MAPPING FIRE SEVERITY FROM RECENT CALIFORNIA WILDFIRES USING SATELLITE IMAGERY

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ABSTRACT

Urban sprawl has become a huge concern for cities like Los Angeles, New York, and Chicago in recent years. As urban sprawl pushes urbanization into city suburbs and outskirts, forest fragmentation becomes evidently prevalent and exposes forests to high temperatures, pollution, pests, and fires that threaten forest health. A 2021 report titled Rebuilding for a Resilient Recovery affirmed that the frequency and damage potential of wildfires have been exacerbated by climate change and urban sprawl especially in California. Globally, these fires can be attributed to both natural and anthropogenic drivers such as deforestation, agriculture, mining, and industrialization. Future projections predict that these incidences of fires will only worsen as the planet continues to warm further, with emphasis on the spread and intensities of the annual California wildfires over the decade. Quantifying the consequences of these fires on global climate change has become crucial and with the emergence of advanced GIS mapping tools, focus, visualization, and interpretation of fire and burn severity has become easier. However, knowledge and understanding of wildfire dynamics is limited especially in terms of fuel load, impacts on vegetation health, aerosol release and associated movement in the atmosphere. It is therefore important to address these gaps to make better and informed actions towards forest use, protection, management, and policies and broadly towards ambitious climate goals such as the UN's Carbon Neutral goal by 2050. This study uses Sentinel 2A data from the Copernicus fleet between 2018 and 2022 to identify and assess the burn severity of affected areas in Sonoma County, California. The aim of the study is to understand the impacts of fires of fire on vegetation health and the post-fire recovery process. The Normalized Burn Ration Index (NBRI) was used to identify and measure the extent of the burnt areas within the county and their severity and Normalized Difference Vegetation Index (NDVI) was used as a measure of forest heath. The results show that Sonoma County has become a high burn severity area with a major decrease in unburned areas between 2018 and 2022. NDVI values recorded all decrease from January to December for all the years because of pre-fire season drought. The wildfire season begins in May and before then there are seasonal droughts that occur hence accounting for the initial decline in NDVI. The least values recorded were between 0.5 and 0.57 for September, indicating sparse and unhealthy vegetation because of sharp declines during the fire season.

INTRODUCTION

1.1 Climate change and Climate impacts on fire hazards

Fire is the rapid oxidation of a material in the exothermic chemical process of combustion, releasing heat, light and various reaction products. Wildfires, however, have become constant occurrences due to increasing warming of the planet. Archibald et al. 2013 describes the current state of the Earth as a flammable planet supporting wildfires anywhere there is sufficient biomass. Several drivers like fuel type, climate, lightning, and topography affect the incidence and spread of fires (Rodriguez-Trejo, 2008). In North America, several studies have reported increases in fire frequency, intensity and burnt area (Flannagan et al., 2009) which have resulted in alterations to known fire regimes. Disruptions to fire regimes has detrimental effects on the resiliency of ecosystems to climate change.

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LITERATURE REVIEW

Understanding, mapping fire severity and Post-fire Impacts on Ecosystems

Mapping fire severity involves assessing the degree of impact that a fire has on an ecosystem, which can range from low to high severity. Fire severity is influenced by several factors, including the intensity of the fire, the type and amount of fuel available, and the topography and weather conditions of the area.

There are several methods for mapping fire severity, including remote sensing techniques and field assessments. Remote sensing techniques involve using satellite imagery, aerial photography, or other forms of remote sensing data to detect changes in vegetation or other indicators of fire severity. These techniques can be useful for mapping large areas and identifying patterns of fire severity.

Field assessments involve physically visiting burned areas and conducting surveys to evaluate the extent of the damage. Field assessments can provide more detailed information on the ecological impacts of the fire but are more time-consuming and labor-intensive than remote sensing techniques.

In addition to mapping fire severity, it is also important to consider the spatial and temporal scales of the analysis. For example, fire severity can vary within a single burned area, so mapping at a fine scale may be necessary to fully capture the impacts of the fire. Similarly, fire severity can change over time as ecosystems recover, so repeat mapping may be necessary to track the long-term effects of the fire. Mapping fire severity is an important tool for understanding the impacts of wildfires and informing management decisions. It requires a combination of remote sensing and field assessment techniques, as well as careful consideration of the spatial and temporal scales of analysis.

