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Evaluating the Impact of Wildfires on Mixed Conifer Forest Regeneration and the Effectiveness of USFS Management Strategies on Restoring Ecosystem Services

Wyatt Farino
University of San Francisco, wpfarino@dons.usfca.edu

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Evaluating the Impact of Wildfires on Mixed Conifer Forest Regeneration and the Effectiveness of USFS Management Strategies on Restoring Ecosystem Services

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Wyatt Farino

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Content

Abstract

Wildfires are increasing in frequency, duration, and severity across Western North America. 20,438,720 acres (20.1%) of California has burned at least once since 2010. Projections suggest a statewide increase in burned area between 36% and 74% by 2085, with some forested areas in Northern California exceeding 100% in all modeled scenarios. Fire regimes have deviated far from their historical norm, significantly increasing the risk of type conversion from forest to other ecosystems. Californians rely on the myriad of ecosystem services produced by these forests to meet their basic needs. Access to these fundamental services will be severely reduced if appropriate action is not taken to ensure the regeneration of these ecosystems. This paper explores the impact of wildfire on ecosystem services and the programs and processes executed by the United States Forest Service (USFS) in response. A geospatial analysis of the North Complex fire (2020) tracks regeneration over three years and quantifies the loss of sediment retention services due to severe wildfire. The USFS invested significant resources in developing decision support tools, devising long-term reforestation strategies, and conducting assessments of post-fire conditions. However, findings reveal the stark loss of land cover to non-forest vegetation in the absence of reforestation treatments applied by the USFS. Over the last decade, only 6% of the post-wildfire reforestation activities identified by the USFS were implemented. Three years post-fire, sediment delivery to the stream networks within the boundaries of the fire perimeter increased by 15%. The USFS has considerable grounds to make up to achieve the REPLANT Act's mandated reforestation goals. Established programs and processes are sufficiently thorough, but this research uncovered lagging execution of reforestation activities in affected areas. Consolidating existing decision support tools, commitments to long-term monitoring, and adopting new geospatial technologies are paramount to the agency's ability to scale its reforestation program.

Keywords: wildfire, regeneration, reforestation, Sierra Nevada, Forest Service, USFS, adaptive management, ecosystem services, conifer, forest

Introduction

Background

Mixed-conifer forests in Northern California, integral to the region's environmental integrity, hydrological cycles, and cultural identity, are increasingly subjected to the multifaceted impacts of climate change (Costanza et al. 1998, Westerling et al. 2006). These forests provide valuable ecosystem services substantially impacted by the increasingly large and severe wildfires throughout the northern Sierra. Forests provide humans with various ecosystem services, including carbon sequestration, wood products, biodiversity conservation, water regulation, soil conservation, climate regulation, nutrient cycling, medicinal resources, and cultural and spiritual values (Stewart, William et al. 2016). They also contribute to air and water purification, provide recreational opportunities, and support wildlife habitat. Forests are essential for timber production and are crucial in mitigating climate change, maintaining water quality and quantity, and preserving biodiversity. They also have cultural and aesthetic value, providing a sense of connection to nature and offering opportunities for outdoor recreation.

The United States Forest Service (USFS) plays an outsized role in the long-term viability of California's forest ecosystems. 57% of the forestland in California is owned by the federal government, of which the USFS manages 9 million acres (48%) (Christensen et al. 2016, Fire and Resource Assessment Program 2018). Of the 65% of protected conifer forest habitat types, most are managed by the USFS (Fire and Resource Assessment Program 2018).

