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Investigating spatiotemporal trends of large wildfires in California (1950–2020)

Sarah Ostertag [a,b,*], Matthew Rice [a], John J. Qu [a]

[a] *George Mason University, Geography and Geoinformation Science Department, Fairfax, Virginia, United States of America, Sarah Ostertag – sostert@gmu.edu, Matthew Rice – rice@gmu.edu, John J. Qu – jqu@gmu.edu*

[b] *Ramboll US Consulting, Inc. (Environment and Health), Arlington, Virginia, United States of America, Sarah Ostertag – sostertag@ramboll.com*

* Corresponding author

Abstract:

A database capturing large wildfire perimeters (> 1,000 acres / 405 hectares; n=2,857) in the state of California in the United States was used to document trends in fire occurrence (as frequency of large wildfires per year) and fire severity (using total burned area as a proxy) per ecoregion for the study period 1950–2020. Approximately 20.67% of the total area of California has been burned by large wildfires during the study period; of this, approximately 8.01% of the total area of California has been burned repeatedly. Large wildfires are becoming more severe in the state of California, burning an average of 5,068 additional acres (2,051 additional hectares) of land each year, however large wildfires are not occurring more frequently across the entire state as originally postulated. Rather, certain ecoregions, particularly mountainous regions with coniferous forests, exhibit statistically significant increasing trends in both large wildfire severity and occurrence compared to other regions of the state, likely contributing to the sentiment that wildfires are becoming worse in the state overall. As conditions relating to climate change, extreme weather events, invasive species, population distribution, and fire management decisions continue to change, the impacts of larger, more frequent fires will likely be felt more broadly across the state of California.

Keywords: Climate change, wildfires, GIS, California, spatiotemporal trends

1. Introduction

The threat of wildfires is of paramount concern to California residents, communities, businesses, and civic leaders. Communities regularly drill for fire emergencies and are well-versed in and legally required to assist with fire-prevention efforts. Anecdotally, many members of the public operate with the belief that wildfires are becoming more severe and occurring more frequently as time passes, "…who for years have been living with the reality of hotter, more frequent and more intense wildfires." (Smith 2022). This belief became the motivation for this study.

This research explores the scientific basis for the sentiment described above that has been engrained in public consciousness. Are wildfires in California actually getting more severe and occurring more frequently?

Several researchers have analysed trends in wildfire causes, occurrence, and impacts for the state of California over various administrative regions. Research indicates that over the past two decades, the frequency of small (< 500 acres [ac] / 202 hectares [ha]), human-caused wildfires has increased most rapidly (Li and Banerjee 2021); over the past 100 years in California, the frequency of wildfires declined significantly after 1980 while the frequency of total annual burned area of all wildfires increased significantly (Keeley 2021; Li and Banerjee 2021). Extreme fire events (>10,000 ha) have occurred during various periods historically and have increased again in recent years (Keeley 2021), possibly attributed to a "fire deficit" in the western United States of America (U.S.) caused by human activities, ecological, and climate changes (Marlon et al, 2012).

The variables directly considered in this study are somewhat limited. Due to the quality and types of data available, this study only directly considers wildfire occurrence (as frequency of large wildfires per year, defined as > 1,000 ac / 405 ha) and severity (using total burned area as a proxy) by ecoregions (defined below) in order to ascertain what spatiotemporal trends may be present in California. While burned area may not be an appropriate proxy for fire severity in all cases, this project focuses on analysing vector data products, thus inclusion of raster data products such as the Monitoring Trends in Burn Severity (MTBS) dataset is beyond the scope of this analysis. Many more variables likely explain a portion of trends that may be exhibited by wildfires, such as weather patterns; climate variables; population density; utility and transportation network distribution; invasive species; fire ecology characteristics; and, economic variables, such as availability of funds for wildfire prevention, protection, and emergency response (Dennison et al., 2014; Li and Banerjee 2021; Marlon et al, 2012; Weber et al., 2020; Williams et al., 2019). These variables should be considered in future work to ascertain a more

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comprehensive understanding of large wildfires in California and how increased climate change and wildfire resiliency might be achieved.

