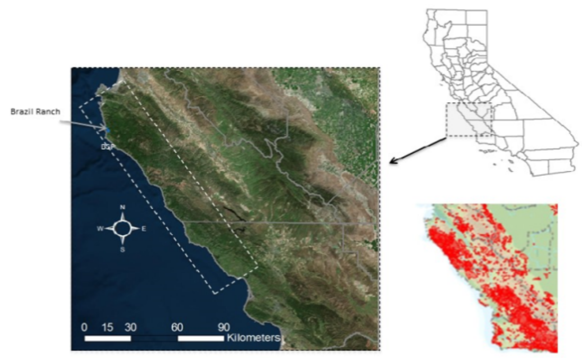

Figure 1: True colour (red-green-blue) aerial image and map of the Big Sur study area (delineated by the white dashed line), showing the BSP weather station location and county boundaries (gray lines). Inset map shows wildfire burned areas shaded in red from the California Department of Forestry, Fire and Resource Assessment Program.

Soil moisture measurements

Soil moisture probes were placed in coast redwood and mixed hardwood/pine forest stands at the Brazil Ranch at depths of 10, 30, and 50 cm in the soil profiles. As described by Potter [23], volumetric water content (VWC) was monitored on an hourly interval using EC-5 frequency domain probes (Decagon Devices Inc.).

Landsat image data

Near cloud-free imagery from the Landsat sensor was selected from the United States Geological Survey (USGS) Earth Explorer data portal (available online at earthexplorer.usgs.gov) for every year from 1985 to 2015. Landsat scenes from path/row 43/35 were acquired between April 1 and June 30 each year, around the peak of the Pacific coastal growing season [23]. All images used in this study were geometrically registered (UTM Zone 10) using terrain correction algorithms (Level 1T) applied by the U.S. Geological Survey EROS Data Center.

For the Landsat 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 [24]. 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.

The normalized difference vegetation index (NDVI) from Landsat imagery has been frequently used to monitor live vegetation canopy cover and trajectories of forest growth during and after ecosystem disturbances [9,25]. NDVI was computed for this study using Landsat bands as:

$$NDVI = (NIR - Red) / (NIR + Red)$$

Where Red is the reflectance from 0.63 to 0.69 µm and NIR is the near-infrared reflectance from 0.77 to 0.90 µm.

NDVI was scaled from 0 to 10000 (by multiplying by 10000 and omitting negative, non-vegetation values). Low values of NDVI (near 0) indicate barren land cover whereas high values of NDVI (above 7000) indicate dense canopy vegetation cover. Schiffman [26] found that summer NDVI values greater than 5000 corresponded to a leaf area index (LAI) above 1 and NDVI values greater than 7000 corresponded to a LAI above 3 in California montane forests. 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 [25].

Spatial data layers

Vegetation types for the study area were determined based on the National Agricultural Statistics Service (NASS), California Cropland Data Layer (CDL) from 2012 (available online at nassgeodata.gmu.edu/CropScape). The CDL is a raster, geo-referenced land cover data layer with a ground resolution of 30 m produced using satellite imagery from the Landsat sensor collected during the summer season.

Perimeter boundaries for wildfires that occurred within the study region over the past century were delineated from the database compiled by the California Department of Forestry, Fire and Resource Assessment Program (FRAP; data available online at frap.cdf.ca.gov). Elevation, slope, and aspect were determined at 30-m spatial resolution from the USGS National Elevation Dataset (NED).

Forest zone delineations

All CDL-defined forest covers within the Big Sur River and the Big Creek coastal drainages (delineated by USGS Hydrologic Unit 10-digit basin boundaries, Seaber et al. [27] were separated into three elevation zones for NDVI analysis and comparison (Figure 2). The riparian coast redwood-dominated (RCR) forest zone was delineated at elevations lower than 60 m [5]. The mixed hardwood/pine-dominated (MHP) forest zone, with interspersed stands of *Quercus agrifolia* and *Pinus ponderosa* growing most commonly on north-facing slopes and ridge tops, was delineated at elevations between 60 m and 850 m [4]. Examples of these forest zones are shown in Figure 3. The Coulter pine-dominated (CLP) forest zone was delineated at elevations higher than 850 m, predominantly along ridgetops and on moderate slopes of the Santa Lucia range [4]. Within each of these three forest zones, 1000 point locations were randomly selected for sampling and statistical analysis of the 30 yr NDVI time-series.

