Impacts of the CZU Lightning Complex Fire of August 2020 on the forests of Big Basin Redwoods State Park

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FULL RESEARCH ARTICLE

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Abstract

The CZU Lightning Complex Fire started on 16 August 2020 and burned across more than 35,000 ha (80,000 acres) of forest lands in Santa Cruz County, California. In this study, Landsat satellite images of pre- and post-fire vegetation cover from 2020 were used to first map burn severity (low, moderate, high fraction) patterns on the CZU Fire landscape in and around Big Basin Redwoods State Park (BBRSP). For mapping of live regrowing versus currently dead forest stands, changes in the normalized difference vegetation index (NDVI) derived from 10-m resolution Sentinel satellite imagery (post-CZU Fire) were transformed into a new assessment metric called the Recovery-Regrowth-Green-Index (RRGI). The RRGI result derived from Sentinel NDVI change from October 2020 to July 2022 showed that just 24% of the burned forest cover in BBRSP was still alive and regrowing to a moderate level of new green canopy cover. Field surveys in BBRSP in July 2022 showed that trees not having attained a RRGI class level of 3 or greater, with sprouting of new green foliage on most of their horizontal limbs two years after the CZU Fire, were no longer alive and growing back. The unprecedented intensity of the CZU Fires together with two successive years (2021 and 2022) of extreme drought and summer heat has inflicted severe damage on the majority of old-growth trees in BBRSP.

Key words: burn severity, coast redwood, CZU Lightning Fire, forest, Landsat, NDVI, wildfire

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Introduction

The CZU Lightning Complex Fire started on 16 August 2020 in Santa Cruz County, California as a result of hundreds of lightning strikes in the Pacific coastal mountains. Lightning ignited the Waddell Fire near Waddell Creek as well as three fires on what would become the northern edge of the CZU Complex fire. Two days after the lightning storm, a change in wind conditions caused these northern fires to rapidly expand and merge with the Waddell Fire (CAL FIRE 2020).

The CZU Fire was fully contained on 22 September 2020, after a total of 35,009 ha (86,509 acres) were burned and 1,450 structures were lost (WERT 2020). These intensely hot fires burned more than 97% of the 7,366 ha Big Basin Redwoods State Park (BBRSP) forest area, devastating the ecosystems of California's oldest State Park, established in 1902 in the heart of the Santa Cruz Mountains. BBRSP's most renown features have been its ancient coast redwood trees, some of which are over 100 m (300 ft) tall and 1,000–2,500 years old (Bliss 2021).

Prior to the CZU fire, nearly all of BBRSP was covered with dense live vegetation cover, except for along The Chalks ridgetops at 400-m (1,200 ft) above sea level, along Henry Creek north of Hoover Road, and along Hihn Hammond Road above 400-m elevation. Forests in BBRSP are dominated by coast redwood (*Sequoia sempervirens*) trees, with scattered Douglas-fir (*Pseudotsuga menziesii*) and tanoak (*Notholithocarpus densiflorus*). Redwood forests in the BBRSP can be differentiated into a widespread Upland Redwood Forest type and a very narrowly distributed Alluvial Redwood Forest type (Martin 2001). Together, these similar plant communities cover more than 50% of BBRSP. Upland Redwood Forest occurs in moist locations primarily at low to middle elevations of BBRSP, especially in drainages with a perennial surface water. In deeper canyons and ravines, redwoods grow in nearly pure stands, and on drier ridge areas in association with Douglas-fir and other arboreal species. In the western portions of BBRSP, tree cover is frequently made up partially of knobcone pine (*Pinus tuberculata*) together with the occasional Douglas fir or redwood growing in more mesic drainages. Based on the National Land Cover Dataset from 2019 (Dewitz and USGS 2021), pre-CZU vegetation cover in BBRSP was 83% Evergreen Forest, 10% Mixed Forest (with pine trees), and 3% Shrub Cover (**Fig. 1**).