Remote Sensing Techniques: There are several remote sensing techniques used to map fire severity, including multispectral and hyperspectral imagery, LiDAR (light detection and ranging) data, and thermal imaging. Multispectral and hyperspectral imagery can detect changes in vegetation reflectance and identify areas where vegetation has been burned or removed by the fire. LiDAR data can provide information on changes in topography and vegetation structure, while thermal imaging can detect the heat signature of the fire and map areas of high intensity.

1. Field Assessments: Field assessments involve physically visiting burned areas and collecting data on the extent of the damage. This can include measuring the height and density of vegetation, identifying the types of vegetation that were burned, and assessing changes in soil properties. Field assessments can provide more detailed information on fire severity than remote sensing techniques but are more time-consuming and labor-intensive.

2. Fire Severity Metrics: Fire severity can be measured using a variety of metrics, including the percentage of vegetation that was killed, the depth of soil burn, and the extent of crown scorch (damage to the tops of trees). These metrics can be used to classify the severity of the fire into different levels, such as low, moderate, or high severity.

3. Management Implications: Mapping fire severity can have important implications for fire management and restoration activities. For example, areas that were burned at high severity may require more intensive restoration efforts to recover, such as reseeding or planting vegetation. In contrast, areas that were burned at low severity may require less intervention and may recover naturally over time. Mapping fire severity can also help fire managers identify areas that are at high risk of future fires and prioritize fuel reduction treatments in those areas.

Mapping fire severity is an important tool for understanding the ecological impacts of wildfires and informing management decisions. It involves a combination of remote sensing and field assessment techniques and requires careful consideration of fire severity metrics and management implications. The importance of fire severity mapping is included.

1. Understanding fire behavior: Mapping fire severity can help us understand how a fire behaved, including its intensity, rate of spread, and the types of fuels that were burned. This information can help us better predict and manage future fires.

2. Assessing ecological impacts: Mapping fire severity can help us understand how a fire affected ecosystem, including changes in vegetation, soil, and wildlife habitat. This information can help us make more informed decisions about restoration and management activities.

3. Identifying areas at risk: Mapping fire severity can help us identify areas that are at higher risk of future fires and prioritize mitigation efforts and resources accordingly.

4. Evaluating fire management strategies: Mapping fire severity can help us evaluate the effectiveness of different fire management strategies, including prescribed burns, fuel treatments, and fire suppression efforts.

Fire severity maps provide valuable information for fire managers, scientists, and land managers, helping us better understand and manage the complex ecological and social systems affected by wildfires.

PROBLEM STATEMENT

As urban sprawl pushes development into rural areas, fragmentation of forest estates is inevitable. Eventually all forests will become urban forests but in the face of a continuously warming planet, high temperatures and fuel availability will not only promote wildfires but enhance the frequency and intensity. It is therefore crucial to understand, map and update fire regimes, their dynamics and how they can be used in future management, policies and approaches to climate mitigation and adaptation.

OBJECTIVES

The objectives of the study were to:

1. Use satellite imagery to identify and map key regions in California affected by the recent wildfires.

2. Assess the extent of burn severity in Sonoma County using Normalized Burn Ratio Index between 2018 and 2022

3. Understand the impacts of wildfires on vegetation health and post-fire recovery process.

METHODOLOGY

Study Area

California is one of the southwestern states of the United States of America. It is bordered by Oregon to the North, Nevada, and Arizona to the east and to the South by Mexico (State of Baja California). Although it is the third largest state after Alaska and Texas, covering an estimated area of 163,696 square miles, most of California's terrain is mountainous, forming most of the Sierra Nevada Mountain Range. Mount Whitney is the highest point in California at 14,494 feet above sea level. The lowest point, however, is

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Badwater Basin at 282 feet below sea level. The Basin, part of Death Valley, is remarkably the lowest point in North America as well. The state of California can be divided into nine geographical regions: Greater Los Angeles, which includes the greater Los Angeles metropolitan area and other nearby cities such as Santa Barbara and Ventura. The Central Valley, which is known for its extensive agricultural production. Northern California, which includes the San Francisco Bay Area, Sacramento Valley, and Sierra Nevada Mountain range. The Inland Empire, which is located east of Los Angeles and includes Riverside and San Bernardino counties. The High Desert, which is home to desert landscapes such as Death Valley National Park. The Pacific Coast Region, which encompasses the coastline from Mendocino County to San Diego County (World Atlas, 2023).