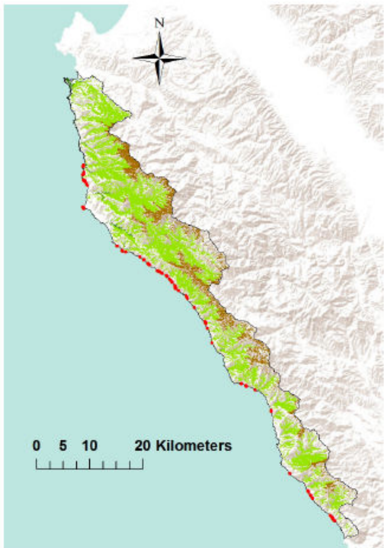

Figure 2: Map of forest zones in the Big Sur coastal study area, as delineated in the Methods section. Colour key: Dark green: RCR zone; Light green: MHP zone; Brown: CTL zone. Steepest coastal bluffs above 80 m elevation are labelled in red.

For comparison to forested areas, a fourth zone of ocean-front vegetation cover growing along the upper-most ridges of the steepest coastal bluffs in Big Sur was delineated by selecting all point locations above 80 m elevation situated within 100 m horizontal distance from the sea-level coastline (Figure 2). These 240 resulting coastal bluff locations would have been directly exposed to the full force of Pacific winter storms and year-round sustained wind speeds that frequently exceeded 12 ms-1 (25 mph) along the cliffs of the Big Sur coast [3,17].

Citation: Potter C (2016) Thirty Year Analysis of Forest and Scrub Canopy Cover on the Big Sur Coast of California using Landsat Imagery. J Ecosys Ecograph 6: 199. doi:10.4172/2157-7625.1000199

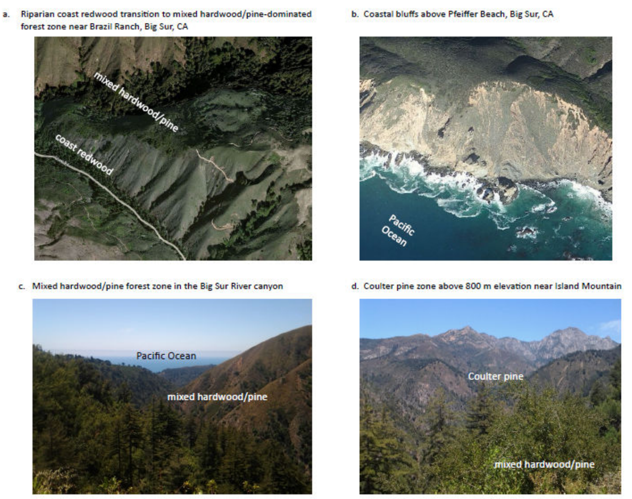

Figure 3: Examples for forest zones a) Riparian coast redwood transition to mixed hardwood/pine-dominated forest zone near Brazil Ranch, Big Sur, CA b) Coastal bluffs above Pfeiffer Beach, Big Sur, CA c) Mixed hardwood/pine forest zone in the Big Sur River canyon d) Coulter pine zone above 800 m elevation near Island Mountain.

Trend analysis and statistics

A trend model was fit to multi-year Landsat NDVI time series using least squares regression on time using the StatPlus© 2009 software from AnalystSoft. Calculations of statistical significance (p values) of the fitted trend (with the R^2 coefficent of determination) were computed to test the hypothesis of chance deviations from a flat trend (long-term average) for any single year, following the same analysis approach applied by Lebassi et al. [28]. A 95% confidence interval for a yearly sample mean difference was reported as greater than (plus or minus) 2 standard errors [29], and a $p<0.05$ value means that the results are significant the 95% confidence level.

Descriptive statistics of the distributions of sampled NDVI data sets were computed, including skewness [30]. Negative skewness indicates that the tail on the left side of the probability density function is longer than the tail on the right side, with values between -3 and +3 indicative of a normal distribution.

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 [31]. 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., $p<0.05$), it can be concluded that the two groups were sampled from populations with significantly different distributions.