2. Data

The spatial coverage of this research is the state of California in the U.S. The California Department of Forestry and Fire Protection (CALFIRE) Fire and Resource Assessment Program (FRAP) fire perimeters database was selected for use in this study (CALFIRE 2021). The fire perimeter database provides a spatial distribution of past large wildfires and is a multi-agency state-wide database, including data from CALFIRE, the United States Forest Service Region 5 (USFS), the Bureau of Land Management (BLM), and the National Parks Service (NPS). It consists of more than 21,000 mapped wildfire perimeters, stored in polygon vector format in a file geodatabase, with temporal coverage spanning 1878 through 2020. While CALFIRE asserts that this database reports the most complete digital fire record of fire perimeters in California, it is not without limitations. According to the metadata, the definition of fires whose perimeters were recorded has evolved over time, changing approximately every 30 years; fires may be missing from the database or have incorrect attribute data; some fire perimeters may have been over- or under-generalized; and/or fires may have been omitted due to evolving reporting cut-off limits. Current CALFIRE cut-off limits for reporting require 10 ac (4.05 ha) or greater for timber fires, 30 ac (12.14 ha) or greater for brush fires, and 300 ac (121.41 ha) or greater for grass fires; the USFS has maintained a 10-ac minimum cut-off limit for reporting since 1950.

United States Environmental Protection Agency (EPA) Level III ecoregions for California were also included in this study (EPA 2012). Data was extracted as a polygon feature class from the seamless national shapefile. Ecoregions denote areas with similar ecosystems and the type, quality, and quantity of environmental resources available in that region. Generally, ecoregions were compiled through analysis of patterns in biotic and abiotic phenomena, including geology, physiography, vegetation, climate, soils, land use, wildlife, and hydrology (USEPA 2012). In the numerical hierarchy, Roman numeral Level I represents the coarsest level, while Level IV represents the most granular; there are 105 Level III ecoregions in the coterminous United States (CONUS), and 13 within the state of California (Figure 1). Broadly speaking, this research assumes that ecoregion definitions capture a wide variety of variables contributing to wildfire characteristics and that differing ecoregion characteristics explain a portion of wildfire trends present in California.

To assess some additional variables not directly analysed by this study, fire regime groups (FRGs) were qualitatively assessed. The National Interagency Fuels, Fire, and Vegetation Technology Transfer (NIFTT) maintains a Fire Regime Condition Class (FRCC) assessment system, which is an interagency tool used to determine the degree of ecological departure from historical, or reference condition, vegetation, fuels, and disturbance regimes to help guide management objectives and treatment strategies for wildfires (NIFTT 2010). FRGs are considered a reference condition for the FRCC; FRGs serve as a general classification of the "role fire would play across a landscape in the absence of modern human intervention" (NIFTT 2010, p. 14). Five natural FRGs are classified based on the fire frequency (e.g., mean fire interval) combined with characteristic fire severity reflecting percent replacement of dominant overstory vegetation (NIFTT 2010, p. 15); in essence, FRGs serve to capture historical fire characteristics for a given region. FRGs were extracted from the LANDFIRE[1] (LF) Biophysical Settings (BPS) dataset, which is a geotiff raster dataset covering the CONUS, and were clipped to cover only the state of California (LANDFIRE 2016).

3. Methods

Datasets were loaded into ArcGIS Pro (GIS) for analysis. A spatial join was performed to attach the Level III ecoregions to wildfire perimeter data based on the ecoregion with the largest overlap in the burned area of the fire (e.g., the attributes for the ecoregion defined in the majority of the fire area were utilized) (Flater 2012). Zonal statistics were calculated for each ecoregion and the state of California to determine the majority fire regime present in each. Data tables and summary statistics were exported from GIS for use in Microsoft Excel©, from which additional descriptive statistics and charts were generated along with the Mann-Kendall trend tests utilizing the XLSTAT add-on (Addinsoft, 2021).

To mitigate limitations presented by the FRAP fire perimeters data, the study period is defined as 1950 – 2020 and was chosen due to greater consistency in data recording reported by FRAP during this timeframe; perimeters without temporal attributes and perimeters completely outside of California borders were excluded. Additionally, for the purposes of this study, large wildfires are defined as fires burning 1,000 ac (405 ha) or greater (e.g., Class F fires or higher) (NWCG, undated), regardless of cause[2], vegetation type, or resulting damages; this cut-off was chosen as it is greater than any of the variable reporting requirements mentioned in the metadata for wildfires during the study period. A total of 2,857 wildfire perimeters were included for analysis in this research with the parameters described above.

With wildfire data in particular, it follows that variables contributing to wildfire occurrence are not completely independent from one another. As discussed above, this

[1] The Landscape Fire and Resource Management Planning Tools (LANDFIRE) is a shared program between the wildland fire management programs of the U.S. Department of Agriculture Forest Service (USDA) and the U.S. Department of the Interior (DOI).

[2] Fire cause was not considered in this study as analysis revealed that 57.24% of reported fires causes in the data are listed as "Unknown/Unidentified" or "Miscellaneous."