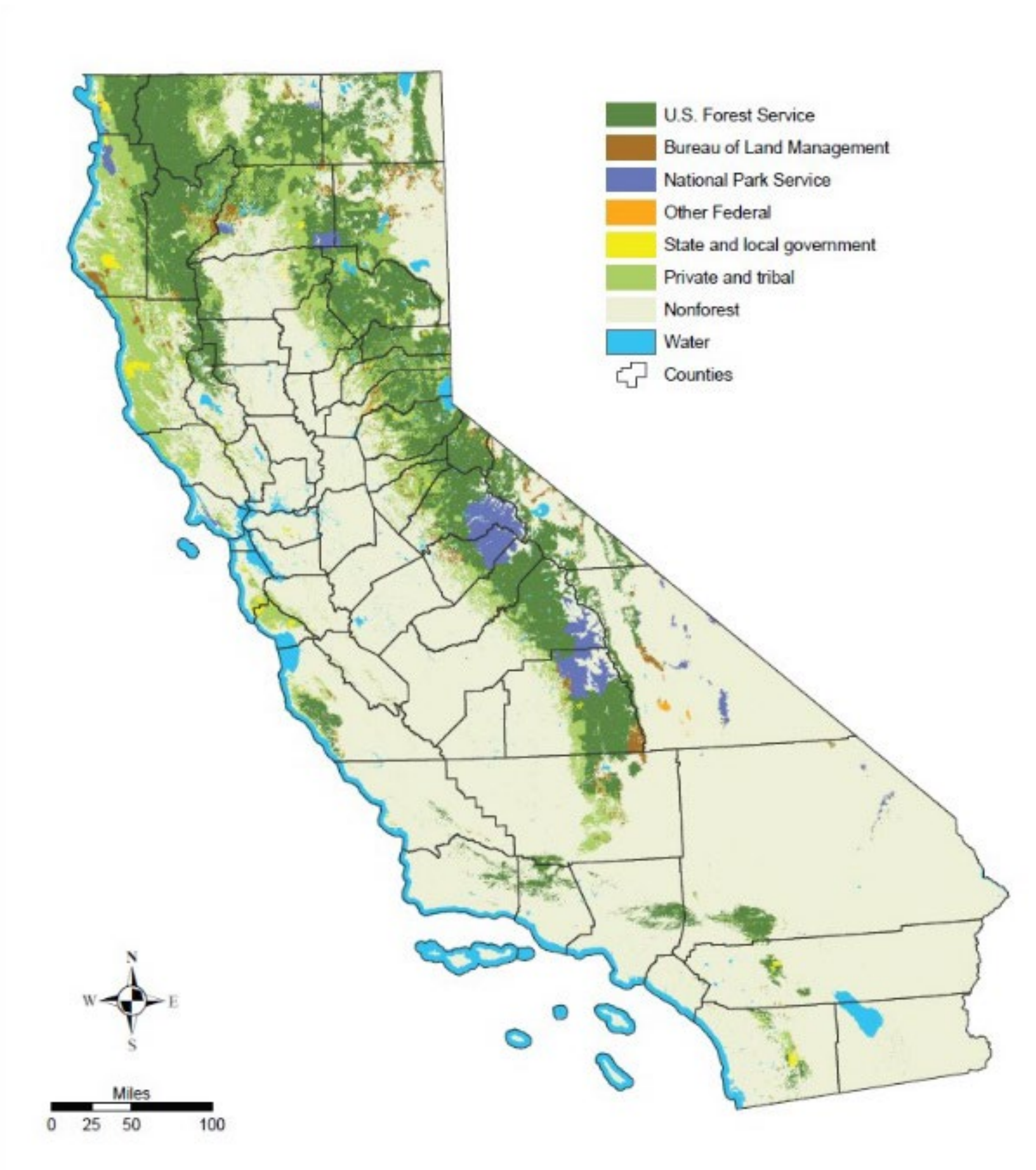

Figure 1: Forestland ownership by ownership category (Fire and Resource Assessment Program 2018)

Predominant land management practices employed in the Western United States over the last 150 years and anthropogenic climate change have altered the composition and range of forests (Williams et al. 2019, Berkey et al. 2021, USFS 2021a, Knight et al. 2022, Sterner et al. 2022, Paudel and

Markwith 2023). Factors such as fire suppression, climate shifts, and land-use changes have rendered mixed conifer forests in Northern California particularly vulnerable to wildfire and loss by type conversion (Coop et al. 2020). Fire suppression in the 20th century allowed conifer species to expand beyond their historical range and encroach on neighboring chaparral patches (Paudel and Markwith 2023). Simultaneously, timber production in the Sierra Nevada produced increasingly dense homogeneous forests (Paudel and Markwith 2023). Fire suppression tactics increased fuel loads and fire potential (Abatzoglou and Williams 2016). The significant increase in wildfire activity Northern California has experienced over the last decade is a direct result of the conditions produced by legacy land management strategies and climate change (Westerling et al. 2006, Williams et al. 2019).