Results

NDVI trend analysis

Tests for near-normal distributions the mean NDVI values calculated over 30 years for three forest zones and the coastal bluff points used for trend analysis found no significant skewness (at between -0.37 and -1.0) in the majority of the regression input data sets. Tests for temporal autocorrelation in the NDVI time series showed that the autocorrelation coefficient was weak (not statistically significant) at a values between -0.18 and -0.25 for the three forest types and for the coastal bluff sample points.

Figure 4: Thirty year time-series for mean NDVI sampled from 1000 randomly selected locations for each of the three forest zones in the Big Sur study area; (a) RCR, (b) MHP, (c) CLP, and (d) coastal bluffs.

Time series regression results showed that the entire 30-yr time-series for mean NDVI sampled from each of the three forest zones showed no significant positive or negative change in canopy density since 1985 (Figure 4a). There were, however, three periods of significant (K-S test $p<0.05$) decrease in the mean annual RCR zone NDVI from the 30-yr NDVI mean of 7235 units, namely in 1992, 2008, and 2015 (Figure 4b). Across all 30 years, 2 SE of the mean annual

Citation: Potter C (2016) Thirty Year Analysis of Forest and Scrub Canopy Cover on the Big Sur Coast of California using Landsat Imagery. J Ecosys Ecograph 6: 199. doi:10.4172/2157-7625.1000199

NDVI sampled for the RCR zone varied between 50 and 95 units, whereas the three negative departures from the 30-yr NDVI mean for these three periods were between 300 and 600 units. These three periods of decreased RCR NDVI were each preceded by the largest negative anomalies in annual or seasonal precipitation recorded at the BSP weather station since 1985 (Figure 5), but were not preceded by any extensive wildfires in the Big Sur area.

There were three periods of significant (K-S test $p<0.05$) decrease in mean MHP zone NDVI from the 30-yr mean of 7316 units, namely in 1992, 2009, and 2015 (Figure 4b). Across all 30 years, 2 SE of the mean annual NDVI sampled for the MHR zone varied between 35 and 75 units, whereas the three negative departures from the 30-yr NDVI mean for these three periods were each nearly 800 units. The year 2009 mean decrease of 700 units in MHP NDVI was preceded by the Basin Complex and Indians Fire of June-July 2008.

There were four periods of significant (K-S test $p<0.05$) decrease in mean CLP zone NDVI from the 30-yr mean of 6950 units, namely in 1992, 2000, 2009, and 2015 (Figure 4c). Across all 30 years, 2 SE of the mean annual NDVI sampled for the CLP zone varied between 40 and 120 units, whereas the four negative departures from the 30-yr NDVI mean for these three periods were between 300 and 1200 units. The year 2000 mean decrease in CLP NDVI of 800 units was preceded by the Tassajara and Kirk Complex Fires of September-November 1999, and the year 2009 mean decrease of 2400 units in CLP NDVI, the largest single-year negative deviation observed in the forest zone time series, was preceded by the Basin Complex and Indians Fire of 2008.

There were no significant correlations between elevation and mean annual NDVI in either the forest MHP or the CLP zones for any of the 30 years analyzed. Nonetheless, all of the lowest density stands (with NDVI values of less than 5000 units) within the MHP zone were sampled at elevations higher than 500 m. These low density forest sites became more even common in the upper-most MHP zone between 700 m and 850 m elevation. Low density (NDVI <5000 units) forest sites were equally distributed across the entire CLP elevation zone.

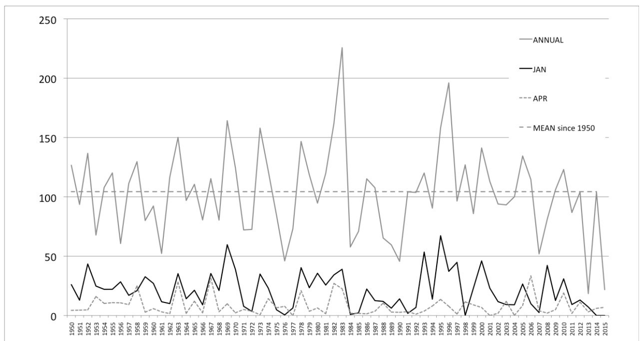

Figure 5: Time-series for annual precipitation totals (cm; summed from October to May), plus January and April totals, at the BSP station from 1950 to 2015.