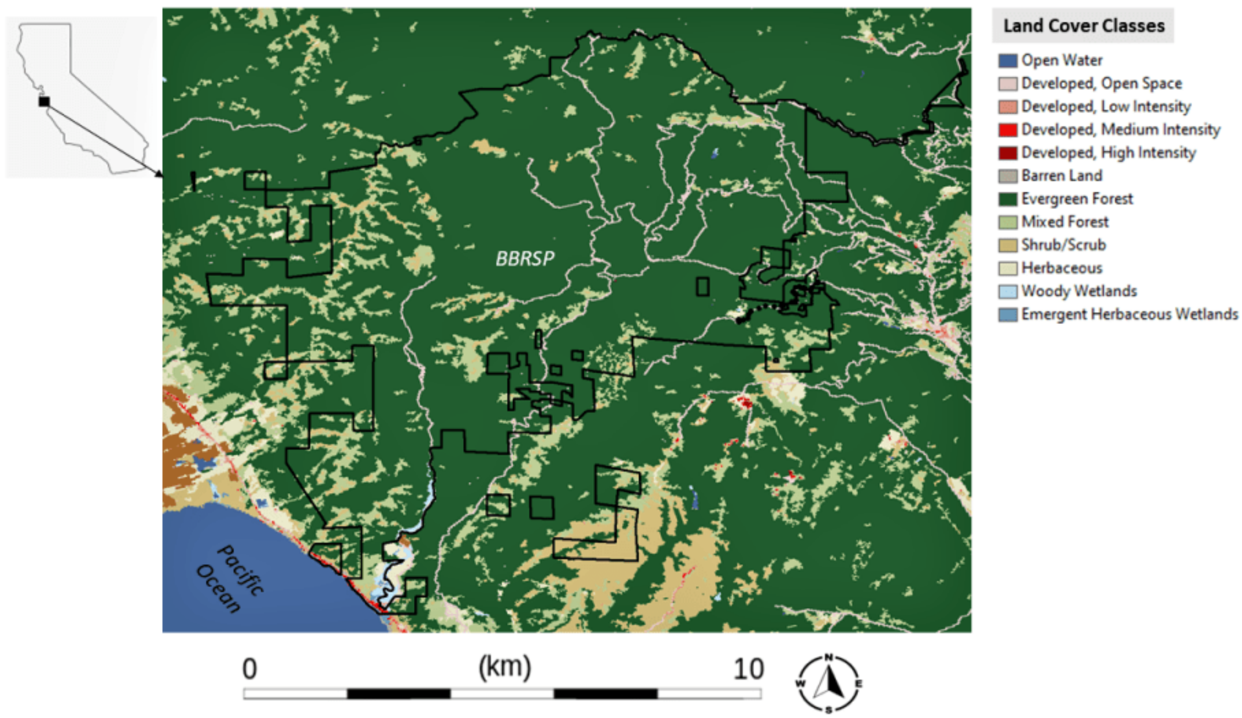

Figure 1. National Land Cover Dataset from 2019 (Dewitz and USGS 2021) for pre-CZU vegetation cover in Big Basin Redwoods State Park.

In the winter months of 2020 following the summer wildfires, a primary concern for the severely CZU-burned watersheds was the increased potential for damaging flood debris flows, rockfall from steep slopes, and hillslope erosion (WERT 2020). Concerted efforts were initiated to assess and address urgent safety and access issues. This included removal of hazardous trees along CA Highway 236 and near key access roads to the State Park. During the subsequent two years since CZU fires, focus has shifted to plans to replace all historic building and facilities damaged or destroyed in 2020 (CA State Parks 2022), and community-wide dialog has prompted the formulation of a new vision for protection of BBRSP's old-growth redwood trees, which still face a highly uncertain future in their survival and recovery from the CZU fires.

Nonetheless, a park-wide accounting of CZU-related tree mortality versus survival levels and mapping has yet to be provided as the scientific basis for "Reimagining Big Basin." Given the still hazardous terrain and inaccessible backroads of most post-CZU watersheds, satellite remote sensing is the most practical method currently available to accurately assess the status of trees (living/regrowing versus dying/dead) over the entire BBRSP area of 73 km^2 (28 mi^2). For mapping the severity of the wildfire impacts on vegetation cover, the use of multispectral burn severity metrics has become common across North American forests (French et al. 2008). The normalized burn ratio (NBR; Key and Benson 2006) from satellite imagery has been used routinely to assess the immediate post-fire changes in reflectance of live vegetation in forests of California (Potter 2016). Burn severity in forests has been shown to be a product of pre-fire vegetation conditions and fuel loads (Boucher et al. 2016; Lydersen et al. 2017; Potter and Alexander 2022) and topography (Krawchuk et al. 2016). Localized weather conditions, such as wind speeds and surface temperatures during the periods of intense burning, can strongly influence fire behavior and combustion rates of tree biomass (FCFDG 1992; Krawchuk et al. 2016).

The purpose of this study was to use a combination of Landsat and Sentinel satellite image data to quantify and map the coverage of living/regrowing trees versus dead trees across all of BBRSP resulting from burning during the 2020 CZU Fire. For mapping of live regrowing versus currently dead forest stands in 2022, changes in the normalized difference vegetation index (NDVI) derived from 10-m resolution Sentinel satellite imagery (post-CZU Fire) were transformed into a new metric called the Recovery-Regrowth-Green-Index (RRGI).

Methods

Analysis Using Satellite Image Data

I calculated the NBR index for the 2020 CZU Fire from satellite image dates, pre- and post-August of 2020, from the near infrared (NIR; 0.85-0.88 micrometers) and shortwave infrared (SWIR; 1.57–1.65 μm) bands of the Landsat 8 sensor Collection 2 images at 30×30-m pixel size, according to the equation:

$$NBR = (NIR - SWIR)/(NIR + SWIR)$$

Pre-fire (24 July 2020) and post-fire (26 September 2020) NBR images were differenced to generate a dNBR map product for the CZU Complex Fire. Burn severity classes of low, moderate, and high levels can cover a dNBR value range of –500 to 1,200 over burned land surfaces. Positive dNBR values represent a decrease in vegetation cover and a higher burn severity class, while negative values represent an increase in live vegetation cover following the fire event.

I defined four classes of burn severity for this study as: unburned to very low burn severity (0-VLBS) at dNBR < 500, low burn severity (1-LBS) at dNBR > 500 and <= 1000, moderate burn severity (2-MBS) at dNBR > 1000 and <= 5000, and high burn severity (3-HBS) at dNBR > 5000 (Potter 2016). These classification levels generally followed the burn severity thresholds determined by Miller and Thode (2007) based on a composite burn index (CBI) for California forests. The CBI was developed to assess on-the-ground fire effects on plants and soils (i.e., burn severity) by sampling over strata of the vegetation remaining post-fire: litter, low shrubs, small trees, tall shrubs and sapling trees, intermediate trees, and tall trees. All of these strata are detected by satellite image data for greenness index changes.

I chose Landsat image data from 26 September 2020 for post-fire imagery to establish burn severity classes because it was the first clear image after the CZU Complex Fire was contained. It is important to use the image closest to the fire containment date, rather than waiting 9–12 months after the fire containment, because minimal regrowth of vegetation would have occurred in September 2020 in this case. No major fire spread was reported afterwards, and it implausible that smoldering activity after September 2020 affected the burn severity classes in any manner.

The Sentinel (10-m pixel resolution) and Landsat 8 Collection 2 (30-m pixel resolution) normalized difference vegetation index (NDVI) of the near-infrared (NIR) and red spectral bands provides consistent spatial and temporal profiles of relative vegetation canopy biomass (Verbesselt et al. 2010) according to the equation:

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

resulting in values between –1.0 and 1.0 NDVI units. Negative NDVI values indicate water bodies, low values of NDVI (near 0.1) indicate barren land cover, and high values of NDVI (above 0.8) indicate dense forest canopy cover. NDVI has been shown to be an accurate index of herbaceous green cover in grasslands of California and can be converted into seasonal herbaceous biomass (grams carbon per square meter) each year (Potter 2014).