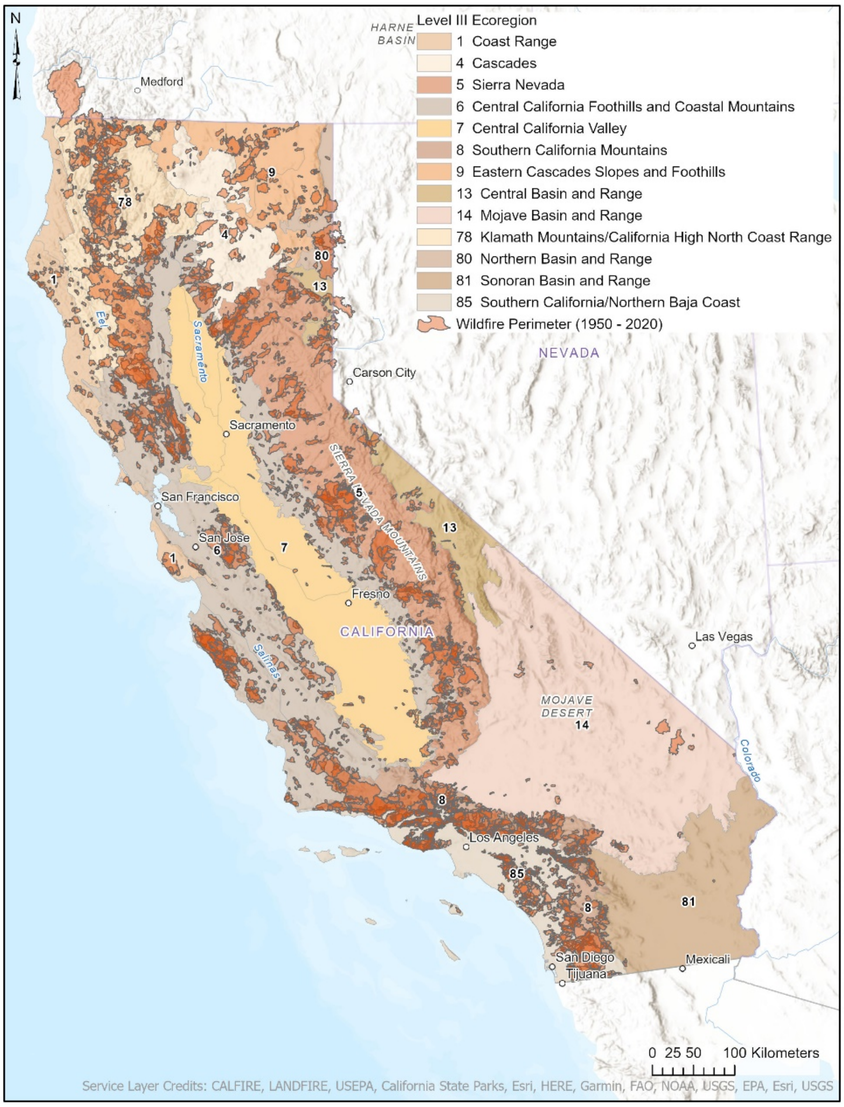

Figure 1. Historic Large Wildfire Occurrence (1950 – 2020) by Level III Ecoregion. There is visible dispersion (i.e., spatial autocorrelation) in the wildfire perimeter dataset; wildfires appear to align closely with certain ecoregion boundaries.

study only directly considers large wildfire occurrence, wildfire severity (using total burned area as a proxy), and Level III ecoregion characteristics. Logically, one can assume that certain ecoregions and fire regimes may be more susceptible to large wildfires than others given the phenomena that the same areas keep burning and often experience burn-on-burn effects (Figure 1) (Patel 2018; Weber et al., 2020). Numerous other variables likely contribute to possible trends presented by large wildfires in California, including but not limited to climatic patterns, population density, utility and transportation distribution networks, invasive species, fire ecology characteristics, and economic variables (such as funding for fire prevention/protection efforts) (Dennison et al., 2014; Li and Banerjee 2021; Marlon et al, 2012; Weber et al., 2020; Williams et al., 2019). These variables naturally vary geographically as does the occurrence of large wildfires in line with Tobler's first law of geography, which states that observations that are near each other are more related when compared to observations that are further away (Tobler, 1970); this is the basis for spatial autocorrelation.

