Post-Fire Vegetation Recovery Monitoring using MODIS Time Series: A Case Study in California

JULIA EDJE
Abstract
Post-Fire Vegetation Recovery Monitoring using MODIS Time
Series: A Case Study in California

Human-caused forest fires have increased in magnitude and frequency, affecting global vegetation and requiring a re-evaluation of fire regimes. Changing fire regimes have led to reduced burned areas in fire-dependent ecosystems and increased areas in fire-independent ecosystems, resulting in changes in land cover and posing a threat to native plant communities. This study focuses on monitoring vegetation recovery after fires in California, USA, using the Enhanced Vegetation Index (EVI) from MODIS time series. The goal is to determine the full recovery time and half recovery time (HRT) after forest fires in year 2017 and analyze the influence of burn severity on three land cover classes in two different climate zones in California.

Analyzes show that the "Closed Forest" land cover type exhibits the longest recovery period, followed by the "Open Forest" type and “Herbaceous/Shrub” type in both climate zones but no general connection between recovery time and climate zone was observed. It is found that burn severity degree affects HRT but not the full recovery time in both Mediterranean and Semi-arid climate zones. The study mainly highlights the variations in forest fire recovery patterns between land cover types, as well as differences observed between climate zones.

Keywords: vegetation recovery, MODIS, HRT, EVI, fire, burn severity, land cover, climate zone, California
Sammanfattning

Skogsbränder orsakade av människan har ökat i omfattning och frekvens, vilket påverkar den globala vegetationen och kräver en omvärdering av brandregimer. Förändrade brandregimer har lett till minskade brända områden i brandberöende ekosystem och ökade områden i brandberoende ekosystem, vilket resulterar i förändringar i marktäcke och utgör ett hot mot inhemska växtsamhällen. Denna studie fokuserar på att övervaka vegetationens återhämtning efter bränder i Kalifornien, USA, med hjälp av Enhanced Vegetation Index (EVI) från MODIS-tidsserier. Målet är att bestämma den fullständiga återhämtningstiden och halv återhämtningstid (HRT) efter skogsbränder 2017 och analysera påverkan av brännskadans svårighetsgrad. Tre marktäckningsklasser i två olika klimatzoner i Kalifornien kommer att undersökas.

Analyserna visar att markäcket ”Closed Forest” uppvisar den längsta återhämtningsperioden, följt av ”Open Forest” och ”Herbaceous/Shrub” i båda klimatzoner, men inget generellt samband mellan återhämtningstiden och klimatzon kunde identifieras. Det visade sig att brännskadans svårighetsgrad påverkar HRT men inte den fullständiga återhämtningstiden i båda klimatzoner. Studien belyser främst variationerna i återhämtningsmönster för skogsbränder mellan marktäckningstyper, samt skillnader som observerats mellan ”Mediterranean” och ”Semi-arid” klimatzon.

Nyckelord: vegetation recovery, MODIS, HRT, EVI, fire, burn severity, land cover, climate zone, California
Tables of Content

1 Introduction 5
  1.1 Background to fire 5
  1.2 Post-fire vegetation recovery 6
  1.3 Research question 8

2 Study Area and Data sources 10
  2.1 Study Area: Mediterranean California 10
  2.2 Data description 11
    2.2.1 Global Land Cover Layers: CGLS-LC100 Collection 3 11
    2.2.2 Köppen Climate Classification System 12
    2.2.3 MODIS Burned Area Product 14
    2.2.4 MODIS Combined 16-day EVI 14
    2.2.5 MODIS Burn date 15
    2.2.6 Burn severity 15

3 Methodology 16
  3.1 Workflow 17
  3.2 Post-fire recovery metrics 20
    3.2.1 Differenced EVI (dEVI) 20
    3.2.2 Half Recovery Time (HRT) 20
  3.3 Sample Grouping and Comparison 21

4 Result 24
  4.1 Post-fire recovery in various climate zones 24
  4.2 Post-fire recovery across land cover 25
  4.3 Post-fire recovery across burn severity 26

5 Discussion 29
  5.1 Impacts of climate zone on post-fire recovery 29
  5.2 Impacts of land cover on post-fire recovery 30
  5.3 Impacts of burn severity on post-fire recovery 32
  5.4 Recovery profiles 33
  5.5 Future studies and implications 35

6 Conclusion 36

7 References 37
1 Introduction

1.1 Background to fire

The escalating environmental issues in the world have become increasingly apparent and constitute one of the most pressing challenges of our time. Prominent among these concerns is global warming, which is a result of greenhouse gas emissions and human activities (Houghton, 2005). The consequences of this warming can be seen in different environments, where heat becomes a critical factor in urban areas. Therefore, it is imperative to understand the mitigation and propagation of these effects in order to protect and preserve our environment to avoid the negative consequences. One of the direct consequences of rising temperatures is the increased occurrence of wildfires (Running, 2006). Elevated temperatures create drier conditions, increasing susceptibility to ignition and rapid fire spread. The increase in wildfires stems from various factors, which include both natural causes and those caused by human activity.

Historically, many natural fires have been ignited by lightning but today, despite significant efforts to contain them, wildfires are primarily caused by human activity (de Groot et al., 2013). Anthropogenic fuel-driven wildfires have escalated in both severity and frequency worldwide each year as a result of the changing fire regimes (Allen et al., 2005; Weber and Stocks, 1998; Jin et al., 2012; Miller et al., 2012). Extensive research shows that humans contribute significantly to the escalation of forest fires through actions such as deforestation, incorrect land use and contribute to increasing carbon dioxide emissions (Balch et al., 2017). Although wildfires are usually perceived as dangerous and catastrophic for both society and nature, some fires of natural origin are fundamental to the dynamics and structure of ecosystems. These fires contribute to increased biodiversity, reduced biomass and fuel loads, nutrient release and effects on plant community composition and health (de Groot et al., 2013). Additionally, previous research has shown that natural wildfires can mitigate the spread of infectious diseases among humans, wildlife, and plants (Scasta, 2015).

Regardless of the cause of a forest fire, the consequences are devastating and large-scale. The negative impact on forest ecosystems extends beyond the nearest forest areas and affects environments outside the forest and plant communities. These effects include ecosystem damage, conversion of forests to non-forest habitats, and the failure of plant communities to regenerate (Bond, 2013; Lucrecia et al., 2014; Meng et al., 2014; Thom and Seidl, 2016). In addition to the environmental consequences, society suffers from destroyed infrastructure and direct air pollution as a result of forest fires. Consequently, the financial burden on society and individuals to restore affected areas is significant (Wang et al., 2021). Going forward, wildfires are likely to exert a greater influence on the global
carbon budget, especially if they occur in areas characterized by slow post-fire recovery (Mouillot and Field, 2005).

The state of California, in the western United States, is one region that has experienced an alarming increase in wildfires (Dennison et al., 2014). In recent decades, the number of fires in California has increased, along with the size of burned areas and burn severity (Keeley and Syphard, 2021; Miller et al., 2012). From 1984 to 2011, the western United States witnessed a progressive escalation of large fires on an annual basis (Dennison et al., 2014). These recent trends, together with further regional warming and expected growth of human activity in fire-prone areas, have led to forecasts indicating that the future is likely to witness not only more frequent fires but also fires of greater severity, frequency and extent, with an extended wildfire season (Syphard et al., 2007; Conrad and Weise, 1998). Fire regimes in California are expected to exhibit spatial heterogeneity, with variation determined by climate zones and ecosystems. Fire characteristics are dependent on factors affecting landscape composition and climate (Keely et al., 2009; Li et al., 2019). In California, southern regions characterized by dryness tend to experience more frequent, smaller and short-lived fires, in contrast to wetter, more forested areas, which are prone to larger and more catastrophic fires (Li and Banerjee, 2021; Keeley and Syphard, 2021).