Climate change is a significant driving factor in changes to the fire regimes of Northern California conifer forests (Williams et al. 2019). Fire regimes have deviated far from the historical norm resulting in increased annual area burned, number and frequency of fires, and severity (Skinner and Chang 1996, Stevens-Runmann and Morgan 2016, Stevens-Rumann and Morgan 2019, Williams et al. 2019, Busby et al. 2020). Beginning in the 1980s, California experienced an abrupt regime change from one of infrequent large wildfires of short duration (average of 1 week) to one with much more frequent and longer burning fires (5 weeks) (Westerling et al. 2006). The increase in wildfire activity results from a warmer, drier climate (Williams et al. 2019, Jager et al. 2021). Wildfire season, defined as the time between the discovery of the first wildfire and the extinction of the last, increased by 78 days in the western United States between 1987 and 2003 (Westerling et al. 2006). The relatively rapid increase in annual wildfire has the USFS struggling to maintain enough workforce capacity to effectively implement preventative and regenerative management strategies (USFS 2022a, California Wildfire & Forest Resilience Task Force 2024).

Problem Statement

The uncharacteristically large and severe wildfires occurring in Northern California are overwhelming the evolutionary traits of native species that have adapted to more frequent low-severity fires, resulting in an increased likelihood of forests failing to regenerate naturally on their own. Thus, without proper intervention, California is poised to lose potentially a significant amount of forestland to type conversion (Coop et al. 2020)**.** Many conifer species native to

California exhibit fire-adaptive traits (Coop et al. 2020). These traits include resprouting and germination by heat and smoke, which are advantageous in fire-prone environments (Keeley et al. 2011). In forests with historically frequent and low-to-mixed-severity fire regimes, conifer species like Douglas fir, ponderosa pine, and lodgepole pine have developed fire-adaptive traits and drought tolerance, such as thick bark and shedding of old branches (Busby et al. 2020). Changing fire regimes and climate can compromise forest resilience by overcoming resistance and recovery mechanisms. This can lead to fire-driven forest conversion, where the composition of a forest is altered or transformed to non-forest vegetation altogether (Coop et al. 2020). The vulnerability to conversion is influenced by factors such as fire severity, seed availability, postfire climate, and fire-vegetation feedback (Coop et al. 2020).

Models produced in 2020 for the California Fire and Resource Assessment Program (FRAP) predict that under a high emissions scenario (RCP 8.5), 15 of 31 California tree species will lose 75% or more of their current climatically viable range (Thorne et al. 2017). Some commentators dismiss the use of RCP8.5 because it is considered extreme, alarmist, and misleading (Hausfather and Peters 2020). However, others argue that these criticisms are regrettable and skewed, emphasizing that RCP8.5 is a valuable tool for quantifying physical climate risk, especially over near-to-midterm policy-relevant time horizons (Schwalm et al. 2020). Emissions consistent with RCP8.5 are in close agreement with historical total cumulative CO2 emissions, and RCP8.5 is the best match out to midcentury under current and stated policies (Thorne et al. 2017, Schwalm et al. 2020). It is difficult to predict how climate change will continue to affect forest ecosystems in Northern California, but understanding these dynamics is necessary for the long-term viability of our forests and the ecosystem services they provide humanity.

The impact of climate change on wildfire activity in Northern California has significant implications for reforestation efforts. The increasing frequency and severity of wildfires due to climate change have led to challenges and complexities in post-fire reforestation and ecosystem recovery (Stevens-Runmann and Morgan 2016, Stevens-rumann, Camille S. et al. 2017, Coop et al. 2020). Altered fire regimes due to climate change impact the succession of native plant species after a burn event. Mixed conifer forests often experience poor tree sapling recruitment and regeneration following stand-replacing high-severity wildfires (Sterner et al. 2022). Greater management attention to key abiotic and biotic factors, such as elevation, slope, aspect, and competing vegetation, is required to ensure the revitalization of forests after a severe burn event (Stevens-Rumann and Morgan 2019).