The Sentinel 10-m pixel resolution is arguably ideal for this mapping application of large tree green cover change. Any smaller pixel size (e.g., 1-m) would be severely impacted by tree bole shadows and not be capable of averaging out other topographic shadow effects like the Sentinel data. Moreover, the 10-m pixel values for NDVI would account for any additional horizontal areas of green leaf cover from resprouting with sprouts very close to the bole. I obtained Sentinel-2 images acquired on dates in July 2020, October 2020 and 2021, June 2021, and July 2022 for NDVI change analyses. These were the best cloud-free images available in these years. The RRGI was computed as the difference in Sentinel NDVI (per 10×10-m pixel area) between post-fire image dates (acquired either in 2021 and 2022) and the first post-CZU Sentinel-2 NDVI acquired on 14 October 2020 (just one month after fire containment).

Field surveys and geo-tagged photos of standing tree boles, ground cover, and forest canopies within the burned areas of BBRSP were carried out in April–June of 2021 and July of 2022 to define and ground-truth the potential categories of RRGI, ranging from negligible regrowth (and presumed dead after 2 years post-CZU Fire impacts) to low, moderate, and high categories of forest regrowth. I chose the transect used for ground-truth locations based on ease of access via the only open road into BBRSP at these times.

Stratification of Forest Cover Types

I stratified pre-2020 forest and woodland types in the CZU-impacted study area by National Land Cover Dataset (NLCD 2019) land cover classes (**Fig. 1**). The U.S. Geological Survey (USGS), in partnership with several federal agencies, has developed and released five NLCD products over the past two decades. For the 2019 NLCD map product used in this study, a nationwide assessment showed a 91% overall land cover class accuracy.

Slope and Aspect Layers

Digital layers for slope and aspect for the CZU Complex burned area were determined at 30-m spatial resolution from the United States Geological Survey (USGS) National Elevation Dataset (NED) using the ArcGIS Spatial Analyst Toolbox (ESRI 2021). This tool uses a 3-by-3 cell moving window to process the digital elevation data into continuous gridded slope and aspect values. I used these topographic layers to determine which portions of large drainage basins were burned at high-severity.

Results

Landsat Burned Severity Patterns

The CZU burned severity map from 2020 Landsat NBR images (**Fig. 2**) showed the distribution of land area of BBRSP among classes was as follows: low severity 2%, moderate severity 20% (majority of live canopy cover lost), and high severity 77% (all live canopy cover lost). Several small areas of dense live vegetation cover on the western slope of West Waddell Creek (south of Gazos Creek and between Kelly Creek and Timms Creek), and on the western slope of Berry Creek were detected as largely unburned in 2020, but were probably impacted by ground fires during the CZU event, which the Landsat NBR images could not fully detect.