Classic linear regression methods and analysis of variance (ANOVA) were inappropriate for the chosen data sets as the required assumption of a normal distribution and independence of observations could not be met (Burt et al., 2009, Chapter 12). Non-parametric methods, including the Mann-Kendall trend test, were used instead. Using time (e.g., alarm date or year of fire occurrence) as the independent variable, fire severity as total area burned exhibits spatial autocorrelation as a dependent variable, thus violating the regression model assumption that observations are independent; consequently, the errors presented by a standard regression model for this data would also be correlated, and regression coefficients estimated using ordinary least squares (OLS) techniques would be biased and inefficient (Burt et al., 2009, p. 567). To quantitatively assess the assumption that wildfire data may exhibit spatial autocorrelation, the spatial autocorrelation tool was utilized in GIS prior to further analysis to calculate the Global Moran I statistic; this revealed a z-score of -4.576 with a p-value of 0.000005 for total burned area, indicating that there is significant spatial dispersion in the fire perimeter dataset with a less than 1% likelihood that this pattern could be the result of random chance. Additionally, the mean and median annual burned area was compared to assess the normality of the distribution. As the mean annual burned area is consistently higher than the median annual burned area, there is a positive skew to the data and a normal distribution cannot be assumed; the variance in the mean and median may be caused by an increase in abnormally large wildfires (e.g., outliers) in recent years skewing the mean annual area burned up compared to the median (Weber et al., 2020). However, as these recent abnormally large wildfires are validated fire perimeters, the data was included in the overall analysis, and thus a normal distribution was not assumed.

In order to analyse potential trends present in the occurrence and severity of large wildfires in California (using burned area as a proxy for fire severity), a total of twenty-eight (28) Mann-Kendall trend tests were performed (one for each ecoregion and all of California, for both total area burned and total wildfire frequency), and where results exhibited a statistically significant monotonic trend, the Theil-Sen slope estimator was calculated to understand the magnitude of the trend (ITRC, 2013; Addinsoft, 2021). The Theil-Sen slope estimator models how the median concentration varies over time and

Level III Ecoregion	Kendall's τ	p-value	Sen's Slope (acres burned/year)
1 Coast Range	0.034	0.807	--
4 Cascades	0.057	0.653	--
5 Sierra Nevada	0.425	<0.0001	1291.6 (522.7 ha/yr)
6 Central California Foothills and Coastal Mountains	0.142	0.081	--
7 Central California Valley	0.016	0.902	--
8 Southern California Mountains	0.049	0.551	--
9 Eastern Cascades Slopes and Foothills	0.087	0.384	--
13 Central Basin and Range	0.347	0.016	175.9 (71.2 ha/yr)
14 Mojave Basin and Range	0.109	0.390	--
78 Klamath Mountains/California High North Coast Range	0.322	0.001	571.9 (231.5 ha/yr)
80 Northern Basin and Range*	0.590*	0.006*	--
81 Sonoran Basin and Range	0.117	0.463	--
85 Southern California/Northern Baja Coast	-0.022	0.789	--
All Ecoregions	0.287	0.00041	5067.9 (2050.9 ha/yr)

Table 1. Large Wildfire Severity as Total Burned Area Mann-Kendall Trend Test Results with Theil-Sen Slope Estimator for Significant Results. Shaded cells indicate statistically significant results utilizing $\alpha = 0.05$ as the significance level. *Although ecoregion 80 Northern Basin and Range produced a statistically significant result, upon further evaluation, numerous years did not have reported fires which inhibits the effectiveness and accuracy of Mann-Kendall testing for this ecoregion; as such, these results are not considered indicative of a significant monotonic trend.

therefore gives a sense of the magnitude of the monotonic trend (ITRC 2013).

4. Results and Discussion

Mann-Kendall tests reveal statistically significant monotonic trends for only a subset of Level III ecoregions in California. As reported in Table 1, three ecoregions – the Sierra Nevada, Central Basin and Range, and the Klamath Mountains/California High North Coast Range – as well as all ecoregions combined (e.g., the state of California) exhibit statistically significant increasing trends in fire severity as total area burned by large

Level III Ecoregion	Kendall's τ	p-value	Sen's Slope (wildfires/year)
1 Coast Range	-0.376	0.009	-0.029
4 Cascades	0.112	0.428	--
5 Sierra Nevada	0.368	<0.0001	0.100
6 Central California Foothills and Coastal Mountains	-0.070	0.403	--
7 Central California Valley	0.080	0.555	--
8 Southern California Mountains	-0.004	0.971	--
9 Eastern Cascades Slopes and Foothills	0.142	0.201	--
13 Central Basin and Range	0.253	0.127	--
14 Mojave Basin and Range*	0.343*	0.017*	--
78 Klamath Mountains/California High North Coast Range	0.298	0.003	0.050
80 Northern Basin and Range	0.260	0.326	--
81 Sonoran Basin and Range	-0.116	0.527	--
85 Southern California/Northern Baja Coast	-0.162	0.053	--
All Ecoregions	0.120	0.143	--

Table 2. Large Wildfire Occurrence Mann-Kendall Trend Test Results with Theil-Sen Slope Estimator for Significant Results. Shaded cells indicate statistically significant results utilizing $\alpha = 0.05$ as the significance level. *Although ecoregion 14 Mojave Basin and Range produced a statistically significant result, upon further evaluation, numerous years reported the same fire frequency (1 fire/year) which inhibits the effectiveness and accuracy of Mann-Kendall testing for this ecoregion; as such, these results are not considered indicative of a significant monotonic trend.