1.2 Post-fire vegetation recovery
Wildfires have profound effects on vegetation, soil and wildlife, and the intensity and severity of the fire determines the extent of these effects on recovery (Engstrom, 2010). Forest fires can lead to complete or partial destruction of plant communities, leaving behind a charred and barren landscape. In addition to physical damage, vegetation can also experience loss of seeds and reproductive structures, impeding natural regeneration (Barro et al., 1991). The natural regeneration is affected by the changes in the soil caused by increased temperatures. The heat causes the soil to suffer from nutrient loss, erosion and hydrological changes, which also makes recovery difficult (Léon et al., 2012).

Post-fire recovery in plant communities is facilitated by various mechanisms that allow them to adapt and regenerate (Nolan et al., 2021). Some plant species have adaptations such as serotiny, where seeds are stored in fireproof cones, ensuring their survival through the fire and promoting germination afterwards. Other species depend on growing out of underground structures, such as root crowns or rhizomes, which allow rapid regrowth after a fire. Additionally, fire-adapted plants may have specialized seeds that require the heat or smoke of a fire to break dormancy and initiate germination.
These mechanisms allow plant communities to recover and recolonize the burned areas, initiating the process of ecological succession (Pilon et al., 2020).

The timeline for fire recovery varies depending on several factors such as burn severity, climate factors and fire regimes (Allison et al., 2008). Burn severity, characterized by the intensity and extent of the fire's effects, plays a significant role in post-fire recovery. Severe fires can cause extensive damage to vegetation and soil, which can result in a longer full recovery time (Fernandez-Manso et al., 2016). In contrast, lower burn severity has a less severe impact on vegetation and soil, allowing for faster regrowth and recovery (Fernández-García et al., 2018; Keeley et al., 2005). Climatic factors, such as temperature, precipitation and seasonality, play a critical role in vegetation regrowth after fire. The availability of moisture is crucial for seed germination and the establishment of new plants (Appelstein et al. 2021). Adequate rainfall and temperature conditions promote the growth and survival of vegetation after fire, while drought can hinder recovery. The interplay between climate factors and fire regimes determines the trajectory and successional patterns of post-fire recovery (Chen et al., 2022; Nelson et al., 2013). Soil conditions greatly affect post-fire recovery. Fire can alter soil properties, including nutrient content, organic matter content, and physical structure (Fernández-García et al., 2018; Keeley et al., 2005; Zhou et al., 2022). Nutrient loss through burning or leaching can affect the availability of necessary nutrients for plant growth. Changes in soil hydrological properties can affect water infiltration and runoff, affecting moisture availability for plant establishment (Belillas et al. 1998; Jiménez-González et al., 2016)). Understanding the dynamics of nutrient cycling and soil recycling processes is critical to predict and manage post-fire vegetation dynamics.

To measure the full recovery time after a forest fire, there are various tools and methods available. A commonly useful tool is the use of satellite-based remote sensing. By analyzing satellite images before and after the fire, changes in vegetation cover and structure can be mapped. Vegetation coverage indices, such as Enhanced Vegetation Index (EVI) and delta Enhanced Vegetation Index (dEVI), can also be used to quantify vegetation recovery since EVI quantifies vegetation greenness (Wu, 2022). In addition to satellite imagery, ground-based inventories and sample plots can be used to assess full recovery time. By examining the regrowth of plants and their growth, one can get a more detailed picture of how quickly the vegetation recovers after a fire. Soil-based methods can also be used to assess soil recovery and regrowth of different plant species.
Given the expected increase in wildfires due to ongoing climate change, understanding the various recovery processes and impacts on plant ecosystems following wildfires becomes crucial. Accordingly, this research focuses on monitoring vegetation disturbance and recovery in California through satellite imagery following wildfires. The primary objective is to understand the dynamics of different ecosystems and evaluate the effects of wildfires on different land cover classes in the year 2017, within two distinct climate zones and across three different land cover classes. Using the Enhanced Vegetation Index (EVI) time series and its variation, delta Enhanced Vegetation Index (dEVI), this study uses the "half recovery time" (HRT) method to determine the duration required for ecosystems to achieve 50% recovery after a fire event (Pérez-Cabello et al., 2021). This quantitative measure, which includes EVI and dEVI, enables comparison of recovery progress in different areas, thereby providing valuable insights for ecosystem management and restoration strategies.

Furthermore, the research considers burn severity to evaluate the immediate effects of wildfires on ecosystems, as well as the subsequent full recovery time and HRT. By including burn severity as an aspect of this study, it highlights the relationship between burn severity, wildfire intensity, and effects on plant communities. The results of this study improve our understanding of ecosystem dynamics, impacts of disturbances and contribute to effective strategies for environmental conservation and protection, especially in the context of global warming consequences such as wildfires.

1.3 Research questions
The main objective of this study is to investigate vegetation recovery after wildfires in different climate zones, focusing on comparing the recovery patterns of two climate zones, taking into account burn severity, in California in year 2017 with respect to three different land cover classes. Investigating the HRT of post-wildfire vegetation is critical to understanding ecosystem dynamics and developing effective strategies for conservation and management. By analyzing the recovery patterns in distinct climate zones, land cover classes and considering burns, this study aims to gain insights into the recovery behavior of vegetation after fire by analyzing HRT. Such knowledge is critical to inform decision-making processes and implement sustainable practices to protect and conserve ecosystems affected by wildfires. The specific research questions are as follows:

1. What are the variations in half-recovery time (HRT) after wildfires between Mediterranean and Semi-arid climate zones in California regarding the herbaceous/shrub, open forest and closed forest land cover classes?
2. How does vegetation recovery after wildfire differ among herbaceous/shrub, open forest and closed forest land cover classes within the same climate zone, in terms of half recovery time (HRT)?

3. What is the impact of burn severity on vegetation recovery in different climate zones? How does burn severity affect recovery profiles on different land cover types, and what patterns can be observed in half recovery time (HRT)?

This research effort will provide valuable insights into the recovery process of different types of land cover following forest fires, given the local environmental variability. By leveraging Google Earth Engine and available MODIS time series-derived and EVI data, we will gain a comprehensive understanding of spatial patterns of large-scale recovery from wildfire. These findings will contribute to better post-fire management strategies, ecosystem restoration efforts and resilience planning in fire-prone areas.
2 Study Area and Data sources
In this study, the state of California, United States, was chosen to be investigated as the necessary data were available for this area of investigation. The data used was existing in GEE except for the Köppen Climate Classification System which was imported from the internet.

2.1 Study Area: Mediterranean California
Based on Figure 1 panel b), Western California has a Mediterranean climate with coastal areas classified as Csb (Warm summer Mediterranean) and continental areas as Csa (Hot-summer Mediterranean). In the south-eastern direction, this changes to a desert climate and in the eastern part of the state to a high-altitude Mediterranean climate. The dominant land cover classes in California are trees in the northwest, shrub-like land cover types in the southeast, and Grass/Herbaceous in the central parts of the state of California, as visualized in figure 1 panel c). Using the figure shown in panel a), it can be mapped which areas are commonly affected by fires.
Figure 1. Study area Californien. a) MODIS burned area map showing where fires have occurred during the investigated year. b) Köppen climate zones over California. Climate zones include: BSh – Hot semi-arid, BSk – Cold semi-arid, Csa – Hot-summer Mediterranean, BWk – Cold desert, BWh – Hot desert, Dsc – Dry-summer subarctic, Dsb – Warm-summer mediterranean continental, Csb – Warm summer Mediterranean, Csc – Cold-summer Mediterranean, ET – Thunda. Data from Beck et al. (2018). c) Land Cover by the Landscape Change Monitoring System (LCMS).