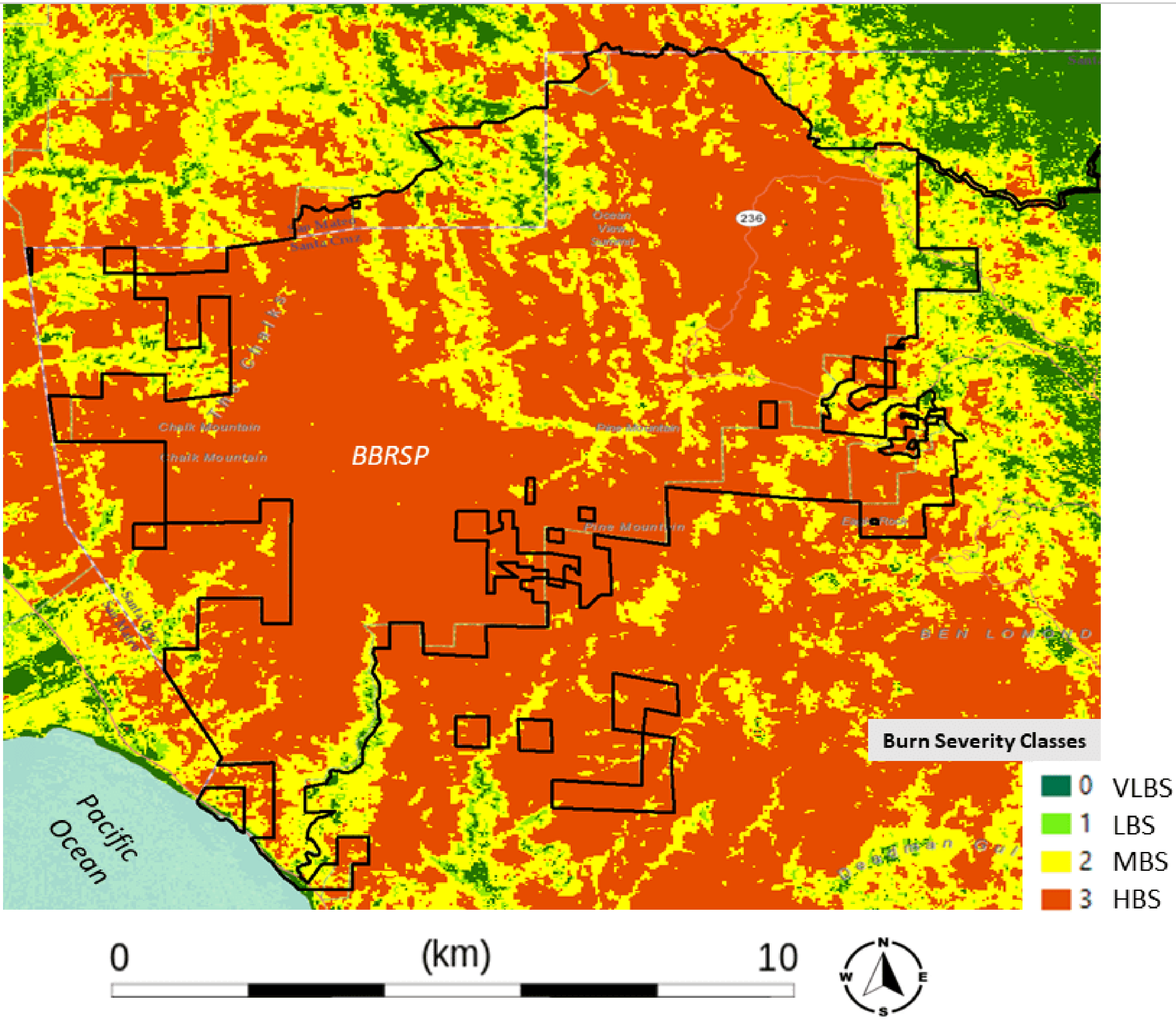

Figure 2. Map of Landsat dNBR burn severity classes resulting from the 2020 CZU Complex fires in the Big Basin Redwoods State Park area (delineated in solid boundary line). Color legend of burn severity class labels is as follows: 0 = very low burn severity, 1 = low burn, 2 = moderate burn severity, and 3 = high burn severity.

Pre- and Post-CZU Fire NDVI Patterns

Maps of pre-CZU fire (July 2020) and post-fire (October 2020) Sentinel NDVI showed nearly complete loss of dense green plant cover across > 90% of BBRSP (Fig. 3). Prior to the 2020 CZU Fires, nearly all BBRSP had forest cover with NDVI levels greater than 0.6, whereas after the CZU Fire, only low and moderate burn severity areas showed NDVI levels greater than 0.1. NDVI at 0.1 is indicative of bare ground with no live vegetation cover.

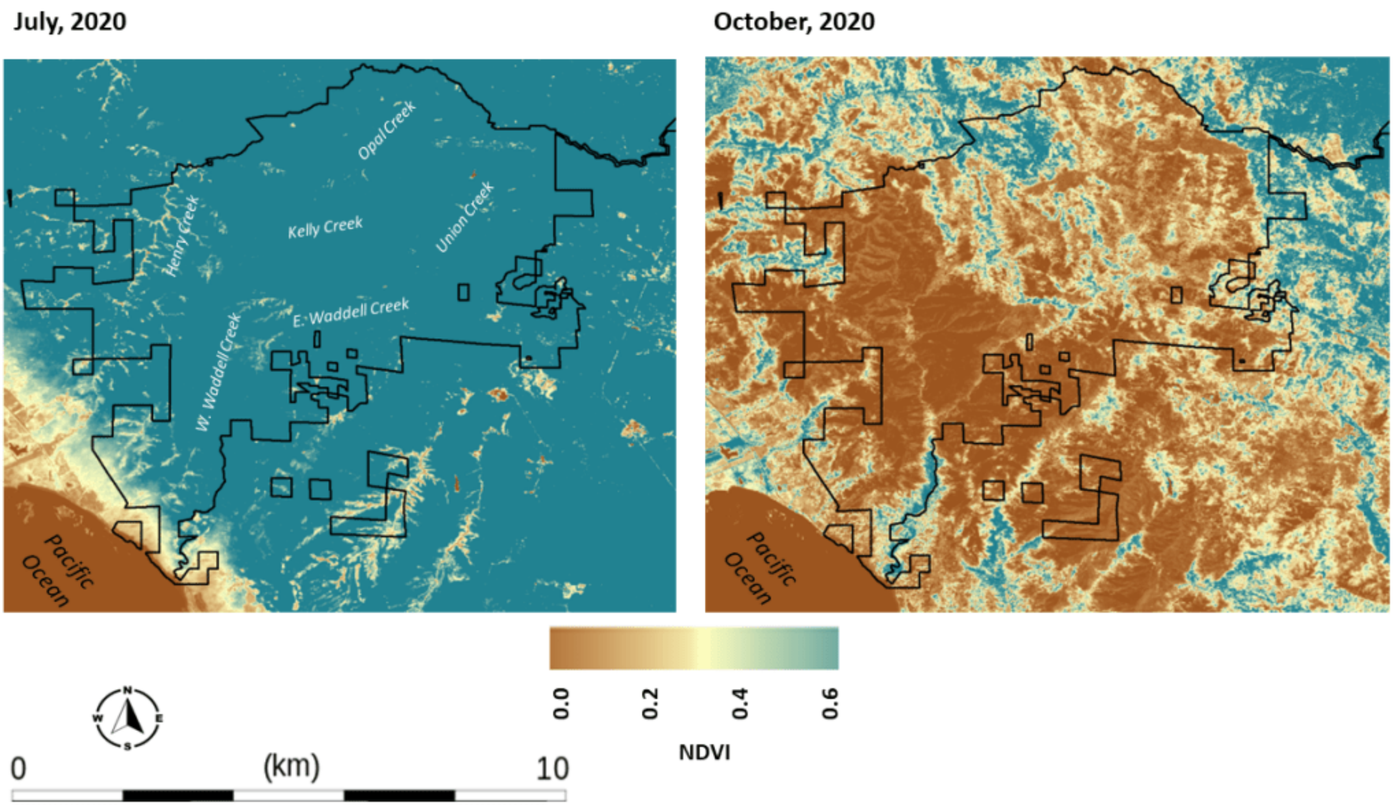

Figure 3. Pre-and post-fire maps of NDVI from Sentinel imagery acquired in 2020 across the CZU Complex burned areas in Big Basin Redwoods State Park.

Post-CZU fire Sentinel NDVI maps from imagery obtained in October 2021 and July 2022 for BBRSP (**Fig. 4**) implied, respectively, that: (1) almost no large tree canopy regrowth and recovery had occurred in BBRSP over the first full year following full containment of the-CZU Fire (October 2020 to October 2021), and (2) a modest amount of large tree canopy regrowth occurred over the next 9 months (November 2021 to July 2022), mainly in the eastern-most creek drainages of BBRSP. Greening of the severely burned forest cover (from NDVI < 0.1 to around 0.25) was most noticeable by July 2022 in the Union Creek, Kelly Creek and E. Waddell Creek drainages on flat slopes and relatively low elevations of 300 m (**Fig. 4**).