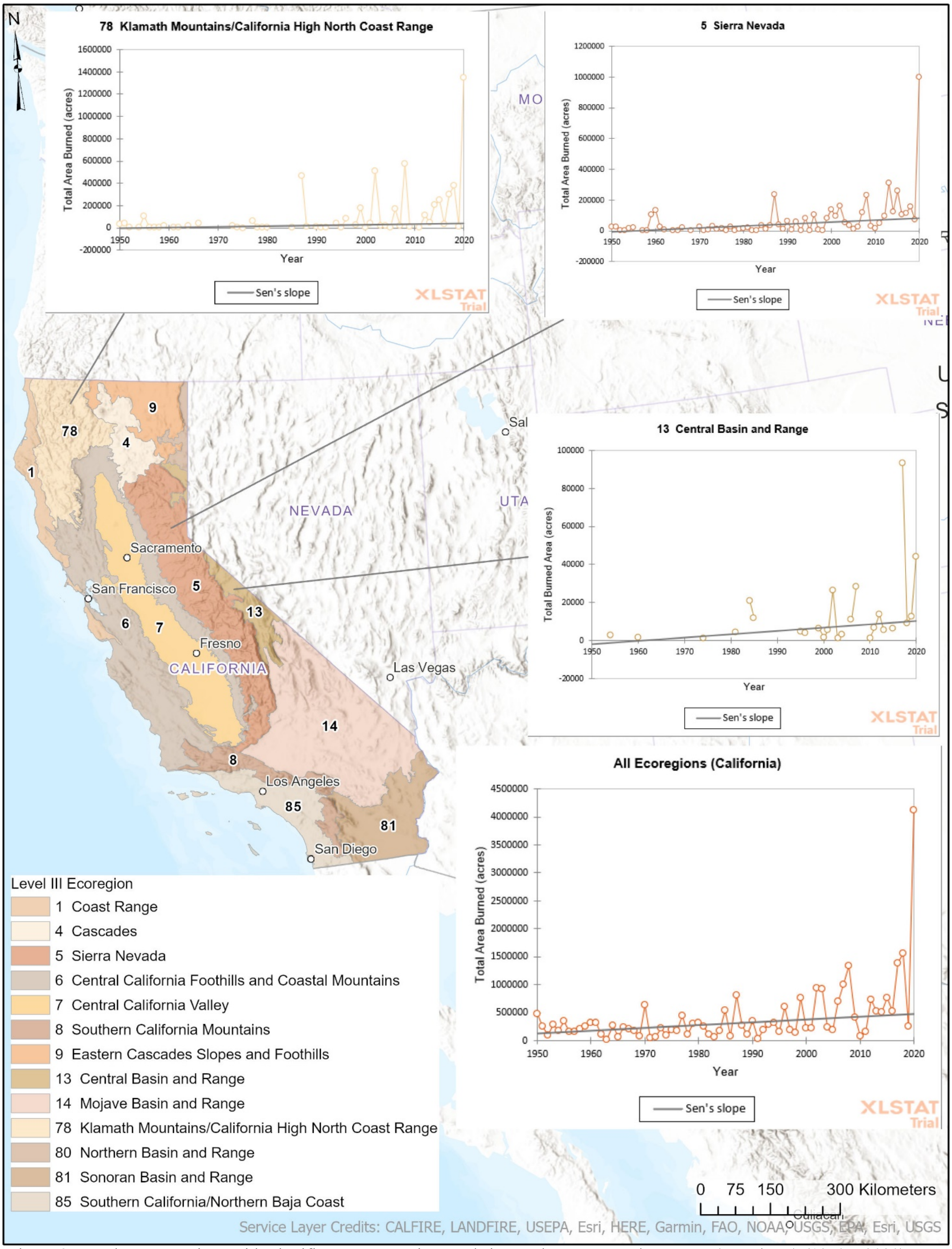

Figure 2. Level III Ecoregions with Significant Monotonic Trends in Total Area Burned per Year (acres/year) (1950 – 2020). Trend testing was performed using the Mann-Kendall test statistic and the slope was calculated for significant results with the Theil-Sen estimator using XLSTAT.

wildfires per year over the study period 1950 – 2020 (Figure 2). Conversely, as reported in Table 2, three ecoregions – also the Sierra Nevada and the Klamath Mountains/California High North Coast Range as well as