Figure 2 was created to also visualize in which climate zones most fires had occurred. By viewing Figure 1 and 2, it is visible that in California the most common area for fires is in the southwest region. Together with the figures in each panel, it is possible to clarify which climate zone and land cover type are most often affected by fires.

Figure 2. Visualizing distribution of burned sampled points across climate zones in California. CZ number 8 symbolize the Semi-arid climate zone and CZ number 9 the Mediterranean climate zone.

2.2 Data description

2.2.1 Global Land Cover Layers: CGLS-LC100 Collection 3
As part of the land service, the Copernicus Worldwide Land Service (CGLS) is designated to drive outputs on the condition and development of the land surface on a worldwide scale (Xu et al., 2019). A new product in the CGLS portfolio, Dynamic Land Cover Map with 100m resolution (CGLS-LC100), provides a worldwide land cover map with 100m spatial resolution. This continuous classification system can more accurately represent areas of heterogeneous land cover than the standard classification system, and as a result it can be adapted for different uses, such as different types of monitoring (Tsendbazar et al. 2018). The PROBA-V 100m time series was used to create consistent Land Cover maps (v3.0.1), which are provided for the period 2015-2019 worldwide. The
maps achieve a high accuracy (80%) at level 1 in all years. The CGLS divides the land surface into 19 (+4) land cover classes and 7 mixed classes, representing pixels where at least 10% of the pixel is covered by an additional class (USDA 2022). From these classes and for the purpose of this research, these were divided into three different groups based on where fires attended during the investigated year, 2017, in California. The land covers addressed in this study hence follow these categories, but are renamed for clarity, see Table 1.

<table>
<thead>
<tr>
<th>CGLC Description</th>
<th>Name</th>
<th>Land cover (LC) Number</th>
</tr>
</thead>
<tbody>
<tr>
<td>Open Evergreen Needle/Deciduous Needle/Deciduous BroadLeaf Forest/ Mixed Forest/ Not Matching Other Forests</td>
<td>Open Forest</td>
<td>126</td>
</tr>
<tr>
<td>Moss and Lichen/Herbaceous wetland/ Herbaceous vegetation/ Shrubs</td>
<td>Herbaceous/Shrub</td>
<td>30</td>
</tr>
<tr>
<td>Closed Evergreen Needle/Deciduous Needle/Deciduous BroadLeaf Forest/ Mixed Forest/ Not Matching Other Forests</td>
<td>Closed Forest</td>
<td>116</td>
</tr>
</tbody>
</table>

2.2.2 Köppen Climate Classification System
The Köppen climate classification system is a widely used method to categorize and describe the Earth's climate zones based on temperature and precipitation patterns. Developed by climatologist Wladimir Köppen in the early 20th century, it provides a standardized way to classify climates based on their dominant vegetation and weather characteristics. The Köppen system recognizes five primary climate groups, which are further divided into several subcategories (Beck et al., 2018).

<table>
<thead>
<tr>
<th>Group</th>
<th>Climate</th>
</tr>
</thead>
<tbody>
<tr>
<td>A: Tropical Climates</td>
<td>Af: Tropical rainforest climate: These areas have high temperatures and abundant rainfall throughout the year.</td>
</tr>
<tr>
<td>Region</td>
<td>Climate Type</td>
</tr>
<tr>
<td>--------</td>
<td>--------------</td>
</tr>
<tr>
<td>B: Dry Climates</td>
<td>BW: Desert climate</td>
</tr>
<tr>
<td></td>
<td>BS: Steppe climate</td>
</tr>
<tr>
<td>C: Temperate Climates</td>
<td>Cfa: Humid subtropical climate</td>
</tr>
<tr>
<td></td>
<td>Cfb: Marine west coast climate</td>
</tr>
<tr>
<td></td>
<td>Cfc: Subpolar marine climate</td>
</tr>
<tr>
<td></td>
<td>Cwa: Monsoon-influenced humid subtropical climate</td>
</tr>
<tr>
<td>D: Continental Climates</td>
<td>Dfa: Hot summer continental climate</td>
</tr>
<tr>
<td></td>
<td>Dfb: Warm summer continental climate</td>
</tr>
<tr>
<td></td>
<td>Dfc: Subarctic climate</td>
</tr>
<tr>
<td></td>
<td>Dfd: Subarctic climate with dry winters</td>
</tr>
<tr>
<td>E: Polar Climates</td>
<td>ET: Tundra climate</td>
</tr>
<tr>
<td></td>
<td>EF: Ice cap climate</td>
</tr>
</tbody>
</table>
The Köppen climate classification system provides a useful framework for understanding and comparing different climate zones around the world.

### 2.2.3 MODIS Burned Area Product

The MCD64A1 Collection 6 Burned Area product is used to identify fires in this thesis. The MODIS standard products provide new and improved tools for moderate resolution land surface monitoring (Justice et al., 1998). The monthly, 500m worldwide gridded product including per-pixel burned-area and quality information is known as the Terra and Aqua combined MCD64A1 Version 6 Burned Area data product. The MCD64A1 burned-area mapping method makes use of 1km MODIS active fire data along with 500m MODIS Surface Reflectance images which enables a shorter processing time (Giglio et al., 2018). As opposed to satellite data with a finer spatial resolution, this collection enables a shorter processing time. As a result, processing for the full research region is made feasible, which with a higher resolution would not be achievable without using Google Earth Engine (Rodrigues et al., 2019).

### 2.2.4 MODIS Combined 16-day EVI

EVI (Enhanced Vegetation Index), a surrogate for photosynthetic activity, was used. With a value range of 1.0 to -1.0, this index is a common indicator of vegetation. The ratio of the red band to the near-infrared band reflectance is used to determine EVI. EVI is usually measured using remote sensing products by the following calculation:

\[
\text{EVI} = G \cdot \frac{\rho_{\text{NIR}} - \rho_{\text{Red}}}{\rho_{\text{NIR}} + C_1 \cdot \rho_{\text{Red}} - C_2 \cdot \rho_{\text{blue}} + L}
\]

In this formula, \(\rho\) corresponds to the reflectance of the band, which is represented by the nir (near-infrared band) and red (red band) band. \(G\) corresponds to a gain factor and \(L\) is a soil adjustment parameter. \(C_1\) and \(C_2\) and the \(\rho_{\text{blue}}\) are used to correct for atmospheric aerosols. Healthy vegetation reflects more infrared light than red light. This relationship is initial for the method as it contributes to vegetation that is less prosperous reflecting more red light and less infrared light. MODIS Combined 16-day EVI data are used to analyze patterns of photosynthetic activity over time and space (Didan, Kamel, 2015).

MODIS has a spatial resolution of 500m and uses MODIS/MCD43A4 surface reflectance composites. Together, the MODIS instruments on the Aqua and Terra satellites provide a temporal resolution of 8 days. The intermediate spatial resolution allows for faster processing times, much like the burned area.
product does. As the scope of this study is large, it is not as important that the spatial resolution is considered.