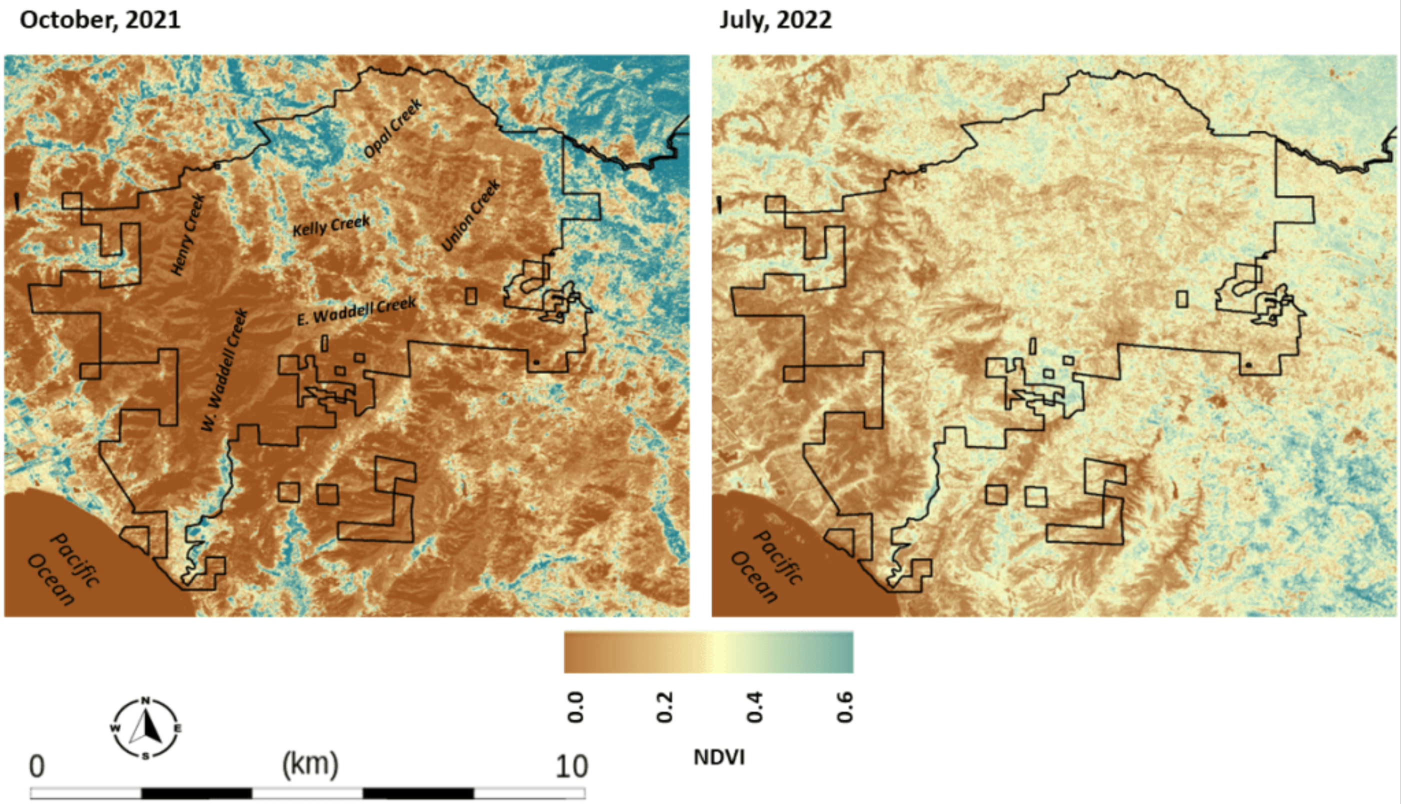

Figure 4. Post-fire maps of NDVI from Sentinel imagery acquired in 2021 and 2022 across the CZU Complex burned areas in Big Basin Redwoods State Park.

Definition of RRGI Classes from Ground-Truth Surveys

Between April and June of 2021, a transect of ground-truth locations (**Fig. 5**) was surveyed with geo-tagged photos in BBRSP along Little Basin Road to characterize and define five classes of the RRGI derived from Sentinel NDVI change since October 2020 ($dNDVI_{1000}$). It was determined that a $dNDVI_{1000}$ level of less than 1000 was typical of areas with negligible sprouting of new plant growth on the ground or in the burned forest canopy. A low regrowth $dNDVI_{1000}$ level between 1000 and 2000 was typical of areas with herbaceous regrowth of vegetation on the ground, but negligible sprouting of new plant growth in the burned forest canopy. Moderate to high regrowth classes of the RRGI were listed and defined in **Table 1** for forest canopy status, with example photos shown in **Fig. 5**.