San Diego County/Imperial County in Southern California's border region with Mexico. Shasta Cascade Region, located in northern California near the Oregon state line, has several national parks, such as Lassen Volcanic and Shasta Lake National Parks. Gold Country, located north of Sacramento in the Sierra Nevada foothills; it is known for its gold mining heritage and outdoor activities (World Atlas, 2023). The climate in California ranges from the Mediterranean along its coasts to alpine in its mountains and deserts in its eastern regions. Its weather patterns are mainly driven by two large ocean currents: El Niño/Southern Oscillation (ENSO) and Pacific Decadal Oscillation (PDO). The ENSO affects temperatures along California's coast, while PDO tends to influence precipitation amounts throughout much of Northern California and higher elevation areas. California also has a diverse biodiversity with many different species found across its regions, such as wolves and grizzly bears in its forests; bobcats, coyotes, and foxes living near river systems; bald eagles along waterways; salmon inhabiting both fresh-water streams and Pacific coastal waters; and desert tortoises living amongst scrublands in southern parts of the state. Sonoma County, located in northern California, has a Mediterranean climate with warm, dry summers and cool, wet winters. The county's proximity to the Pacific Ocean and the coastal ranges to the west contribute to its unique climate (World Atlas, 2023)

In the summer months, temperatures in Sonoma County typically range from the mid-70s to low 80s Fahrenheit (24-27 degrees Celsius) during the day, with cooler temperatures in the evening. The county experiences low humidity during this time and is prone to wildfires due to the dry conditions (World Atlas, 2023).

During the winter months, temperatures in Sonoma County range from the mid-50s to low 60s Fahrenheit (12-16 degrees Celsius) during the day and can drop to the mid-30s to low 40s Fahrenheit (1-5 degrees Celsius) at night. The county experiences significant rainfall during this time, with the wettest months being December through February (World Atlas, 2023).

Overall, the climate of Sonoma County is conducive to wine grape cultivation, and the region is known for its world-renowned vineyards and wineries. However, the county's climate is also susceptible to droughts and wildfires, which can have significant impacts on the local ecosystem, agriculture, and communities (World Atlas, 2023)

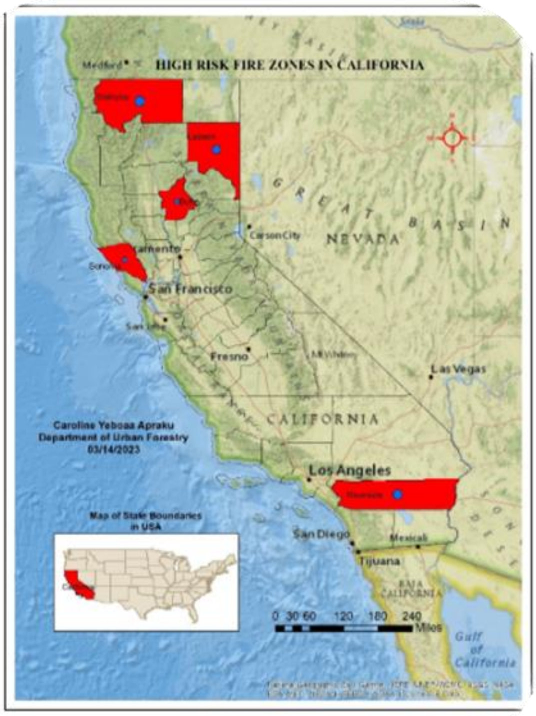

Fig.1 A map of California indicating the study area as well as other high risk fire zones. Louisiana: Caroline Yeboaa Apraku Collection, Southern University and A&M College, 2023. Using ArcMap 10.8 (GIS Software). Version 2.0. Baton Rouge, LA: Department of Urban Forestry and Natural Resources, 2023