2.2.5 MODIS Burn date
MODIS Burn Date is a specific data product derived from satellite observations, primarily captured by the Moderate Resolution Imaging Spectroradiometer (MODIS) sensor aboard NASA's Terra and Aqua satellites. It provides information on the timing and location of vegetation fires, enabling the monitoring and analysis of wildfires on a global scale (Lasko, 2019). The burn date provides information into the temporal distribution of fires and enables the analysis of fire seasonality and trends. The MODIS Burn Date collection consists of a 500m global grid product that analyzes per-pixel burned-area and quality information. The mapping of burned areas uses 500m MODIS surface reflectance images in combination with 1 km MODIS active fire observations. The algorithm uses a burn-sensitive vegetation index (VI) to create dynamic thresholds that are applied to composite data to identify the burn date for the 500m grid cells (Giglio et al., 2021).

2.2.6 Burn severity
Burn severity refers to the degree or extent of the impact a fire has on vegetation and ecosystems. It provides a measure of the intensity and severity of a fire event, helping to assess the ecological and environmental consequences of wildfires (Keeley, 2008). Burn severity data describe the effect of fire on vegetation, including the extent of vegetation mortality or reduction in biomass. It helps to assess the short-term and long-term effects of fire on plant communities and their ability to recover depending on the burn severity grade. Burn severity are often classified into several levels or categories to represent different degrees of fire impact (Miller, 2023). In this particular study case MTBS (monitoring trend in burn severity) and MTBS Burned Area Boundaries was used. MTBS Program maps burn severity and extent of large fires in the US. The program is conducted by USGS and USDA and utilizes Landsat data at a 30m resolution. The fire mosaics used in MTBS include thematic raster images of burn severity classes for completed MTBS fires. These mosaics are compiled annually for each state in the United States and the entire country. The Monitoring Trends in Burn Severity (MTBS) program aims to consistently map the severity and extent of large fires in all US states since year 1984. MTBS Burned Area Boundaries is a government program that maps burn damage and the extent of large fires in all states of the United States since 1984. The MTBS Burned Area Boundaries dataset includes burned area polygons for completed fires in the continental United States, with a minimum size of 1000 acres. The data threshold is determined by NBR or dNBR, with the range varying based on the incoming data type. The MTBS Burned Area Boundaries also maintain
Landsat data that is analyzed through a standardized and consistent methodology, generating products at a 30m resolution (Finco et al., n.d.).

3 Methodology

A large amount of studies has been carried out using remote sensing methods (Cochrane and Ryan, 2009). Regarding post-fire recovery specifically, several studies have successfully estimated post-fire vegetation recovery. Wu (2022) used vegetation indices derived from measurements taken with the Normalized Difference Vegetation Index (NDVI) to evaluate post-fire recovery for a large fire in California, USA. Similarly, Li et al. (2012) studied the impact of fire in North America using Enhanced Vegetation Index (EVI) time series to analyze post-fire recovery and also João et al. (2018) used time series of NDVI derived from MODIS images to study the recovery of burned areas in northern Portugal. Although these studies primarily focus on identifying post-fire recovery dynamics and patterns for different land cover classes, remote sensing has the ability to estimate post-fire recovery at a larger scale by including more factors. By doing so, it is possible better understand how larger ecosystems, or regions, respond to fires, which is critical for effective fire suppression and management (Reid et al., 2006). Currently, there are many studies quantifying and evaluating post-fire vegetation recovery using remote sensing techniques, but these are mostly focused on individual vegetation types or fire events. Relatively few studies compare recovery after fire between different vegetation types or land cover classes or with regard to burn severity, although there are examples.

Following the successful use of remote sensing of EVI time series, this method will be used in this study. By using EVI and dEVI the "half recovery time" (HRT) method can be implemented. This method is also common for analyzing post-wildfire recovery and provides a quantitative measure of vegetation recovery after disturbance. This approach allows for a comprehensive evaluation of the progress and effectiveness of recovery efforts (Pérez-Cabello, 2021). By focusing on the HRT, the study can provide valuable insights into the initial stages of recovery and the relative pace at which different areas or ecosystems are regaining their pre-fire condition. This information can assist in assessing the effectiveness of post-fire management strategies and informing decision-making processes regarding resource allocation and ecosystem restoration priorities (Kong et al., 2019).

In order to estimate post-fire recovery for individual pixels or areas, it is common to use an unburnt reference pixel or area. This approach helps mitigate the impact of local environmental variation (Leeuwen et al., 2010). In addition, climate variability must be considered, as it plays a significant role in determining the trajectory of vegetation recovery (Johnstone et al., 2010). When the goal is to
estimate the absolute value of recovery for a specific area or to examine the influence of local climate, the use of a control plot may be overkill. However, if the aim is to compare recovery times and HRT between different land cover types or vegetation, it is appropriate to use a control area. By considering the burned area in relation to a similar unburned area, the analysis can account for environmental variations. This approach allows for a clearer distinction between the response of different land cover types to fire, rather than being solely influenced by local climate (Veraverbeke et al., 2012).

Burn severity will also be part of the investigation as it, as mentioned earlier, is an aspect that has not been included in many previous studies. By considering burn severity, we can gain insights into the severity of vegetation loss, land degradation and changes in ecological conditions caused by the fire by examining and comparing areas affected by different burn severity grades full recovery time and HRT. This information is critical to developing effective strategies for ecosystem restoration, such as prioritizing areas of high burn damage for immediate intervention or implementing targeted management practices to improve post-fire recovery.

### 3.1 Workflow

In this study, Google Earth Engine (GEE) was used to retrieve and analyze EVI time series data. GEE is a powerful platform that offers the ability to visualize, process and analyze data on a large scale. By exploiting GEE, it was possible to efficiently handle satellite image data with high spatial resolution, which can provide strong indications of the well-being land cover classes use. The choice to focus on the EVI time series was motivated by its relevance for assessing vegetation health and dynamics. EVI is a widely used index that quantifies the greenness and vigor of vegetation based on the reflectance of near-infrared and red light. By analyzing the EVI time series, the researchers were able to gain insights into the temporal patterns and changes in the vegetation during the investigated period.

To identify fire events during the investigated year, the MODIS Burned Area product was collected on a monthly basis. This product provides a comprehensive map of all fire events. Incorporating these data into the analysis allowed the identification and location of burned areas to be accurately identified, which is critical to understanding the effects of fires on land cover classes.

To further improve the analysis, additional data such as climate zones, land cover classes and burns were imported into GEE. This additional information enabled a more comprehensive assessment of the impact of the fire events on various environmental factors. Climatic zones can significantly influence
vegetation dynamics and response to fires, while land cover classes provide a valuable context for assessing the specific types of vegetation affected by fires. Information on the degree of burn severity enables a quantitative measure of the intensity and extent of burn injuries. By incorporating these variables into the analysis, the researchers were able to gain a more comprehensive understanding of the relationships between burns, land cover classes, climate zones and vegetation dynamics.

To collect data points for analysis, buffered areas were created around each fire event. This step ensured that unburned points were collected near each fire event, providing a comparison between burned and unburned areas. A carefully designed algorithm was used to efficiently sample these points. Once the sample points from both burned and unburned areas were collected, they were exported to a CSV file for further analysis in Google Colab. The use of Google Colab for further analysis of the collected data points was motivated by its capabilities for data processing, visualization and integration with other libraries and tools. Google Colab offers a collaborative and interactive environment that supports efficient data manipulation and analysis, making it well suited to the tasks required in this study. The CSV file included important data for each selected point, such as burn date, EVI time series data, burn damage, land cover, climate zone, location, and fire ID. This data export facilitated seamless integration with Google Colab, a popular data analysis and visualization platform.