The time-series of mean NDVI sampled in the zone of vegetation cover along ridges of the steepest coastal bluffs in Big Sur showed a substantially lower range of values, compared to any of the three forest zones, at between 4100 and 5600 NDVI units (Figure 4d). Across all 30 years, 2 SE of the mean annual NDVI sampled for the coastal bluff zone was substantially higher than for any of the three forest zones, varying between 185 and 450 units. There were four periods of significant ($p<0.05$) decrease in the mean annual coastal bluff NDVI from the 30-yr NDVI mean of 5043 units, namely in 1990, 2000, 2008, and 2015. These four negative departures from the 30-yr NDVI mean for the coastal bluff zone were between 500 and 800 units. Similar to the RCR zone NDVI patterns, these four periods of decreased coastal bluff NDVI were each preceded by large negative anomalies in annual or seasonal precipitation recorded at the BSP weather station since 1985 (Figure 5).

Soil moisture differences

The record of hourly soil moisture for RCR and MHP stands at the Brazil Ranch from 2008 to late 2014 (Figure 6) showed that the months of May to September in 2008 and 2013 had the lowest consistent VWC levels at all three soil depths during the time series. The RCR soil was recorded with hourly soil VWC levels at or above 0.1 from May to September in both 2013 and 2014 at 50 cm depth. In comparison, the MHP soil declined to below 0.1 VWC at 50 cm depth by June 2013 and to below 0.05 by September 2013.

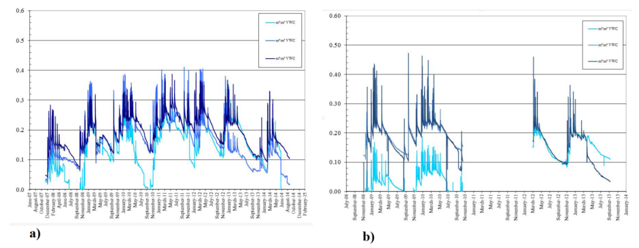

Figure 6: Plots of hourly soil moisture from 2008 to 2014 at Brazil Ranch forest measurement stations; (a) RCR, and (b) MHP (missing data due to logger malfunctions).

Discussion

The results from this study offer new evidence that annual growth rates for coast redwood stands in the Big Sur area, the southern-most range for S. sempervirens on the Pacific coast, are influenced strongly by periods of severe drought that exceed -1.2 standard deviations of long-term annual precipitation. There was no evidence from the Landsat record that recent large wildfires have affected region-wide coast redwood stand structure or growth rates, despite the fact that 15% of the redwood locations sampled for NDVI trends were within historical (past 30 years) burned area boundaries.

The record of hourly soil moisture for RCR and MHP stands measured at the Brazil Ranch confirmed that the severe droughts of 2007 and 2013-2014 were associated with drying of the soil profiles to below 0.1 VWC in the summer months of 2008, 2013, and 2014. To put these low VWC into some regional hydrologic context, the lowest soil moisture level measured at between 30 and 50 cm depth by Wosika [32] in second-growth redwood forest at Jackson State Forest in Mendocino County, CA was 0.34 VWC. The lowest soil moisture level measured by Xu et al. [33] at a young ponderosa pine plantation in northern California during the warmest summer periods was 0.09 VWC.

On top of the 1990-1991, 2007 and 2013-2014 drought impacts on all Big Sur forest and coastal bluff zones, the Basin Complex and

Indians Fire of 2008 did have a marked (albeit temporary) impact on canopy density of the region's mixed hardwood and Coulter pine zones, equivalent to the extreme drought effects of 1990-1991 and 2013-14 on these higher elevation forest zone NDVI values. Within the Basin Complex and Indians Fire burned perimeters, less than 5% of the area was covered by RCR, 35% by MHP, and 12% by CLT forest types [34]. These proportions of burned forest areas on the Big Sur coastal watersheds are consistent with the observed decreases in NDVI from 2008 to 2009 for all three forest zones.

The NDVI time-series sampled from the zone of vegetation cover along ridges of the steepest coastal bluffs in Big Sur suggested that plant growth is inherently more limited on these bluffs than in any of the Big Sur forest zones sampled. Ford et al. [35] reported that Big Sur plant communities growing on vertical cliff faces and terraces near the shore are partially drought-deciduous and subjected to the influences of unstable substrates, rock slides, and a marine climate with cool, moist, salt-laden air and constantly gusty winds. Judging from the NDVI record analyzed, plant growth on these steep coastal bluffs is highly sensitive to drought periods, but resilient enough to recover during above average rainfall years.