Counties	Name of Fire	Acres Burnt in 2022
El Dorado, Placer	Mosquito Fire	76,788
Siskiyou	McKinney Fire	60,138
Siskiyou	Mountain Fire	13,440
Riverside	Lost Lake Fire	5,856
Modoc	Barnes Fire	5,843
Los Angeles	Route Fire	5,208
Mariposa	Washburn Fire	4,886
Amador, Calaveras	Electra Fire	4,478
San Diego	Border 32 Fire	4,456
Inyo	Airport Fire	4,136
Siskiyou	Mill Fire	3,935
Kern	Thunder Fire	2,500
San Bernardino	Radford Fire	1,079

Fig. 2 Table showing the counties that were most affected by recent California wildfires (Source: California Department of Forestry and Fire Protection-CAL FIRE)

Data Collection and Processing

Data was obtained using Sentinel-2 sensors from the Copernicus open access fleet. Fire severity data were derived using the established NDVI differencing method:

$$\text{NDVI} = \frac{NIR - VR}{NIR + VR}$$

where NIR is the near infrared band and VR is the visible red band, and $NDVI_{Difference} = NDVI_{pre-fire} - NDVI_{post-fire}$ (Chafer et al. 2004).

Atmospheric correction of the imagery was done.

RESULTS

The results indicate that Sonoma County is increasingly becoming prone to wildfires. For decades, anthropogenic factors have increased temperatures globally, especially in industrious cities like California. Warmer temperatures have been linked to increased incidences of wildfires. Hence the maps derived for the years 2018, 2020 and 2022 show a decline in unburnt areas respectively and progressively. There is Enhanced regrowth" refers to the process of increased plant growth after a wildfire, resulting from the release of nutrients and decreased competition. This is a natural occurrence following many wildfires, leading to the establishment of a diverse plant community.

Regarding fire severity, enhanced regrowth typically takes place after low to moderate severity fires that remove smaller vegetation but leave larger trees relatively unscathed. These fires create conditions for new vegetation to grow, helping restore ecosystem function and wildlife habitat.

However, after high severity fires that burn through the canopy and kill many larger trees, enhanced regrowth may not occur as conditions for new growth become much more challenging. In such cases, ecosystem recovery may be slower and require active management interventions, such as reforestation or habitat restoration efforts.

The severity of a wildfire can impact various parts of vegetation in different ways. High-severity fires, which burn more intensely and for longer periods, can significantly affect the uppermost layers of vegetation, such as the leaves and branches of trees, resulting in a considerable loss of biomass and a reduction in NDVI. High-severity fires can also damage the roots and soil, which can hinder vegetation regeneration.

Low-severity fires typically burn through the understory of the forest and may only affect the lower branches of trees, leading to a less severe impact on vegetation and a smaller reduction in NDVI.

It's important to note that the impact of fire severity on vegetation can vary based on the type of vegetation. Some species of plants may have adaptations that help them survive and even thrive after a fire and moderate-severity fires can even stimulate new growth and regeneration in certain types of vegetation.

In summary, the severity of a wildfire can impact different parts of vegetation in varied ways, and understanding these impacts is crucial for managing and protecting ecosystems and biodiversity.

The understanding that fuel dynamics coupled with exacerbating climate issues will only accelerate this process makes it topmost priority for wildfire studies and response. Several states including California have annual wildfire map updates to predict trends and understand wildfire regimes. With innovative approaches in GIS and mapping, results can be obtained readily and comparatively faster. It has become easier to be able to study wildfires.

The emergence of policies to support climate change has also boosted local response to wildfires and the protection of resources that are most affected. These include tree and forest policies and prescribed burning as a means of fuel control. This has been successful in minimizing fire impacts on economic species such as fir and birch trees. Although these feedbacks ae positive, there is still a lot to be done with management policies, silviculture and restoration of burnt forests.