In Google Colab, the CSV file was imported to perform the necessary data processing steps. One of the most important conversions used was to convert the burn dates to every 16 days as burn dates. The conversion of burn dates to every 16 day burn dates was a crucial step to ensure a more accurate mapping of burned areas. This transformation accounts for the temporal resolution of the data and aligns the burn dates with the available satellite images, allowing a more accurate assessment of the vegetation response to fire events. Figure 3 visualize in the left graph the distribution of fire ignition during the investigated year. In the right graph, also visible in Figure 3, the result is shown when after transformation to 16th day.
The grouping of data points based on different factors such as burns, land cover, climate zone and burns enabled a more nuanced analysis of the effects. By examining the EVI time series within these subgroups, it was possible to evaluate how different factors interacted and influenced vegetation dynamics. This approach provided valuable insights into the variations in vegetation response across conditions, enabling a more comprehensive understanding of the study area.

A calculation of mean EVI values and standard deviation for the burned and unburned groups was done to allow quantification of the overall vegetation response to fire events. These statistical measures provided a meaningful assessment of the impact of wildfires on different land cover classes and climate zones and facilitated comparisons between burned and unburned areas. This quantitative analysis supported the interpretation and discussion of the findings, enhancing the overall validity and reliability of the study. See Figure 4 to visualize the workflow as a chart.
3.2 Post-fire recovery metrics

3.2.1 Differenced EVI (dEVI)

Seasonal and climatic variations are likely to be seen in any time series of EVI because they are generally the primary regulators of photosynthetic activity. It is preferable to choose time series that are not affected by regional climate change because the goal of this study is to assess the recovery between different land cover classes at a regional level. Another preferred measure to avoid regional changes is to compare the average EVI time series obtained from the burned area with that of the nearby unburned area. From these, a difference between these time series is calculated to evaluate the recovery through the following formula:

\[
dEVI = EVI_{\text{burned}} - EVI_{\text{unburned}}
\]

3.2.2 Half Recovery Time (HRT)

Half Recovery Time (HRT), in this study, includes the number of days which is needed for dEVI to reach 50% of its value just after ignition day. According to Viktor Wu (2022) the two main factors determining why HRT is used as a short-term recovery indicator are that it is a measure that has been shown to be more sensitive to phenology and the vegetation structure community, or land cover type (Bousquet et al., 2022). Another advantage of using a HRT is that it can be easily derived from satellite data because it only needs a short period of time. In this study the average HRT was used since we consider that giving a more robust and fair outplay of the result of the collected data.

In the study, the average and standard deviation of the EVI time series were calculated. This was important to ensure a fair comparison between the burned and unburned points. All points were divided into subgroups based on which of the two investigated climate zones they belonged to. This step helped to categorize the data according to different climate conditions, which was an important basis for the survey to be able to compare recovery between climate zones. Within each climate zone subgroup, the points were further sorted based on the type of the three selected land covers they represented. This categorization allowed for analysis based on land cover classes and enabled a comparison between the different land cover classes. The standard deviation and mean values of the EVI time series were calculated separately for both the burned and unburned points within each land cover class. This step provided insights into the variability and means for each group. The mean EVI time series calculated for each land cover class in both the burned and unburned groups were
subtracted with each other to obtain a measure of dEVI time series. This subtraction enabled the identification of potential differences in post-fire recovery between land cover classes and in different climate zones. This analysis helped to understand the influence of climate on post-fire recovery and the variations observed between different areas. This approach enabled a comprehensive investigation of the fire impact and response time on vegetation under different environmental conditions and enabled the interpretation of HRT from each subgroup.

In order to be able to identify differences in recovery with respect to burn severity, all selected points was distributed regarding their burn severity within each land cover class. Then each group was divided into unburned and burned groups thus the mean and standard deviation of EVI time series could be calculated for the respective burn severity grouping and unburned points. Lastly, subtraction between unburned and burned EVI values for each burn severity grade was done to identify differences for the recovery after wildfire, the dEVI.

### 3.3 Sample Grouping and Comparison

In this study, an analysis of the post-fire recovery process between land cover classes within the same climate zone will be investigated. The same land cover class will also be analyzed within two climate zones to possibly identify differences in the recovery process depending on the climate zone. The fires used in the study, which can be illustrated in Figures 1 panel a) and 2, are collected over a full year. With the help of these maps, climate zones where most fires occurred during the investigated year could be identified.

The three climate zones in California where most fires occur frequently: Csa (Hot-summer Mediterranean climate), Csb (Hot-summer Mediterranean climate), BSk (Cold Semi-arid climate), which can be seen in Figure 1 and 2. In the study, the fires in Csb and BSk were therefore examined only in California. The Csb climate zone will be mentioned as Mediterranean climate zone, and BSk will be called Semi-arid. For the analysis of this study, we assumed that points with the same fire id belonged to the same climate zone.

With data of different points, standard deviations and averages of EVI time series could be calculated for the recovery of the vegetation types in the investigated climate zones, which are visualized in graphs to identify potential differences. While analyzing the EVI time series we also assumed that no other fire event occurred during the full recovery time to exclude resistance in the recovery process. Average EVI time series was calculated to make a comprehensive comparison between different settings for identifying the isolated impacts of a specific factor. In this thesis, we didn’t adopted
quantitative evaluation of HRT since peak shift may happen and it may lead to misinterpretation (such as false positive recovery) when EVI at different stages are compared. ) The approach used in Wu’s (2022) study in counting the HRT may fail when comparing shifted time series that peaks at different dates and dEVI calculates the EVI difference of burned and unburned areas at different regrowth phases, as shown in the result Figure 11 panel c).

To determine the dEVI a subtraction between burned and unburned points EVI time series was done. In this analysis, the unburned point was collected with polygons around each fire event, as shown in Figure 5. By creating these buffered areas around fire events, it could be ensured that the unburned points were collected form an unburned area near to the fire event. Since we assume that points within same fire id belongs to same climate classes, we can also assume that the points collected from the surrounding buffer belongs to the same climate zone as the burned points.

![Figure 5. Visualizing buffer area around fire event. Area within the blue lines symbolizes an unburnt area and the blue dots unburnt points. Area within the redlines represent burnt area and the red dots burned points.](image)

Figure 6 shows the land cover distribution of sampled points. According to the result in the figure the land cover classes open forest (LC number 126), herbaceous/shrub (LC number 30) and closed forest (LC number 116) was chosen for this study to do further analysis of.
Figure 6. Visualizing the frequency of fires in each land cover class. LC number 30 represent herbaceous/shrub, number 116 closed forest and 126 open forest.
4 Result

4.1 Post-fire recovery in various climate zones

In the Figure below, Fig. 7, the average MODIS EVI Time Series for each land cover in both Mediterranean and Semi-arid climate zones is plotted. The widened area represents the standard deviation. The green line corresponds to dEVI - the difference between the average values of burned and unburned points. As shown in Figure 7 panel a) the burned points of open forest in the Mediterranean climate zone seems to follow the same pattern as unburned points after 650 days. It can be seen that a half recovery time is reached at day 350. Following panel b), it is visible that open forest in semi-arid climate showed data representing a recovery status after 550 days and HRT at day 390. The graphs in panel a) and b) show different patterns despite being the same land cover class. In panel c) a recovery period of 355 days is illustrated and a half recovery time at day 330 for Herbaceous/Shrub in the Mediterranean climate zone. For the same land cover type in the Semi-arid climate zone the full recovery time is 570 days and the HRT 310 days, as highlighted in Figure 7 panel d). For closed forest in the Mediterranean climate zone, shown in panel e), it is visible that the full recovery time is 1020 days and the HRT at day 670. The full recovery time for closed forest in a Semi-arid climate zone is 1050 days. The half recovery time is at day 610, which is visible in Figure 7 panel f). It is therefore visual that a difference in HRT patterns between the climate zones of closed forest occurs.