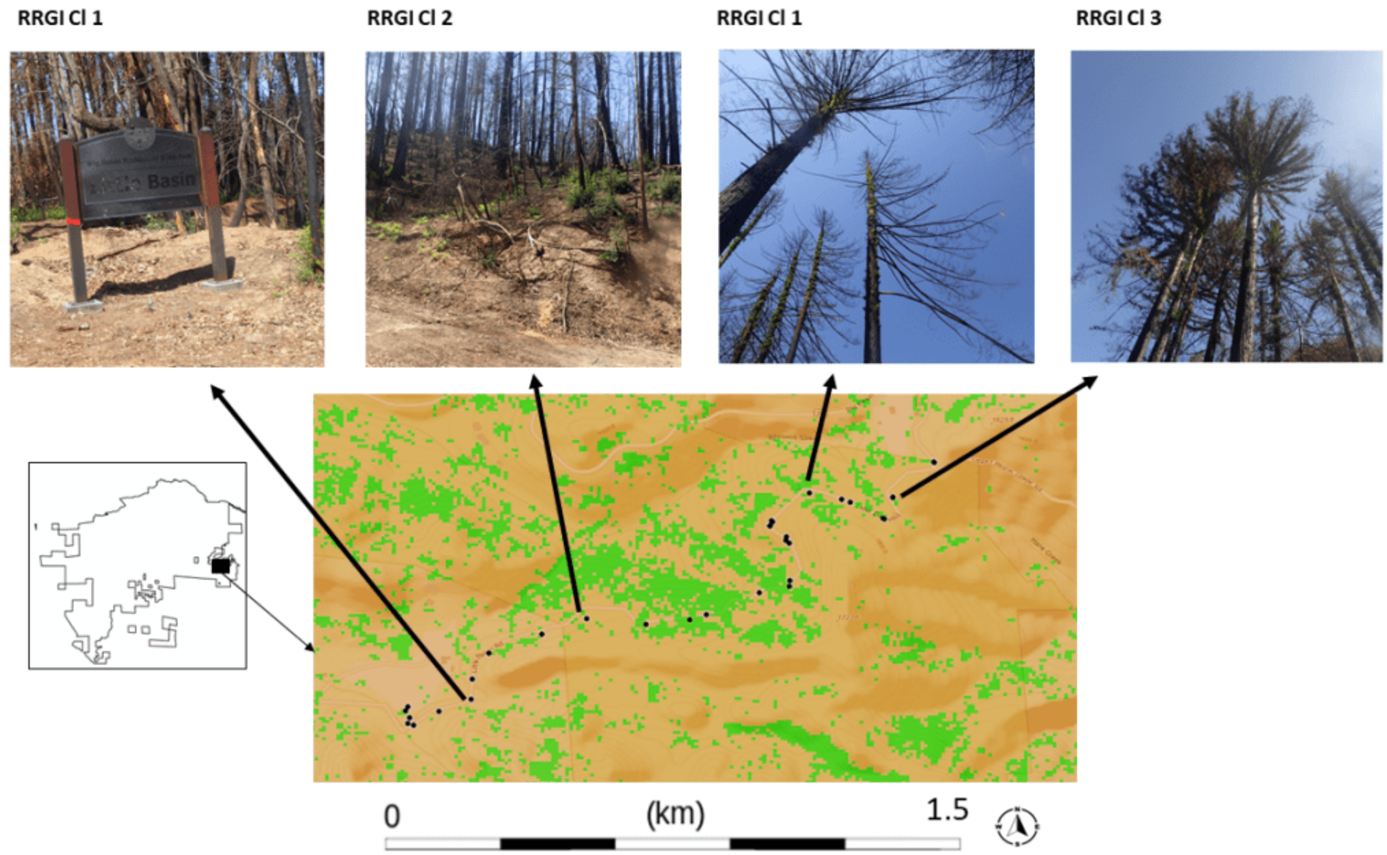

Figure 5. Example photos taken on a transect of ground-truth survey locations in 2021 in Big Basin Redwoods State Park along Little Basin Road, used to define five classes of the RRGI derived from Sentinel NDVI change since October 2020. The lower map colors of RRGI classes (Cl) derived from June 2021 Sentinel imagery shows Cl = 1 in brown and Cl = 2–3 in green shades. Photo points are labelled as the black dot symbols.

Table 1. Recovery-Regrowth-Green-Index (RRGI) classes, derivation, and definitions.

Class No.	Class Name	Range of the $dNDVI_{1000}$ Equation	Definition
1	Negligible recovery/regrowth	< 1000	Little sprouting of new growth on the ground or in canopy
2	Low regrowth	< 2000	Sprouting of new herbaceous regrowth on the ground
3	Moderate regrowth	< 3000	Sprouting of new herbaceous and woody regrowth on the ground and on tree limbs
4	High regrowth	< 4000	Dense woody regrowth on the ground and in canopy
5	Complete regrowth/No burn	>= 4000	Vigorous canopy growth following normal seasonal cycle

RRGI Mapping of Forest Recovery in BBRSP

The RRGI result derived from Sentinel NDVI change from October 2020 to June 2021 showed that only 14% of the burned forest cover in BBRSP was regrowing to a new low level of green canopy cover (**Fig. 6**). The most notable areas of tree survival and regrowth in BBRSP in June 2021 could be detected along the Waddell Creek drainages in those creek-side forest stands of BBRSP.