The evidence strongly linking satellite NDVI to forest growth and structural patterns comes from a series of ground validation studies in the western United States. For instance, forest stand NDVI values greater than 5000 have been correlated with heavy fuel types in conifer forests of the Sierra Nevada mountains [9]. Schiffman [26] also reported a close correlation between NDVI and Leaf Area Index (LAI) measured across Sierra forest stands. These ground-truth studies have established NDVI as a reliable remotely sensed surrogate for variations in stand LAI and canopy biomass in this region.

Assuming that satellite NDVI is closely related to stand-level LAI, several field measurement data sets of conifer forest growth and stand structure in the western U.S. have further demonstrated a strong linear relationship between LAI and stem (basal area) growth. For example, Kashian et al. [36] showed a significant relationship ($R^2 = 0.6$, $p<0.01$) between LAI and basal area increment (BAI) for 48 lodgepole pine stands aged 45 - 350 years in Yellowstone National Park, Wyoming. Previous measurements by Knight et al. [37] at eight stands of lodgepole pine in the Medicine Bow Mountains of southeastern Wyoming showed the same basic patterns between LAI and basal area. Peterson et al. [38] reported a close correlation ($R^2 = 0.9$, $p<0.01$) between LAI and BA across six lodgepole and whitebark pine stands in the Eastern Brook Lakes watershed of the Inyo National Forest in the Sierra Nevada. Based on this review of the field plot measurements, it can be concluded that LAI and (hence NDVI) is a reliable predictor of annual stem growth in western U.S. forest stands.

Johnstone et al. [39] reported physiological evidence that coast redwood and other ecosystems along the Pacific coast may be increasingly drought-stressed under a summer climate of reduced fog frequency, higher solar radiation flux, and greater evaporative demand. Carroll et al. [8] found that correlations between tree-ring chronologies and summer drought indices were statistically significant at ten California coast redwood forest locations, but the correlations were by far the strongest on the Big Sur coast, at Big Creek in southern Monterey County, where the summer drought index was 46% coincident with the stem growth chronology. The tree-ring chronologies further showed that stem growth in redwoods on the Central Coast decreased significantly with maximum temperature in April and June.

Potter [23] used satellite-observed canopy density variations to quantify carbon cycling in coast redwood forest ecosystems on the Big Sur coast. Despite warmer monthly temperatures at the southern-most forest sites (namely at Big Creek) and a marked decrease in estimated stand growth following a drought period (2007-2008), these redwood stands still showed evidence of sequestration of CO_2 from that atmosphere into forest biomass for a net positive ecosystem carbon balance each year.

Carroll et al. [8] reported a negative relationship between annual stem growth in Pacific coast redwood stands and summer fog frequency, suggesting that cloudiness can reduce summer plant growth by decreasing light availability for photosynthesis. Latitudinal trends in correlations implied that decreasing summer cloudiness (i.e., increasing light availability) has a significant positive effect on redwood growth only at locations where water is the least limiting to photosynthesis, generally at locations north of Monterey and the Big Sur coast. On the Big Sur coast, periodic drought does limit plant water availability [23] such that moderating effect of frequent on-shore sea breezes and the marine layer may be vital to reduce the diurnal temperature range and evaporative demand significantly at lower (coastal scrub and riparian forest) elevations [18].

It is plausible that, at the warmest southern-most habitat for *S. sempervirens* on the Pacific coast, foliar uptake of fog water and lowered temperature extremes largely compensate for plant growth impacts of lower summer light availability that comes with frequent marine layer inversions. This supposition is supported by the results from Simonin et al. [39] who showed that regular fog water absorption by *S. sempervirens* crowns can partly decouple these trees from summer-time soil water deficits. If redwood foliage is frequently hydrated throughout the summer by fog water subsidies, and mid-day temperatures are moderated, then these stands can maintain higher photosynthetic rates and extend the length of their warmest growing season [40].

The patterns of future climate change are uncertain and likely to be complex in the Pacific coastal regions. For example, Potter [18] analyzed 20 years of daily temperature records from the BSP location, and reported that, even as average monthly maximum temperatures (Tmax) have decreased gradually, the number of extreme warm summer days (Tmax>37°C) has increased by several fold in frequency. Overall patterns in the station records since the mid-1990s indicated that diurnal temperature ranges are widening on the Big Sur coast, with markedly cooler nighttime temperatures (frequently in the wet winter season) followed by slightly higher-than-average daytime temperatures, especially during the warm, dry summer season [41].