MODIS EVI Time Series for each land cover in different climate zones

<table>
<thead>
<tr>
<th>Mediterranean</th>
<th>Semi-arid</th>
</tr>
</thead>
<tbody>
<tr>
<td><img src="image1" alt="MODIS EVI Time Series - Open Forest in Mediterranean" /></td>
<td><img src="image2" alt="MODIS EVI Time Series - Open Forest in Semi-arid" /></td>
</tr>
</tbody>
</table>
Figure 7. Graphs of HRT sorted by burned and unburned point for each land cover and climate zone. The difference between the respective pairs is calculated by subtraction between the burned and unburned points, which is visualized with the green line. The shaded areas around the lines represent the standard deviation of the data of all collected points.

4.2 Post-fire recovery across land cover

In the following figure, Figure 8, all points are grouped according to land cover in the investigated climate zones. The graphs visualize the average full recovery time and standard deviation for each land cover. The dashed lines symbolize the dEVI for all points within respective land cover type, meaning the difference between all burned and unburned points for each land cover. In Figure 8, panel a), it is visible that the burnt points follow the same pattern for all land covers in the Mediterranean climate zone. It can be seen that herbaceous/shrub has shortest full recovery time and fastest HRT followed by open forest and closed forest. Despite similarities in patterns, there are big differences in appearance and it is possible to identify differences in full recovery times and half recovery times. Panel b), Figure 8, shows all land cover in the Semi-arid climate zone. In this graph, the lines for respective land cover follow the same pattern without major differences in full recovery time and half recovery time.
Figure 8. Shows HRT for sampling all surveyed land cover types within the same climate zone. a) shows HRT for open forest (LC_116), herbaceous/shrub (LC_30) and closed forest (LC_126) in the Mediterranean climate zone, b) shows HRT for open forest (LC_116), herbaceous/shrub (LC_30) and closed forest (LC_126) in the Semi-arid climate zone.

4.3 Post-fire recovery across burn severity
To visualize the result representing the investigation of the effect of burn severity on recovery profiles in climate zones, similar graphs were plotted. In Figure 9, panel a) the lines for the respective degrees of burn severity follow roughly the same pattern. There are minor differences, but full recovery time can be estimated to be roughly the same but burn severity grade 3 had slightly faster recovery time at 1010 days, followed by burn severity grade 4 with full recovery time at day 1200 and then grade 2 with full recovery time at day 1240 after ignition day. The HRT values vary between the burn severity grades. It is possible to identify a faster HRT for points belonging to burn severity 2 at day 500. The HRT for burn severity grade 3 is the second longest at day 650. Burn severity grade 4 in open forest has the longest HRT in the Mediterranean climate zone at day 1000, as shown in Figure 9 panel a).

The result for the same land cover type but in a semi-arid climate zone shows different results after distribution according to burn severity. In panel b), Figure 9, this is illustrated. From the graph, it can be interpreted that the full recovery time for points with burn severity grade 3 is reached at day 620, followed by burn severity grade 4 with full recovery time to day at 670. In this graph, the points belonging to the group burn severity grade 2 do not seem to reach full recovery in open forest in the Semi-arid climate zone. The HRT for burn severity grade 3 and 4 is at day 410 respectively 450 for open forest in Semi-arid climate zone. Panel c), in Figure 9, shows that all points regardless of burn severity achieved full recovery time at day 700. In this Figure it is also visualized that the peaks for all dEVI values correspond to the valleys on the line for non-burned points for herbaceous/shrub in the Mediterranean climate zone. This will be discussed further in the discussion.
Herbaceous/shrub in Semi-arid climate zone has strong indications that points affected by burn severity grade 2 and 3 do not seem to be as affected as points with burn severity grade 4 by the wildfire, which is visible in Figure 8 panel d). The points belonging to burn severity 4, dEVI_burned4_points, do not seem to integrate towards a stable value around the zero-line, which means that the full recovery period is more than 1250 days for herbaceous/shrub in the semi-arid climate zone. In contrast, a full recovery time for burn severity groups 2 and 3 can both be estimated to day 320 after ignition for herbaceous in the Semi-arid climate zone. The HRT for these burn severity grades is at day 100 respectively at day 110. Recovery time can be seen in panel e) for closed forest in the Mediterranean climate zone. Here it is visible that, despite the fact that points belonging to group burn severity grade 4 were affected harder by the fire, still show a full recovery time as long as the remaining burn severity groups.

For all burn severity groups, the full recovery time can be interpreted as 1300 days. Despite similarities in full recovery time the HRT differs significantly. Group with burn severity grade 2 reached HRT at day 500, followed by burn severity grade 3 at day 720 and burn severity grade 4 at day 1000. Panel f), Figure 9, shows closed forest in a Semi-arid climate zone. In this graph, no indications are made visible that points belonging to group burn severity 4 must have been affected severely by wildfire than the rest. All recovery time series follow the same pattern and at day 1050 the full recovery time is reached. Despite this, HRT differs between the burn severity grades. The shortest HRT has burn severity grade 2, which was achieved on day 390. Following grade 2 is grade 3, which achieves an HRT on day 510. Finally, burn severity 4 achieves HRT on day 610. This is visible in Figure 9 panel f).
### Figure 9

Graphs of HRT sorted by burn severity on each land cover type and climate zone. The difference between the respective pairs is calculated by subtraction between the burned and unburned.
points, which is visualized with the dashed lines. The shaded areas around the lines represent the standard deviations of the data of all collected points.

5 Discussion

In this study, the average EVI time series was used to avoid potential problems with the quantitative evaluation of HRT when analyzing recovery from fire events as mentioned before. One such issue is the presence of peak shift, which can lead to misinterpretations of the full recovery time. Peak shifts can occur due to various factors, such as measurement errors. These changes can distort the assessment of the full recovery time, making it difficult to determine the exact moment when the land cover has fully recovered. By using average recovery time, the focus shifts from determining the exact full recovery time to obtaining a more representative measure of the overall recovery process. It takes into account the average duration it takes for the land cover to return to its pre-event or pre-power state, taking into account potential variations and fluctuations.

HRT, or half recovery time, is another metric that helps capture the overall rate of recovery. It measures the time it takes for the vegetation to reach halfway between the initial state and the fully recovered state. By considering the half recovery point, it provides a standardized reference point for comparing recovery rates between different systems or scenarios. Overall, using average full recovery time and HRT enables a more robust and reliable evaluation of recovery, minimizing the effect of peak shifts and facilitating a more accurate interpretation of the recovery process. These metrics provide a broader perspective and more credible results.

5.1 Impacts of climate zone on post-fire recovery

When comparing the post-fire recovery dynamics between different climate zones, one key aspect can provide valuable insights: The Half Recovery Time (HRT). The HRT represents the time it takes for a burned area to reach half of its pre-fire vegetation condition.