Historically, reforestation after commercial harvest or wildfire has involved planting seedlings grown from locally sourced seeds, known as geographically based reforestation (Findlater et al. 2022). This practice assumes that the seeds will perform well in the environment after replanting (Findlater et al. 2022). However, some species may no longer be viable to replant, given changes in local abiotic conditions (Coop et al. 2020, Hill and Field 2021). Additionally, high-intensity wildfires can cause high levels of tree mortality and soil impacts that result in delayed reforestation (Buchholz et al. 2021). The challenges and complexities associated with post-fire reforestation and ecosystem recovery underscore the need for adaptive and sustainable reforestation strategies in the face of increasing wildfire activity driven by climate change.

Research Significance

The historical management of conifer forests in the Sierra Nevada primarily for timber production altered age structure, density, and species composition (Hessburg et al. 2016). Modern strategies are more holistic and encompass the greater ecosystem. However, challenges remain in quantifying the value of ecosystem services and the effects of management strategies and natural disturbances on these services. The USFS and other agencies have yet to fully evolve their strategies to consistently evaluate and quantify the effectiveness of their land management techniques in protecting or restoring desired ecosystem services. Therefore, this research is critical as it presents a model for quantifying ecosystem services and assessing the impact disturbances and management techniques have on them.

Research Objectives

This paper seeks to provide a comprehensive review of the ecological dynamics of conifer regeneration in the face of climate change and its associated ecosystem services. It also evaluates the USFS's national and regional management strategies aimed at addressing the issue of reforestation. The agency’s existing land management programs and procedures are scrutinized for gaps in ensuring the regeneration of conifer forests against the latest scientific literature. Funding mechanisms for these programs are reviewed to inform whether the relative investment in reforestation, as compared to preventative treatments, is adequate to meet the stated goals of the REPLANT Act. Finally, a geospatial analysis is employed to quantify the impact of wildfire on a conifer forest's regeneration and related ecosystem services. This analysis serves as a model for how the USFS could include ecosystem services as part of their planning and monitoring programs to ensure agency goals are achieved. The insights gleaned from these analyses support the overall objective of this research, which is to evaluate the effectiveness of federal reforestation programs in ensuring the long-term sustainability of California's mixed conifer forests.

Research Questions

Main Research Question: Are USFS reforestation strategies and programs sufficient to ensure the long-term sustainability of mixed conifer forests in the Northern California Sierra Nevada Mountains?

Sub-Questions:

a. How is climate change affecting the fire regimes of northern California's mixed conifer forests?
b. What impacts do altered fire regimes have on conifer forests?
c. How may geospatial technology be utilized to improve the effectiveness of reforestation programs?
d. What ecosystem services do conifer forests provide humanity? Is it possible to quantify the ecosystem services provided by these forests via remote sensing?
e. What management strategies are most effective at successful conifer regeneration and recovery?
f. How can the USFS scale its reforestation programs to meet the objectives as mandated in the REPLANT Act?

Research Design

This paper employs three analytical methods to answer the research questions: literature review, policy and program evaluation, and geospatial analysis. First, the literature review seeks to answer the fundamental questions that underpin the shifting dynamics of conifer forest regeneration because of historical management strategies and anthropogenic climate change. Then, a policy evaluation of federal reforestation programs scrutinizes the USFS's reforestation strategy and post-wildfire restoration and recovery programs. Funding mechanisms for these programs are also reviewed. Finally, a geospatial analysis of a specific fire quantifies the impact a severe wildfire has on the regeneration of a mixed conifer forest in Northern California and its associated ecosystem services. USFS restoration and reforestation management techniques applied in the immediate aftermath of the fire are evaluated for their effectiveness in ensuring regeneration and maintenance of ecosystem services. The final product of this analysis will be made public and data accessible so that other interested parties may replicate the analysis.