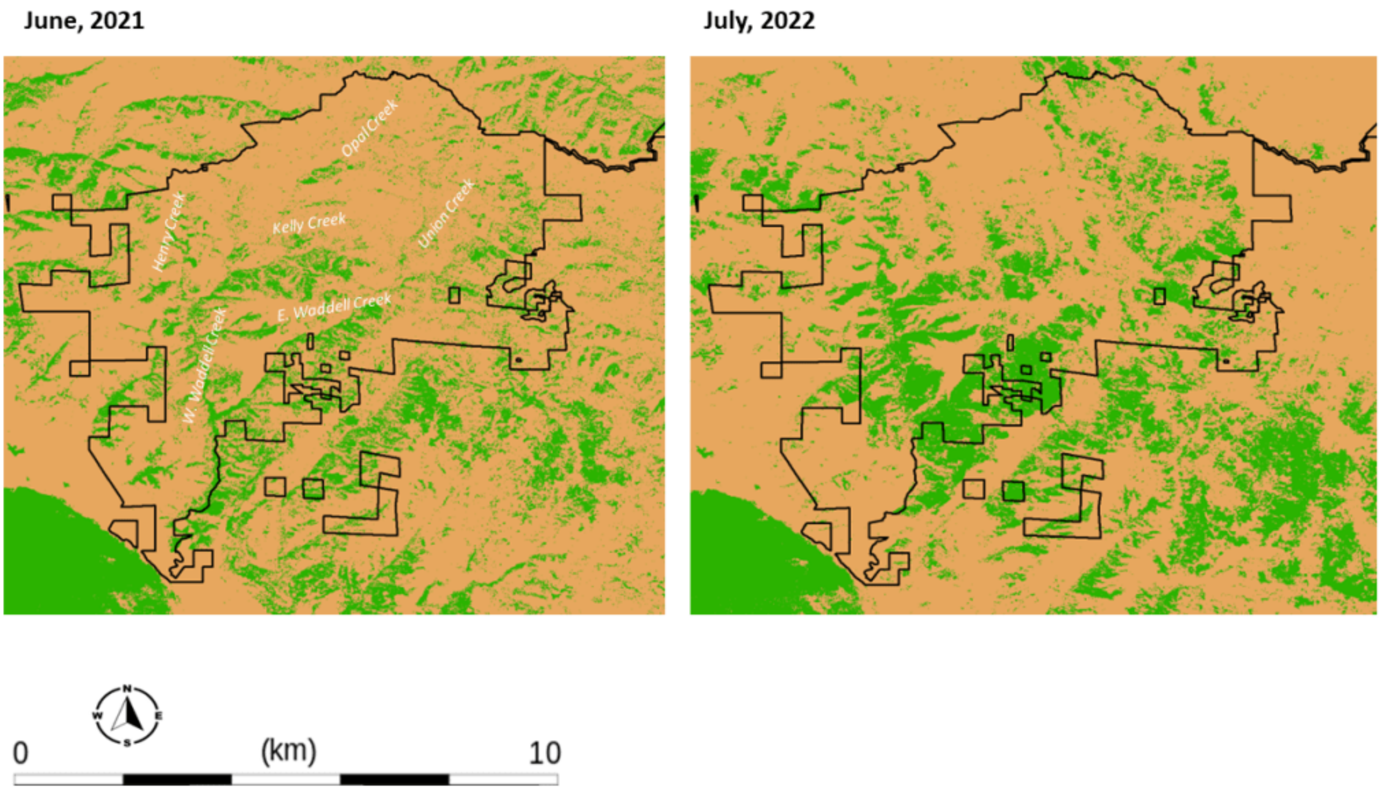

Figure 6. Recovery-Regrowth-Green-Index (RRGI) maps derived from 2021 and 2022 Sentinel NDVI change since October 2020, with RRGI CI = 1 in brown and CI = 2-3 in green shades.

The RRGI result derived from Sentinel NDVI change from October 2020 to July 2022 showed that just 24% of the burned forest cover in BBRSP was still alive and regrowing to a moderate level of green canopy cover (**Fig. 6**). Based on resurvey of the ground-truth locations along Little Basin Road locations (**Fig. 5**) in July 2022, it was evident that trees not having attained a RRGI class level of 3 or greater (with sprouting of new green foliage on most of their horizontal limbs; examples in **Fig. 7**) two years after the CZU Fire were no longer alive and growing back. Tree stands that remained at a RRGI class of 1 in July 2022 had not grown back any new leaf canopy over the past year and most likely will have to regenerate a new living forest solely from the sprouting of seedlings between the many dead standing tree boles (example photos in **Fig. 7**).

Figure 7. Example photos taken on a transect of ground-truth survey locations in July 2022 in Big Basin Redwoods State Park along Little Basin Road.

The densest areas of forest survival and regrowth in BBRSP could be detected in 2022 at relatively low elevations along the Waddell Creek and Union Creek drainages at around 300 m above sea level. Extensive upslope and ridgetop portions of the Henry Creek and Kelly Creek drainages above 400 m elevation have lost all their living tree cover to severe burning during the 2020 CZU Fires. In summary, based on satellite image analysis, 75% of the former forests of BBSRP must be regrown from the sprouting of new redwood seedlings, rather than experiencing regrowth on old-growth redwood and Douglas-fir tree boles that appear to have succumbed to the intensive burning of the CZU Fires.

RRGI results derived from Sentinel NDVI change from October 2020 to July 2022 were further stratified by NLCD (2019) land cover classes (**Fig. 1**), to separate predominantly Evergreen forest from Mixed forest (with pine trees) and from Shrub dominated vegetation communities. Zonal statistics demonstrated that pre-fire (2019) Mixed forest cover (with pines) and Shrub cover both had around 50% lower RRGI values on average in 2022 compared to Evergreen Forest cover areas (**Table 2**). However, even the majority of pre-fire Evergreen Forest cover had not recovered a notable green canopy cover after 2 years post-CZU, showing RRGI values lower than 1500 on average in 2022 across BBRSP. Pre-fire Barren and Herbaceous land cover classes within BBRSP had not recovered a positive green cover since the CZU Fires of 2020.

Table 2. Recovery-Regrowth-Green-Index (RRGI) values derived from Sentinel NDVI imagery of July 2022 summarized by NLCD land cover classes within Big Basin Redwoods State Park. (SD = Standard Deviation)

Land Cover Name	Area (ha)	Mean	SD
Developed, Open	2,196	642	1653
Developed, Low	44	–192	747
Developed, Medium	68	–102	486
Developed, High	17	153	597
Barren	26	–322	448
Evergreen Forest	52,971	1200	1505
Mixed Forest	6,373	537	769

Land Cover Name	Area (ha)	Mean	SD
Shrub	2,075	473	886
Herbaceous	136	–773	1394
Woody Wetlands	232	277	1219
Herbaceous Wetlands	54	–416	1080

Discussion

Healthy, sustainable redwood forests are crucial to the future of Pacific coastal ecosystems. *Sequoia sempervirens* has some inherent resilience to wildfire, but also a dependence for growth on cooling marine layers originating from the Pacific Ocean (Johnstone and Dawson 2010). Nonetheless, widespread timber harvesting in the Pacific coastal redwood zone over the past centuries has changed stand structures, with a marked increase in fine fuels from more young trees; these structural biomass changes have increased potential for high severity crown fires (Mahdizadeh and Russell 2021). The 2020 CZU Complex fires were an extreme case of high severity burn impacts that will last for decades on even the oldest trees heretofore preserved within BBRSP.