By analyzing the HRT of post-fire recovery in Mediterranean and semi-arid climate zones, distinct patterns emerge. Between Mediterranean and Semi-arid climate zones, as illustrated by Figure 7, HRT varies mostly between land cover types. Closed forest exhibits the longest HRT in the Mediterranean climate zone compared to herbaceous/shrub and open forest in both climate zones. The fastest HRT belongs to the herbaceous/shrub in the Mediterranean climate zone. According to Viktor Wu's study (2022), grasslands generally have a relatively fast short-term full recovery time, and therefore the climate immediately after fire plays an important role in the recovery of herbaceous vegetation (Wu,
In what follows, the data show that there is no evidence that HRT within a particular climate zone is more affected by fires as results differ between vegetation types. This result agrees with the result of Viktor Wu's study (2022). Despite this result, the data show that the majority of HRT results are faster in the Mediterranean climate zone with herbaceous/shrub leading. This suggests that herbaceous/shrub species recover relatively generally faster in both climate zones, likely due to the presence of fire-adapted species and regenerative mechanisms specific to this vegetation type. Although it might have been expected that Semi-arid, would adopt a lower HRT, it does not necessarily provide the conditions for a slower recovery unless moisture is the limiting factor in both zones.

As mentioned, closed forest in the Mediterranean climate zone shows longer HRT values. The differences in HRT can be attributed to the complexity of closed forest ecosystems, which often require more time to regenerate and establish a diverse vegetation structure. This is a hypothesis supported by the data in the results, see Figure 7, that open forest has shorter HRT compared to closed forest in both climate zones, see Figure 7 panel a) and b), due to the smaller amount of compact growth of trees in this land cover. The species composition can also affect the full recovery time in addition to the lack of compactness. For example, species of trees can vary between climate zones where there are studies showing that coniferous trees have a longer full recovery time than deciduous trees (João et al., 2018). As mentioned in Viktor Wu's (2022) study, the data analyzed in this study are more likely to include more conifers in the Mediterranean climate zone than in the Semi-arid. This reinforces and confirms the result as differences in HRT are shown between the climate zones.

The results of HRT between climate zones do not differ markedly and distinct patterns emerge. The interesting differences are between the land cover types. The similarities between climate zones may indicate that recovery rates across land cover types are more consistent, potentially depending on specific adaptive strategies and the fire regime characteristic of the two climate zones.

5.2 Impacts of land cover on post-fire recovery
A comparison between land cover classes shows that a greater number of statistically significant differences exist when comparing the recovery between land cover classes. This further indicates that short-term post-fire vegetation recovery in California is potentially more dependent on land cover type than climate zones.
By analyzing the HRT for different land cover classes, Figure 7 and Figure 8 present an overview of the recovery dynamics within the investigated climate zones. In the Mediterranean climate zone, Figure 7 panel c), it is clear that herbaceous/shrub exhibits the shortest HRT, followed by open forest and closed forest. This suggests that the herbaceous/shrub recovers relatively quickly, due to its regenerative capacity and adaptability to post-fire conditions. Open forest exhibits a slightly longer HRT, while closed forest exhibits the longest HRT, emphasizing the challenges and extended full recovery time required for these complex ecosystems that contain more compact growth of trees.

In the Semi-arid climate zone, Figure 8 panel b), HRT values among land cover types are relatively consistent, with no significant differences observed. This means that all land cover classes in the semi-arid climate zone show similar rates of recovery and adaptability to post-fire conditions. However, it is visible that the closed forest achieves a recovered status. Contrariwise, there are no signs of open forest and herbaceous/shrub reaching a status of recovered. These results differ from the results plotted in the individual graphs for each MODIS EVI Time Series, see Figure 7 panel b), d) and f). The results in these graphs indicate the same conclusions as for the land cover types in the Mediterranean climate zone. That is, the longest HRT for closed forest followed by open forest and herbaceous/shrub.

Based on the results in Figure 7 for the land cover types in the Semi-arid climate zone and the results for recovery for the land cover types in the Mediterranean climate zone, the key finding is that closed forest has a significantly greater HRT. With the help of previous research, this result is reinforced as it previously emerged that between herbaceous and woody land cover classes, the herbaceous vegetation has a faster recovery (Viedma et al., 1997).

The results in Figure 8, panel a), and Figure 7, panel b), d) and f), agree with the HRT found in Viktor Wu's (2022) results. This indicates that a possible error must have occurred in the plotting of Figure 8 panel b). It could be, for example, that different amounts of points were included in the respective plotting, which could affect the curve for HRT for the respective land cover.

The differences between closed forest and open forest could be explained by the species composition again as well as the compactness of the growth. This is because different species react differently to fire depending on composition and environment.
5.3 Impacts of burn severity on post-fire recovery

The burn severity of a wildfire can significantly impact the recovery trajectory of vegetation. Analyzing the effect of burn severity within the same land cover class and between different land cover types provides valuable insights into the post-fire resilience and response of vegetation.

When comparing HRT in the Mediterranean climate zone for open forest, it is visible that the points belonging to a higher degree of burning are more affected by the fire. It appears that HRT increases for each burn severity level, even though the full recovery time is approximately the same. This may be because the large species composition in this land cover type is broad, suggesting that different plants respond more strongly to burns, but that the full recovery time is still the same within this land cover.

Even for open forest in a semi-arid climate zone, the recovery curve follows the same pattern for all burns. The same recognition of patterns can also be illustrated for HRT of closed forest in both Mediterranean and semi-arid climate zones. In the Mediterranean climate zone, an indication is also given that points affected by burn degree 4 are hit hardest by the fire, but here, too, the land cover type recovers in interaction with each other regardless of burning. Similar results are found for closed forest in Semi-arid, where all burns also recover simultaneously but HRT separates them. Even in this climate zone, the longer the HRT, the more severe the burn severity grade point is affected. This result contradicts the result from Fernandez-Mans et al. research (2016). In their results, it appears that the degree of burn affects the full recovery time. The differences in the results can be due to various reasons such as the previously mentioned: choice of climate zones, climate conditions during the recovery period but also the species composition.

However, differences in full recovery time are very visible between land cover types and between climate zones. If you compare the results for open forest in both climate zones, the HRT is significantly longer in the Mediterranean climate zone. This may be due to the previously mentioned reason, difference in species composition in the different climate zones. The same conclusion can be drawn between the Mediterranean and semi-arid climate zone for closed forest, see Figure 9 panel e) and f). Here, too, the HRT is significantly shorter for all burn severity grades in the semi-arid climate zone. This too must be an example of the difference in species assemblage in the different climate zones.
What is striking about the results of this survey is herbaceous/shrub in both climate zones. For this land cover type in the semi-arid climate zone, burn severity grades two and three do not seem to have affected the vegetation very much and the HRT is very short. The line that follows burn severity grade 4, on the other hand, shows drastic changes in EVI and dEVI. Reasons for this result may be seasonal. As previously mentioned, herbaceous/shrub has a relatively fast full recovery time and therefore the climate after the fire can play a large role in the appearance of the figure. The same argument can defend the appearance of herbaceous/shrub in the Mediterranean climate zone, see Figure 9 panel c). In this it is visible to see how the peaks of the burned points meet the valleys of the unburned points. This can be explained by the climatic conditions immediately after a fire as this can significantly affect vegetation recovery. Herbaceous/shrub vegetation relies on favorable post-fire climatic conditions, including moisture availability, temperature and light, to regenerate and grow rapidly. If climatic conditions are suitable, the recovery of herbaceous/shrub vegetation can be enhanced, leading to the observed pattern in Figure 9 panel c) where the burnt points reach their peaks, coinciding with the troughs of the unburned points.