Literature Review

Introduction

This literature review delves into the nuances of climate change and wildfire activity in the Sierra Nevada, the consequent effects on mixed conifer forests, and the critical ecological and management aspects of resilience and regeneration within these ecosystems. A particular emphasis is placed on evaluating the reforestation programs implemented by USFS and the adaptive management strategies being developed in response to these unprecedented environmental challenges.

Climate change in the region is driving altered precipitation patterns, increased temperatures, and a higher incidence of extreme weather events, setting a complex stage for ecological shifts (Westerling et al. 2006, Abatzoglou and Williams 2016, Thorne et al. 2017). These climatic changes directly influence the vitality and composition of mixed conifer forests, which are crucial for biodiversity, carbon storage, and water supply (Stewart, William et al. 2016). As these forests face heightened stress from changing climatic conditions and increasingly severe wildfires, understanding their resilience and capacity for regeneration becomes paramount. This review critically examines the most relevant literature on how mixed conifer forests adapt to and recover from climate-induced disturbances, focusing on natural regenerative processes and the ecological underpinnings of forest resilience.

Land Management, Climate Change and Fire Regimes

The history of California's forests is detailed and multifaceted, characterized by extensive human interventions and natural dynamics spanning over a century. The initiation of widespread logging activities dates to the mid-19th century, driven primarily by the demands of the Gold Rush (Stewart, William et al. 2016). This period saw the establishment of the first sawmills in the Sierra Nevada, which were essential to support the construction needs of rapidly growing cities and mining operations (Stewart, William et al. 2016). In the post-World War II era, economic expansion led to an increase in timber production. This period also marked the onset of regulated forest management practices, reflecting growing environmental awareness and the consequent implementation of policies aimed at preserving wildlife habitats and maintaining ecological balance (Stewart, William et al. 2016). By the late 20th century, forest management practices had evolved significantly. The establishment of public forest reserves and the introduction of stricter logging regulations underscored a shift towards more sustainable management practices (Rep. Melcher 1976, North et al. 2019, Knight et al. 2022). In recent years, the emphasis has further shifted towards sustainable practices, characterized by reduced harvest volumes and the strategic maintenance of a mix of forest ages to support diverse ecosystems (Stewart, William et al. 2016, Balloffet and Dumroese 2022). Private lands now significantly contribute to timber outputs, effectively balancing economic objectives with ecological sustainability (Christensen et al. 2016). Management of California's timberlands today is not solely focused on wood production but also encompasses their critical roles in biodiversity protection, carbon sequestration, and water regulation (Shaheen et al. 2021, Balloffet and Dumroese 2022, California Wildfire & Forest Resilience Task Force 2024). The various management regimes—private, public, and reserved—each play a distinct role in contributing to these ecological services (Birch et al. 2010, de Groot et al. 2010, Shaheen et al. 2021, Balloffet and Dumroese 2022, Knight et al. 2022, California Wildfire & Forest Resilience Task Force 2024). The current challenges in timberland management include sustaining economic viability while enhancing ecological functions (Tallis and Polasky 2009, de Groot et al. 2010). Innovations in forest management, such as the integration of advanced technologies and more comprehensive ecological monitoring, continue to develop in response to these challenges.

Climate change is profoundly influencing fire regimes in Northern California, where increasing temperatures and altered precipitation patterns have led to more frequent, intense wildfires, particularly in historically wetter, forested regions. This trend began in the mid-1980s and has been characterized by longer wildfire durations and extended seasons, escalating both the frequency and severity of fires across the western United States (Westerling et al. 2006, Westerling and Bryant 2007, Swain 2021). Projections suggest that large wildfires, exceeding 10,000 hectares, may become 50% more frequent by the century's end due to climate change, population growth, and development (Xu et al. 2022).