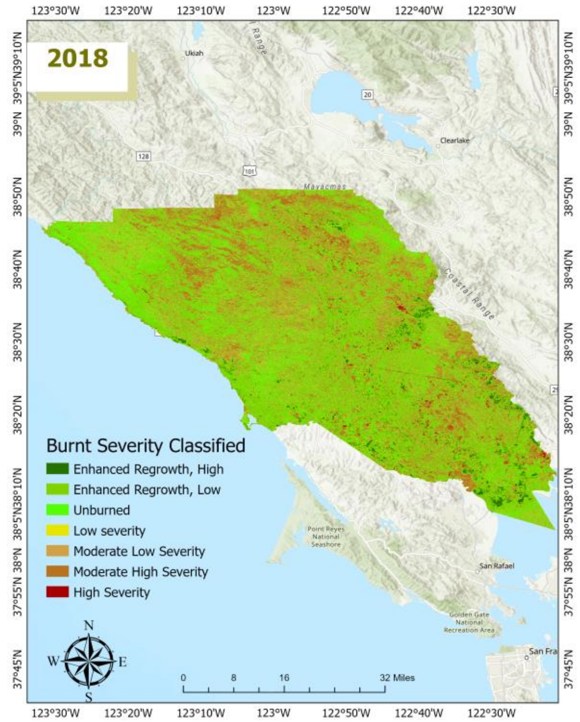

Fig.3 A 2018 map showing burnt severity classes for Sonoma County in California

In 2018, there are a lot of enhanced areas and less high severity. About 90% of the county is unburned. Low severity areas are few, emphasizing that there were least impacts of wildfire. There are still vast amounts of healthy vegetation. There are no areas showing low severity risks hence making that minimal. This may infer the natural recovery process from the previous year's wildfire. The vegetation restoration efforts of the state may also be a major contributing factor to the current vegetation condition. Hence, it can be inferred that the forest management plan is efficient in its restoration effects.

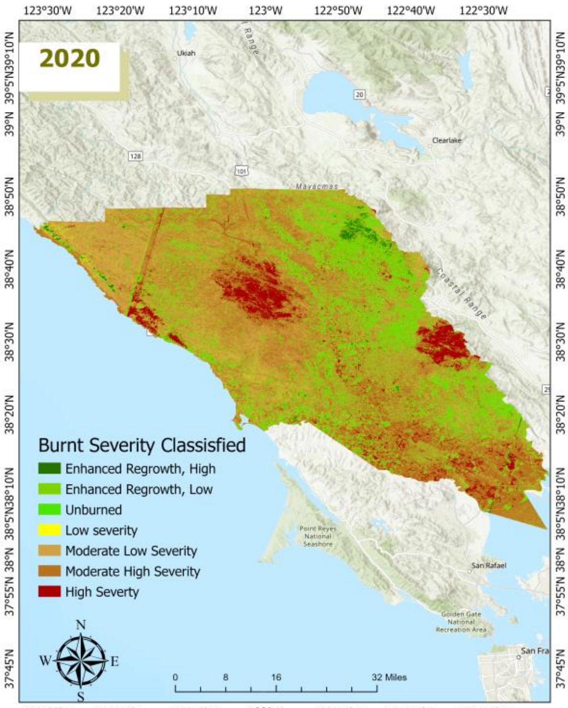

Fig.4 A 2020 map showing burnt severity classes for Sonoma County in California

In 2020, there is a seclusion of enhanced regrowth patches in the north-east part of the county, there is a clear increment in areas that have low severity and moderate high severity. About 50% of the county is now classified as high severity risk zones. Low severity is minimal.

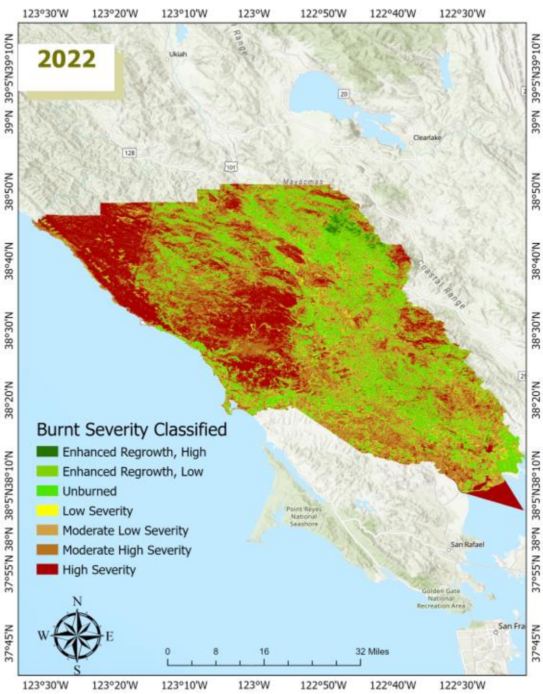

Fig.5 A 2022 map showing the most recent burnt severity classification for Sonoma County in California.