In general, the different behaviors in HRT can also be explained by the fact that, as a difference from many other land cover types, a forest can burn with great intensity due to its large biomass. Other ground cover types such as herbaceous/shrub require less to be complete destroyed. Therefore, trees should be more sensitive to fire severity, because different levels of severity can cause damage of varying magnitudes, while other classes are less sensitive because they more easily reach a maximum disturbance, i.e. they are likely to be more “fuel limited” than trees (Steel et al. 2015).

5.4 Recovery profiles

The graphs reveal variations in post-fire vegetation recovery between different land cover classes, which is also evident in the dEVI time series depicted in Figure 7. The time series shows a significant decrease in dEVI during the fire, followed by a relatively faster initial recovery that gradually slows down. The differences between the land cover classes are observed in the magnitude of the initial decline and the variation in the rate of recovery over time. Among the land cover classes, both closed forest and open forest show the most pronounced decrease in dEVI, probably due to their higher biomass, resulting in a significant difference between burned and unburned areas within these land cover classes.

Although the time series in Figure 7 do not provide quantitative measures of the differences in post-fire recovery, they provide valuable insights into pre- and post-fire behavior. First, the time series
indicates that all land cover classes exhibit positive dEVI values before the fire. This suggests that the burned area had a larger volume or higher vegetation density compared to the surrounding unburned area, which is an unexpected difference. The positive pre-burn dEVI values may indicate an accumulation of excess fuel loads in the burned area compared to the unburned area. Previous research has determined that increased fuel loads contribute to greater severity and probability of wildfires and it is likely that a fire predominantly expands within the burned area, which exhibits a higher EVI (Keelley and Syphard, 2019).

Regarding the recovery profile, herbaceous/shrub shows the highest positive dEVI values before burning. Given that this land cover class typically lacks dense vegetation, it serves as an illustrative example of the importance of fuel loads. Fires in this land cover class are expected to occur only in areas with vegetation cover, as these areas provide the fuel required for ignition, unlike truly barren areas.

Additionally, the time series provides interesting insights into the post-fire recovery trajectory. Around day 200, some land cover classes experience a slowdown in recovery rates, and a similar decline is observed around day 550, with cases of negative rates in some cases. This suggests that recovery is not a linear process but rather exhibits a faster initial phase followed by a more moderate and decelerated phase as later stages of recovery approach. This pattern is consistent with observations and modeling results from previous studies (Bastos et al., 2011). This pattern can be attributed to seasonality, as a significant proportion of fires occur in the same two months (Li and Banerjee, 2021), leading to a recovery profile that follows seasonal patterns. Therefore, the recovery rate used in this study does not accurately describe the recovery patterns, as it is calculated as the slope of a linear trend encompassing the entire post-fire dEVI time series.

As can be seen from the fewer significant differences in full recovery time between land cover classes, it is likely that the full recovery time is determined less by land cover class compared to HRT. In this study, it also appeared that the recovery rate is not affected by the severity of the fire. Burn severity reflects the ecological impact of a fire and the degree of damage to vegetation and the surrounding environment. It considers factors such as vegetation mortality, changes in soil conditions and ecosystem resilience. Although burn damage indirectly affects post-fire recovery, HRT focuses on restoring fire-related hazards rather than the ecological dynamics and rate of recovery. In this study, the burn severity grade it does not seem to affect the result of HRT. Burn severity primarily considers factors related to fuel availability and fire risk, which are affected by burns.
5.5 Future studies and implications

Our results indicate that closed forest is the most sensitive land cover class regarding half recovery time and full recovery time after wildfire ignition, are consistent with the results of previous research on the vulnerability of forests to fire. Forests and woody plant communities play an important role in terrestrial carbon storage, biodiversity, and California’s economy through wood products and recreation. Therefore, it requires further investigation. Although it is known that forests generally take longer to recover, there is still a dearth of valuable knowledge about how specific species and communities respond to fires. To improve land management and preparedness, future studies on fire recovery should delve into fine-scale forest response, focusing on individual species or tree communities.

Studying fire recovery in more detail over time may be important because land cover changes, deforestation, and the ability of certain plant communities to recover after fire show variations in both space and time given that research shows signs of harsher fire seasons in the future. Given these potential scenarios, understanding the temporal evolution of post-fire recovery in different land covers and climates is critical to adapting land-use management to future fire regimes. One aspect not addressed in this study was recovery differences according to fire season. Since the fire seasons are expected to be extended, it would be interesting to do deeper studies in it to complement the results of this study.

The patterns identified in this study, such as the shorter full recovery time for closed forest and herbaceous/shrub land cover types in the Mediterranean, warrant further investigation. Meteorological data can provide valuable complementary information to study these patterns, as many vegetation types are sensitive to drought. While climate zones offer a broad estimate of long-term regional climate, localized weather data would provide a more temporally accurate and appropriate variable for sorting and comparing full recovery times and HRT. For example, if a fire season is considered to be over during a period that is not favorable for plant recovery, it will affect the full recovery time and HRT negatively.

Finally, it is important to recognize that differences in post-fire recovery may be indirectly affected by different types of land cover. For example, trees are more likely to contribute to severe fires compared to grasslands, which strongly affects post-fire recovery characteristics. Because fire regimes play a central role in determining post-fire recovery conditions, studies aimed at identifying recovery differences attributable to land cover type should ideally consider or include fire regimes. Fire regimes
are largely influenced by land cover types and climate zones, emphasizing the importance of understanding both vegetation responses to specific fire regimes and the dependence of fire regimes on land cover types.

6 Conclusion

In this study, we investigated the variation of post-fire recovery across different land cover classes, climate zones and burn severity. The results of this study showed that some differences were observed between climate zones, but no general relationship between full recovery time or HRT and climate zone could be identified. Herbaceous/shrub had the shortest HRT in both climate zones, followed by open forest and finally closed forest. The differences for HRT can be explained by a number of different factors such as seasonality, species composition within each land cover and climate zone and climate conditions. Burn severity does not affect full recovery time within the same land cover with the exception of herbaceous/shrub in the semi-arid climate zone. This may depend on the composition, size and fire resistance of the individual vegetation. On the other hand, there are large differences in HRT between the burn severity degrees within all land cover classes in both climate zones - HRT increases for each degree of severity. This may also depend on the composition of the vegetation but also other factors such as endurance and species cohesion in the respective climate zone and land cover. Consequences of using dEVI-based half recovery time have also been discussed, as its use can contribute to peak shifts in EVI values that can create uncertainties and compromise the accuracy of the result.

In addition to previous research, this study presents estimates for post-wildfire land cover recovery. It not only reinforces the results of previous studies but also introduces new findings concerning burn severity. In general, for post-fire vegetation recovery, this study suggests that HRT is a beneficial measure for analyzing recovery after a wildfire. It is also suitable for discerning variations in short-term recovery among different land cover types and climate zones.
7 References


Leeuwen, W.J.D. van, Casady, G.M., Neary, D.G., Bautista, S., Alloza, J.A., Carmel, Y., Wittenberg,


Miller, C., Harvey, B., Kane, V., Moskal, L., Alvarado, E., (2023). Different approaches make comparing studies of burn severity challenging: a review of methods used to link remotely sensed data with the Composite Burn Index. *International Journal of Wildland Fire* ,32(4), 449-475. [https://doi.org/10.1071/WF22050](https://doi.org/10.1071/WF22050)

Miller, J., Skinner, N., Safford, D., Knapp, E., Ramirez, M., (2012). Trends and causes of severity, size, and number of fires in northwestern California, USA, *Ecological Application* 22, 1, 184-203. [https://doi.org/10.1890/10-2108.1](https://doi.org/10.1890/10-2108.1)