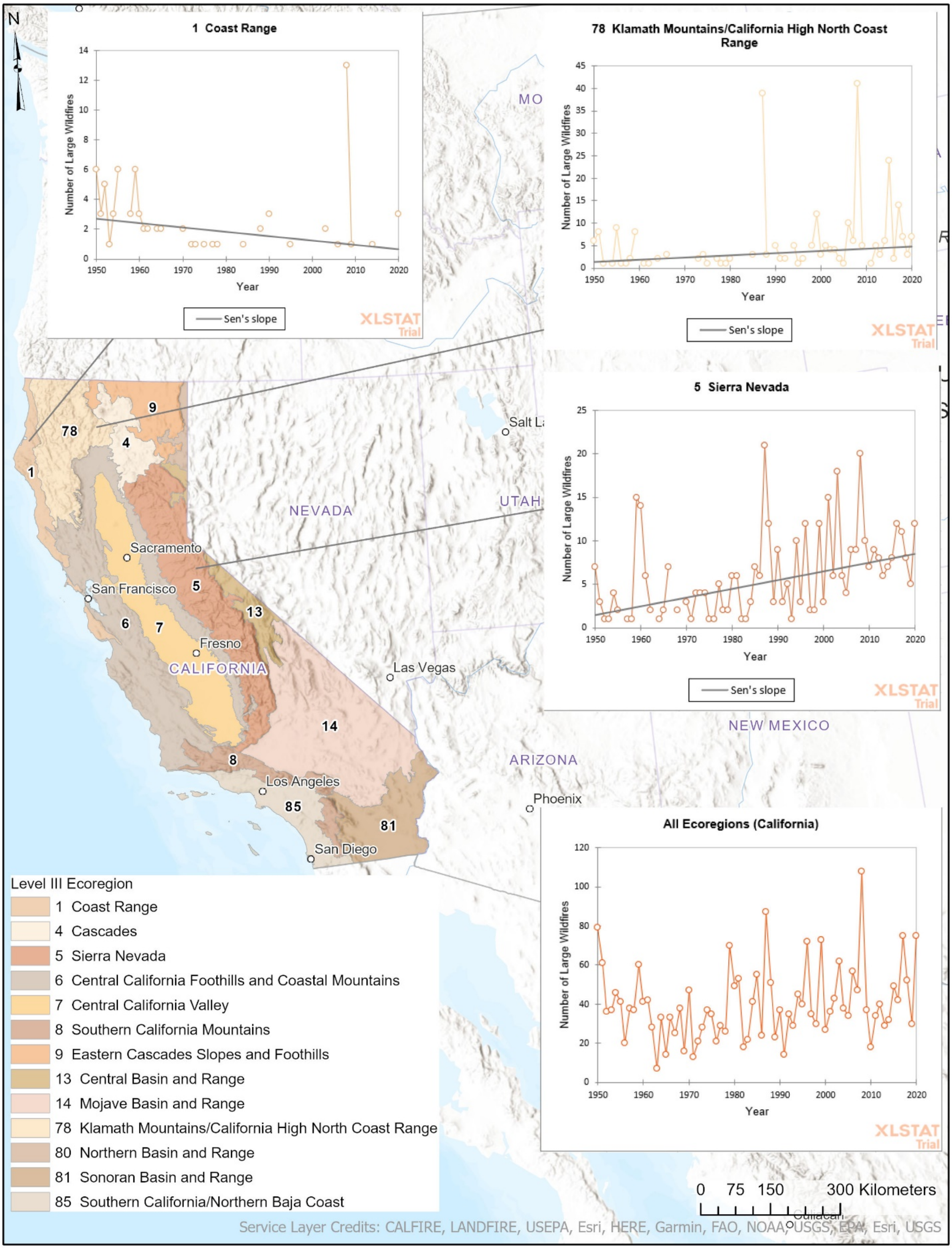

Figure 3. Level III Ecoregions with Significant Monotonic Trends in Large Wildfire Occurrence per Year (1950 – 2020). Trend testing was performed using the Mann-Kendall test statistic and the slope was calculated for significant results with the Theil-Sen estimator using XLSTAT. All ecoregions combined did not reveal a significant trend thus no slope is shown.

the Coast Range – exhibited statistically significant trends in large wildfire occurrence as frequency per year; however, while the Sierra Nevada and the Klamath Mountains/California High North Coast Range show increasing trends in large wildfire occurrence over the study period, the Coast Range shows a decreasing trend

(Figure 3). Notably, the state of California considered as a whole does not show statistically significant trends in large wildfire occurrence over the study period.