Conclusions and Implications

According to the Landsat satellite record, annual growth of all forest and coastal bluff vegetation types on the Big Sur coast was depressed in the years following extreme drought events recorded since 1985. The satellite record lacks evidence that recent large wildfires have affected region-wide coast redwood stand structure or growth rates. However, extensive wildfires of 2008 did have a marked (albeit temporary) impact on canopy density of the region's mixed hardwood and Coulter pine forest zones, equivalent to the extreme drought effects on these higher elevation forest zones.

If the extreme summer maximum temperature trend observed in the coastal weather station records since the mid-1990s continue as long-term climate change along the California coastal region, the productivity and health of many vegetation habitats may be altered in unprecedented ways. The effects of changing growing season initiation date and duration for native plant species in the era of future global warming will require more field study. Establishment of a denser network of climate stations in this region would facilitate more definitive conclusions about the potential effects of climate warming on forest ecosystems.

Acknowledgements

The author is grateful to the U.S. Forest Service, Los Padres National Forest and particularly to Ecosystem Manager Jeff Kwasny for information on Central Coast ecology and management.

References

1. Abatzoglou JT, Redmond KT, Edwards LM (2009) Classification of regional climate variability in the state of California. J Appl Meteorol 48: 1527-1541.
2. Johnstone JA, Dawson E (2010) Climatic context and ecological implications of summer fog decline in the coast redwood region. Proceedings of the National Academy of Sciences 107: 4533-4538.
3. Hiatt C, Fernandez D, Potter C (2012) Measurements of fog water deposition on the California Central Coast. Atmospheric and Climate Sciences 2: 525-531.
4. Bickford C, Rich P (1984) Vegetation and Flora of the Landels-Hill Big Creek Reserve, Monterey County, California (2nd edn) In: Brown M (ed.) Environmental Field Program. University of California, Santa Cruz.
5. Borchert M, Segotta D, Purser MD (1988) Coast redwood ecological types of southern Monterey County, California. Pacific Southwest Forest and Range Experiment Station, Forest Service, U.S. Department of Agriculture, Berkeley, California. pp: 27.
6. Henson P, Usner DJ 1(996) The Natural History of Big Sur. University of California Press, Berkeley. pp: 416.
7. Ricketts TH, Dinerstein E, Olson DM, Loucks CJ, Eichbaum WM (1999) A conservation assessment of the terrestrial ecoregions of North America. Island Press, Washington DC.
8. Carroll AL, Sillett SC, Kramer RD (2014) Millennium-scale crossdating and inter-annual climate sensitivities of standing California redwoods. PLOS ONE 9: 102545.
9. van Wagtendonk JW, Root RR (2003) The use of multi-temporal Landsat Normalized Difference Vegetation Index (NDVI) data for mapping fuel models in Yosemite National Park, USA. International Journal of Remote Sensing 24: 1639-1651.
10. Gitas I, Mitri G, Veraverbeke S, Polychronaki A (2012) Advances in Remote Sensing of Post-Fire Vegetation Recovery Monitoring-A Review. In: L. Fatoyinbo (ed.) Remote Sensing of Biomass: Principles and Applications. pp: 143-176.
11. Potter C (2015) Assessment of the immediate impacts of the 2013 - 2014 drought on ecosystems of the California Central Coast. Western North American Naturalist 75: 129-145.
12. Storey EA, Stow DA, O'Leary JF (2016) Assessing post fire recovery of chamise chaparral using multi-temporal spectral vegetation index trajectories derived from Landsat imagery. Remote Sensing of Environment 183: 53-64.
13. Potter CS (2014) Ten Years of Forest Cover Change in the Sierra Nevada Detected Using Landsat Satellite Image Analysis. International Journal of Remote Sensing 35: 7136-7153.
14. Shreve (1927) The vegetation of a coastal mountain range. Ecology 8: 27-44.
15. California Department of Fish and Game (2009) Instream Flow Program Big Sur River Study Plan, Sacramento. pp: 24.