In 2022, about 70% of the area is classified as high severity zones, there are a lot of low severity areas compared to 2018 and 2020. There is a decline in enhanced regrowth areas compared to 2020. There is an increase in unburned areas, and these can be attributed to several activities including detection and early response.

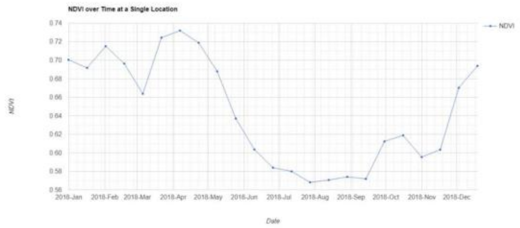

Fig. 6 A 2018 graph measuring NDVI each month from January to December at a single location.

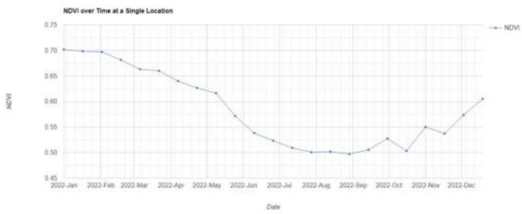

Fig.7 A 2020 graph measuring NDVI each month from January to December at a single location.

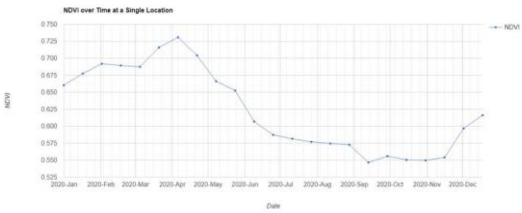

Fig.8 A 2022 graph measuring NDVI each month from January to December at a single location.

NDVI values recorded all decrease from January to December for all the years. This observation can be attributed to drought before the fire season. The wildfire season begins in May and before then there are seasonal droughts that occur hence accounting for the initial decline in NDVI. During the fire season, there is a sharp decline in NDVI because of huge vegetation loss over a short period.

Vegetation Index and NDVI

A vegetation index is a measure of the amount and health of vegetation in a specific region, typically determined through satellite imagery. The index calculates the reflectance of light in specific wavelengths from the Earth's surface, with the Normalized Difference Vegetation Index (NDVI) being the most used index.

The NDVI assesses the difference in the reflectance of near-infrared (NIR) and red light, as healthy vegetation reflects more NIR light and absorbs more red light. By comparing the reflectance of these two wavelengths, the NDVI can estimate the extent and well-being of vegetation in an area.

The NDVI is widely applied in various fields, such as crop monitoring, vegetation mapping, and climate change research. Through monitoring changes in vegetation over time, researchers can identify areas prone to environmental stressors, track shifts in ecosystems, and monitor the impact of climate change on plant communities.

Other vegetation indices include the Enhanced Vegetation Index (EVI), which accounts for atmospheric conditions' effects on vegetation reflectance, and the Leaf Area Index (LAI), which assesses the quantity of leaf material in a canopy.

3. DISCUSSION

Like other studies, there is a direct link between warmer temperatures and corresponding frequency of wildfires. Recent studies in sandstone landscapes in Australia have revealed complex patterns resulting from large fires. These may be attributed directly to landscape ecology. There have been significant changes in vegetation cover in California that have led to a decrease in NDVI (Normalized Difference Vegetation Index) in certain areas. NDVI is an indicator of vegetation health and density based on the amount of photosynthetically active radiation absorbed by vegetation, and changes in NDVI can provide insights into changes in vegetation cover.