These results reveal that trends in large wildfire occurrence and severity in California are not as clear-cut as initially hypothesized. While large wildfires have become more severe, burning an average of 5,068 additional acres (2,051 ha) of land each year (Table 1), there is no statistically significant trend in large wildfire occurrence in California, meaning that although large wildfires are becoming more severe, they are not necessarily occurring more (or less) frequently over the study period; these results align with findings in similar previous studies (Keeley 2021; Li and Banerjee 2021; Marlon et al 2012). In line with this trend, one Level III ecoregion – the Central Basin and Range –shows a significant increase in fire severity, with an average increase of approximately 176 additional acres (71.22 ha) burned per year, but does not exhibit a significant trend in wildfire occurrence over the study period (Table 1). Conversely, one Level III ecoregion – the Coast Range – does not exhibit a significant trend in large wildfire severity, but does show a significant decrease in large wildfire occurrence over the study period, with an average of approximately 0.029 less large wildfires per year (Table 2). Interestingly, only two-Level III ecoregions – the Sierra Nevada and Klamath Mountains/California High North Coast Range – show statistically significant increasing trends in both large wildfire severity and occurrence over the study period, which suggests that characteristics of these ecoregions make these areas more prone to large wildfires than other parts of California.

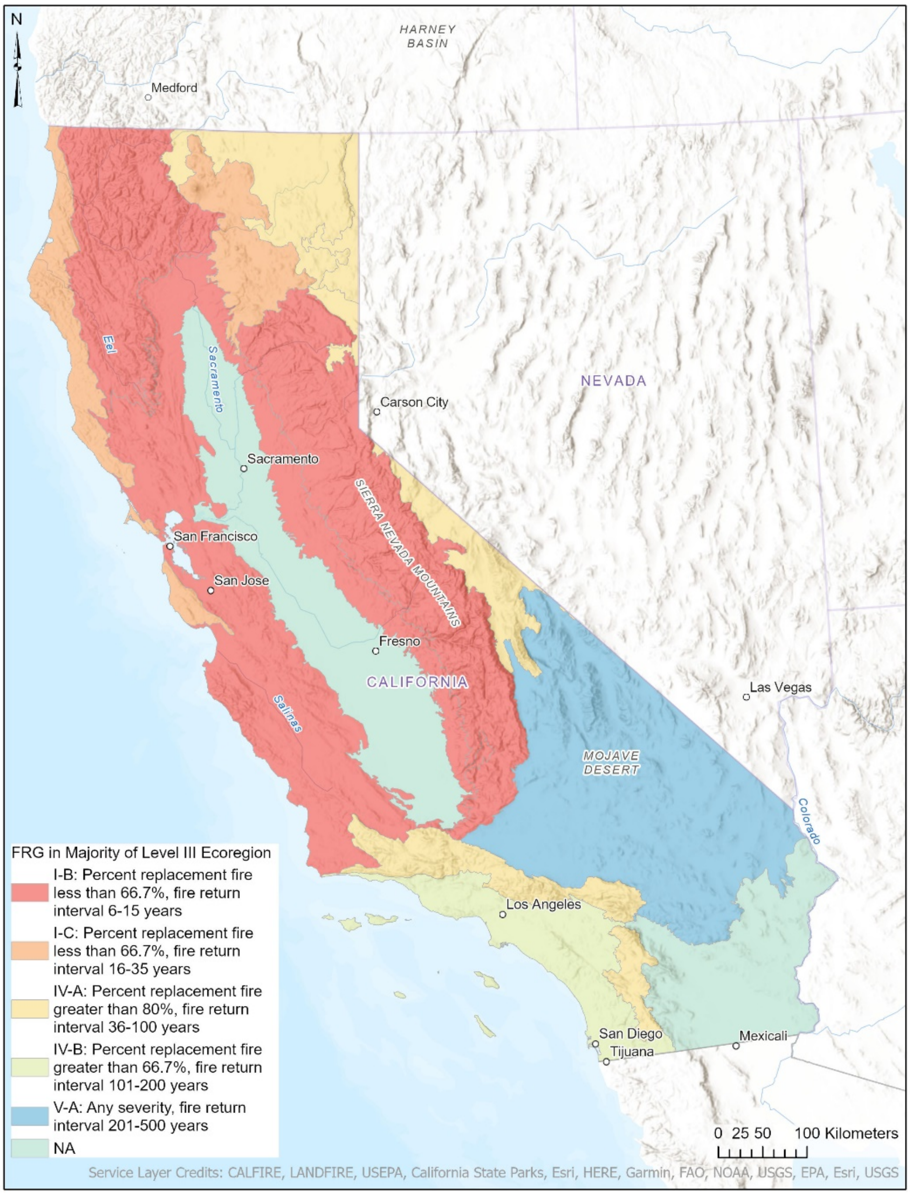

Figure 4. Fire Regime Group (FRG) in Majority of Level III Ecoregion Area.