16. Hickman JC (1993) The Jepson manual: Higher plants of California, University of California Press, Berkeley, CA.
17. Potter C (2012) Net primary production and carbon cycling in coast redwood forests of central California. Open Journal of Ecology 2: 147-153.
18. Potter C (2014a) Understanding climate change on the California Coast: Accounting for extreme daily events among long-term trends. Climate 2: 18-27.
19. http://frap.cdf.ca.gov/data/frapgisdata/download
20. De Santisa A, Asner GP, Vaughan, Knapp DE (2010) Mapping burn severity and burning efficiency in California using simulation models and Landsat imagery. Remote Sensing of Environment 114: 1535-1545.
21. Norman SP (2007) A 500-year record of fire from a humid coast redwood forest. Report to Save-the-Redwoods League.
22. Lorimer CG, Porter DG, Madej MA, Stuart JD, Veirs SD (2009) Presettlement and modern disturbance regimes in coast redwood forests: Implications for the conservation of old-growth stands. Forest Ecology and Management 258: 1038-1054.
23. Potter C (2014) Microclimate influences on vegetation water availability and net primary production in coastal ecosystems of Central California. Landscape Ecology 29: 677-687.
24. Masek JG, Vermote EF, Saleous N, Wolfe R, Hall FG (2006) A Landsat surface reflectance data set for North America, 1990-2000. Geoscience and Remote Sensing Letters 3: 68-72.
25. Lentile L, Holden A, Smith A, Falkowski M, Hudak A et al., (2006) Remote sensing techniques to assess active fire characteristics and post-fire effects. International Journal of Wildland Fire 15: 319-345.
26. Schiffman B (2008) Estimation of Leaf Area Index (LAI) through the acquisition of ground truth data in Yosemite National Park, ASPRS 2008 Annual Conference Portland, Oregon.
27. Seaber PR, Kapinos FP, Knapp GL (2007) Hydrologic Unit Maps: U.S. Geological Survey Water-Supply Paper 2294. pp: 63.
28. Lebassi B, Gonzalez J, Fabris D, Maurer E, Miller N, et al. (2009) Observed 1970-2005 cooling of summer daytime temperatures in coastal California. J Climate 22: 3558-3573.
29. Gelman A, Hill J (2007) Data analysis using regression and multilevel/hierarchical models, Cambridge University Press, New York, USA.
30. Joanes DN, Gill CA (1998) Comparing measures of sample skewness and kurtosis. Journal of the Royal Statistical Society (Series D): The Statistician 47: 183-189.
31. Lehmann E (2006) Nonparametrics: Statistical Methods Based on Ranks, Springer, New York. pp: 464.
32. Wosika EP (1981) Hydrologic properties of one major and two minor soil series of the coast ranges of northern California. M.S. Thesis. Arcata, CA, Humboldt State University. pp: 150.
33. Xu M, Qi Y (2001) Soil-surface CO2 efflux and its spatial and temporal variations in a young ponderosa pine plantation in northern California. Global Change Biology 7: 667-677.
34. SEAT (2008) Basin-Indians Fire, State Emergency Assessment Team (SEAT) Report, Monterey County, CA.
35. Ford LD, Hayes GY (2007) Northern Coastal Scrub and Coastal Prairie. In: Barbour MG, Keeler-Wolf T, Schoenherr A (eds) Terrestrial Vegetation of California (3rd edn.) Berkeley CA: University of California Press. pp: 180-207.
36. Kashian DM, Turner MG, Romme WH (2005) Variability in leaf area and stemwood increment along a 300-year lodgepole pine chronosequence. Ecosystems 8: 48-61.
37. Knight DH, Fahey TJ, Running SW (1985) Water and nutrient outflow from contrasting lodgepole pine forests in Wyoming. Ecological Monographs 55: 29-48.
38. Peterson DL, Arbaugh J, Lardmer MA (1989) Leaf area of lodgepole pine and whitebark pine in a subalpine Sierra Nevada forest. Can J For Res 19: 401-403.
39. Simonin KA, Santiago LS, Dawson TE (2009) Fog interception by Sequoia sempervirens (D. Don) crowns decouples physiology from soil water deficit. Plant, Cell & Environment 32: 882-892.

40. LaDochy S, Medina R, Patzert W (2007) Recent California climate variability: Spatial and temporal patterns in temperature trends. Climate Res 33: 159-169.

41. Mann PS (2007) Introductory Statistics (6th edn.) J. Wiley. pp: 615.