One significant factor contributing to the decrease in NDVI in California is the prolonged drought that the state has experienced over the past several years. Drought has led to reduced water availability, which in turn has led to a decline in the density and health of vegetation in some areas. This is particularly evident in forests, which have experienced increased mortality due to water stress and bark beetle infestations.

Other factors that have contributed to the decrease in NDVI in California include increased wildfires and changes in land use, such as increased urbanization and agricultural expansion. Wildfires have burned large areas of vegetation, leading to a loss of plant biomass and reduced NDVI in affected areas. Land use changes can also impact vegetation cover and NDVI, as areas that were once natural ecosystems may be converted to urban or agricultural land uses. The decrease in NDVI in California is a complex issue that is influenced by multiple factors, including climate, land use, and disturbances such as wildfires. Understanding the underlying causes of these changes is important for managing and protecting California's ecosystems and biodiversity. Wildfires can cause significant changes in NDVI (Normalized Difference Vegetation Index) in California, which is an indicator of vegetation health and density based on the amount of photosynthetically active radiation absorbed by vegetation. The severity of the impact on NDVI can depend on several factors, such as the intensity of the fire, the type of vegetation, and the time of year when the fire occurred.

In the short term, NDVI may decrease due to the loss of vegetation, but it can increase in the longer term as vegetation begins to regenerate. However, the recovery process can take years and is influenced by factors such as the availability of water, the type of vegetation, and the presence of invasive species.

Research conducted in California has shown that NDVI values in areas affected by wildfires were significantly lower in the first year after the fire but began to recover after the second year. The impact of wildfires on NDVI can be more severe in areas with lower rainfall, as these areas are less able to recover from the loss of vegetation.

Understanding the impact of wildfires on NDVI is crucial for managing and protecting California's ecosystems and biodiversity, as it can help inform strategies to mitigate the impact of fires and promote the recovery of vegetation. Land use changes in California can have a significant impact on NDVI (Normalized Difference Vegetation Index), which is an indicator of vegetation health and density based on the amount of photosynthetically active radiation absorbed by vegetation. The amount and density of vegetation in an area can be influenced by changes in land use, resulting in changes in NDVI.

Urbanization, for instance, can convert natural ecosystems into built environments, which leads to a reduction in vegetation cover and a decrease in NDVI. This can have adverse effects on ecosystem health, biodiversity, and human well-being. Agricultural expansion can also impact NDVI by replacing natural ecosystems with crops that have different water and nutrient requirements than native vegetation, and the use of fertilizers and pesticides can further affect NDVI. However, land use changes can also have positive impacts on NDVI, such as when degraded land is restored to its natural state through conservation or restoration efforts, which can increase NDVI over time.

Therefore, it is important to understand the impact of land use changes on NDVI to manage and protect California's ecosystems and biodiversity. This can help to promote sustainable land use practices that strike a balance between human needs and environmental needs, and support resilient and healthy ecosystems.

CONCLUSION

The exploration of fire impacts on the climate and plant health has seen significant growth although there are still many aspects that remain relatively underexploited. Largely, these improvements have mad climate decisions more refined and problem specific. However, the worst component of wildfire is particulate matter. Particulate matter is a term that describes small liquid and solid droplets which pose health risks when they are inhaled. Mapping fire severity and associated implications for environment, resource management is crucial especially under climate change. Ultimately, severity relationships can be best understood using ecological effects and indices from remote sensing. Individual indices are only effective as inferences if the index is correlated to fire effects on the ground. As the globe continues to warm further with predictions of frequent fires, environmental justice concerns will increase and the need and urgency of urban forests as a first defense against urban heat island and wildfires. New places will have an increased risk of severity exposure and hence making it imperative to understand and update fire risk maps taking into account spatial variability, pre-fire vegetation character, physical terrain changes and previous burn histories.

GAPS FOR FUTURE RESEARCH

A study can be done on the amount of carbon dioxide released during wildfire events.

Another study can track annual aerosol movement from the California wildfires. Fuel dynamics and soil impacts may also be assessed over time.

It is also important to conduct a study that quantifies annual particulate matter and or aerosol release and their short-term impacts on plant health and atmospheric conditions.

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