In order to understand possible explanations for these results, the burn-on-burn effect (Patel, 2018; Weber et al., 2020) and FRGs were assessed. Based on the fire perimeter dataset (CALFIRE, 2021), approximately 20.67% of the total area of California has been burned by large wildfires during the study period; of this, approximately 8.01% of the total area of California has been burned repeatedly by large wildfires[3]. FRGs serve to capture historical fire characteristics for a given region including the burn-on-burn effect. Per Table 3 and Figure 4, zonal statistics reveal that the majority of California, including the Sierra Nevada and Klamath Mountains/California High North Coast Range, is assigned an FRG of "I-B: percent replacement fire less than 66.7%, fire return interval 6-15 years"; regions in this FRG are generally characterized by "… low-severity fires replacing less than 25% of the dominant overstory vegetation," but "can include mixed-severity fires that replace up to 75% of the overstory" (NIFTT 2010, p. 15). This indicates that the majority of California is historically

[3] This was calculated by comparing the total area of California (CALFIRE 2019), the total area of all fire perimeters with overlapping boundaries, and the total area of all fire perimeters with dissolved boundaries to remove overlap; overlapping fire perimeters are indicative of areas that have been burned repeatedly during the study period.

Level III Ecoregion	FRG Classification for Majority of Level III Ecoregion Area
1 Coast Range	I-C: Percent replacement fire less than 66.7%, fire return interval 16-35 years
4 Cascades	I-C: Percent replacement fire less than 66.7%, fire return interval 16-35 years
5 Sierra Nevada	I-B: Percent replacement fire less than 66.7%, fire return interval 6-15 years
6 Central California Foothills and Coastal Mountains	I-B: Percent replacement fire less than 66.7%, fire return interval 6-15 years
7 Central California Valley	NA (no historic significant fire characteristics in this region)
8 Southern California Mountains	IV-A: Percent replacement fire greater than 80%, fire return interval 36-100 years
9 Eastern Cascades Slopes and Foothills	IV-A: Percent replacement fire greater than 80%, fire return interval 36-100 years
13 Central Basin and Range	IV-A: Percent replacement fire greater than 80%, fire return interval 36-100 years
14 Mojave Basin and Range	V-A: Any severity, fire return interval 201-500 years
78 Klamath Mountains/California High North Coast Range	I-B: Percent replacement fire less than 66.7%, fire return interval 6-15 years
80 Northern Basin and Range	IV-A: Percent replacement fire greater than 80%, fire return interval 36-100 years
81 Sonoran Basin and Range	NA (no historic significant fire characteristics in this region)
85 Southern California/Northern Baja Coast	IV-B: Percent replacement fire greater than 66.7%, fire return interval 101-200 years
All Ecoregions	I-B: Percent replacement fire less than 66.7%, fire return interval 6-15 years

Table 3. Fire Regime Group (FRG) Classification for the Majority of the Area in each Level III Ecoregion. FRGs in each ecoregion were summarized using zonal statistics in ArcGIS Pro.

plagued by wildfires occurring with regular frequency and supports the observation that much of the state experiences the burn-on-burn effect (as evidenced by regional fire return intervals). It appears that fire return intervals reported in the FRG classifications for each Level III ecoregion explain a portion of the trends revealed by Mann-Kendall testing as the ecoregions exhibiting statistically significant increasing trends in large wildfire occurrence are assigned the shortest FRG fire return interval, suggesting that these regions – the Sierra Nevada and Klamath Mountains/California High North Coast Range, both of which are mountainous, coniferous regions (Griffith et al., 2016) – historically are more prone to wildfires and the burn-on-burn effect than other regions in California.

5. Conclusions

When focusing solely on large wildfires (> 1,000 ac / 405 ha) and their frequency and severity by ecoregion characteristics instead of arbitrary administrative boundaries defined by various agencies, and given the observed spatial autocorrelation in large wildfire variables and the results above, it is evident that not all regions of California are subject to the same wildfire risks as different parts of the state have different characteristics. Large wildfires are becoming more severe and burning more area each year in California as a whole, however large wildfires are not occurring more frequently across the entire state as originally hypothesized. Certain regions of California, particularly the Sierra Nevada and Klamath Mountains/California High North Coast Range, do show significant increasing trends in both large wildfire severity and occurrence compared to other ecoregions of the state. The increasing occurrence and severity of large wildfires in these regions likely contributes to the overall sentiment that wildfires are becoming worse in the state as a whole, when in reality only certain regions of the state are experiencing statistically significant worsening conditions.

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