To put the burn patterns seen in the 2020 CZU Complex Fire into a broader regional perspective, Potter (2017) provided an analysis of the 20 largest wildfires that burned near the California central coast since 1984; this study showed that the fraction of high burn severity area to total area burned ranged from a minimum of 0 to a maximum of 73%, with an average of 21%. The 77% of total area that burned high severity within BBRSP during the 2020 CZU Fire was notably higher than the average of recent Pacific coast wildfires. Potter (2016) reported that the 2016 Soberanes Fire in Monterey County resulted in a high severity burn fraction of 22% and moderate burn severity fraction of 10%, out of the approximately 53,740 ha burned (132,130 acres). Therefore, the Soberanes Fire was more typical of most forest fires on California coast in terms of moderate and high burn severity fractions, and contrasts again with the CZU Fire that had a much higher fraction of both moderate and high burn severity coverage than most any other recorded wildfire on the central California coast. Nonetheless, the pre-fire conditions of fuels cannot be easily generalized across the coastal Pacific forest region, due in part to microclimate effects on surface heating and soil moisture, and these small-scale variations must be accounted for in any method for monitoring post-fire recovery applied to each large forest fire in the region.

A principal finding from this study using satellite data analysis is that the majority of pre-CZU evergreen forest cover in BBRSP has not recovered a notable green canopy cover after 2 years post-fire. Separation of evergreen forest areas from mixed forest (with pine trees) and from shrub-dominated vegetation communities within the 2020 CZU burned area proved to reinforce this conclusion. These results shed light on the fate of different types of woodland cover on the northern coast of California from high-severity wildfire.

Further putting satellite data analysis into a broader context with the use of both pre-and post-fire NDVI mapping, the use of RRGI from Sentinel-2 can serve as a sound scientific basis for restoration prioritization and planning. This imagery is acquired on a predictable (bi-weekly) schedule and offers global coverage at a resolution that maps individual large tree canopies. RRGI is an unbiased index of the site-specific recovery status of burned landscapes, meaning that every forest or shrub canopy is tracked in individual pixels over years before and after wildfires. Recovery rates and geographic patterns are inherent in the change of RRGI images generated each year within a burned area. These changes detected by RRGI in canopy cover conditions can be broadly applied and compared across most forest fires in the western United States. Adjustments in evaluations of vegetation regrowth from each fire should be made by overlaying tree cover types and species maps wherever available.

Post CZU-fire restoration activities within BBRSP included the downing and removal of thousands of dead and dying trees, which were deemed to pose a threat to public safety (KRON4 2020). Trucks stacked with burned tree trunks could be seen on the roads around BBRSP for more than a year after the CZU fires. At least 72 km (45 mi) of public roadways were impacted and had to be made safe by downing of hazardous burned trees. None of these post-fire rehabilitation activities would have influenced the results reported in this study however, since dead tree canopies are not distinguishable in NDVI images from bare ground remaining after their removal or a salvage operation.

From the local historical context, prior to 2020, fires in and around BBRSP would rarely burn at high severity, compared specifically to the CZU fire (SCMBC 2022). Seldom would fires burn into the redwood and Douglas-fir tree stands of BBRSP and up into their crowns (Brown and Baxter 2003). Low intensity fires can blacken the thick outer bark of old-growth conifer trees, but not burn so hot as to kill them. The CZU Fire changed everyone’s perception of what wildfire in the 21st Century era of climate change can do to an ancient coastal forest. For instance, the Santa Cruz Mountains Bioregional Council (SCMBC) recently commented on their website (SCMBC 2022; **http://www.scmbc.org/**):

“While coast redwood trees are renowned for their resistance to fire and their seemingly indomitable resilience, the severity of this fire should not be discounted. The CZU Lightning Complex fire was very damaging to our old-growth redwood forests and their associated flora and fauna. Unlike its cousin, the giant sequoia (*Sequoiadendron giganteum*), coast redwood is not dependent on fire, and it is quite possible that this coast redwood forest will not rebound as fully as we hope.”

The results from satellite image analysis of the BBRSP from 2020 to the present implies that there are diminishing prospects for the rapid (2–5 years post-fire) recovery and regrowth of the majority of the canopy of centuries-old trees burned in the CZU Fire. Consistent with this finding, in a study of wildfire impacts of two old-growth coast redwood forests on the Pacific Coast of California, Carroll et al. (2018) reported data from tree ring analysis to show that severe decline in wood growth rate persisted for up to 7 years post-fire before returning to adding bole wood at roughly the pre-fire rate. Evidence from other fire ecology studies have indicated that post-fire reduction in radial growth commonly points to depleted or diverted plant resources, as burned trees respond to fire-damaged roots, boles, and canopy leaf cover (Seifertet al. 2017).

Old-growth redwood trees blackened from the CZU Fire, with no thick leaf canopy left to shade the ground around them from intense summer heat and soil moisture loss, have since had to endure two consecutive years (2021 and 2022) of one of the driest periods in modern history in California. Data released by the National Oceanic and Atmospheric Administration’s (NOAA) National Centers for Environmental Information showed that precipitation totals in the state from January through April 2022 were the lowest on record dating back to 1895 (Available from: **https://www.ncei.noaa.gov/access/monitoring/us-maps/ytd/202204**). Under this stressful combination of high severity fire followed by extreme drought conditions, the high mortality of even old-growth redwood trees is expected.

In conclusion, the RRGI mapping provided in this study can be used to inform restoration prioritization and planning across BBRSP in years to come. Comparisons of the satellite-derived RRGI can be made to aerial (drone) imaging for validation of tree mortality in the more remote sections of BBRSP. In combination with ground-truth surveys, yearly RRGI mapping can be used to determine the success of planting/restoration efforts 5, 10, and 20 years into the future.

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