In response to these changes, the mixed conifer forests of the Sierra Nevada are undergoing significant ecological shifts. The historical fire regime of these forests, characterized by frequent low to moderate severity fires primarily ignited by lightning, is being replaced by conditions that favor increased fire severity and size, impacting species richness, cover, and the broader landscape heterogeneity (Skinner and Chang 1996, Amacher et al. 2008, Paudel and Markwith 2023). These shifts in fire dynamics are occurring alongside declines in tree growth and health, heightening susceptibility to threats such as bark beetle outbreaks and potentially leading to a conversion of forests to grasslands or shrublands, which would entail substantial losses in carbon storage, wildlife habitat, and economic value (Battles et al. 2007, Meng et al. 2015, Wayman and Safford 2021).

The increasing frequency and intensity of wildfires, driven by climate variables such as vapor pressure deficit, temperature, and fuel flammability, necessitate a reevaluation of forest management and conservation strategies. Particularly concerning is the potential for fire-driven forest conversion, where major shifts in species and forest functions occur following high-severity fires, often exacerbated by insufficient seed sources and warmer, drier post-fire conditions (Coop et al. 2020, Chen et al. 2021). The adaptive management strategies required must account for these dynamic conditions, focusing on maintaining the ecological integrity and resilience of these forests to ensure they continue to provide essential ecosystem services (Miller et al. 2008, Fertel et al. 2022). This entails a comprehensive approach to managing fire regimes and forest health, characterizing vulnerability to conversion, providing plausible scenarios of post-fire ecological futures, and assessing the feasibility of managing or directing these conversions to mitigate ecological and social consequences.

Impact on Forest Ecosystems

The resilience and regenerative capacity of mixed conifer forests in the Northern California Sierra Nevada are increasingly challenged by a changing climate and heightened wildfire activity. This vulnerability is highlighted by a marked decline in post-fire tree regeneration, attributed to more severe annual moisture deficits and increasingly unfavorable growing conditions, which threaten the transition of dry forests at the climatic tolerance edge to non-forested landscapes (Meng et al. 2015, Stevens-rumann, Camille S. et al. 2017). Tree regeneration varies by elevation, species, and proximity to seed sources, which are crucial for seedling establishment, especially under the constraints of water stress and competition (Stevens-Rumann and Morgan 2019).

The impact of forest management practices, particularly those aimed at enhancing resilience to wildfires and climate change, is also under scrutiny. During the extreme drought conditions of 2012-2015 in California the constraints associated with these treatments may limit their ability to bolster forest resilience, as interventions appeared unaffected by tree mortality (Lydersen 2019). Recovery trajectories in areas affected by repeated wildfires show that low-severity fires tend to maintain an open forest structure, whereas areas with repeated high-severity fires might transition to non-forested cover types, indicating that the order of burn severity significantly influences post-fire forest characteristics (Stevens-Runmann and Morgan 2016).

Moreover, the mixed conifer forests are experiencing significant impacts on their ecosystem services due to increased fire severity, drought conditions, and interactions between bark beetle outbreaks and wildfires. These disturbances disrupt post-fire recovery, impacting crucial ecosystem services such as carbon sequestration and habitat provision. Fire and mechanical fuel treatments also affect small mammal populations, which are vital for seed dispersal and overall ecosystem health, thus influencing the provisioning of ecosystem services (Amacher et al. 2008, Wayman and Safford 2021).

The regeneration of conifer species post-wildfire is influenced by a variety of factors beyond burn severity. One of the primary determinants is the distance to seed sources, as seed availability is crucial for successful regeneration. Conifer regeneration heavily depends on the availability of seeds from nearby mature trees (Stevens-Rumann and Morgan 2019). The proximity to these seed sources significantly influences the density and success of seedling establishment (Stevens-Rumann and Morgan 2019). Regeneration markedly declines at increased distances from living seed sources, demonstrating the importance of spatial proximity to seed-bearing conifers for effective forest recovery (Stevens-Rumann and Morgan 2019). Tree regeneration density decreases significantly at distances ranging from 40 to 400 meters from a living mature tree, highlighting the critical role of seed source proximity regardless of the dominant conifer species present (Stevens-Rumann and Morgan 2019). Additionally, short intervals between fires has resulted in a decline in post-fire tree regeneration compared to once-burned areas (Stevens-Rumann and Morgan 2019).

The local climate, including factors such as precipitation patterns and temperature, plays a crucial role in conifer regeneration (Davis et al. 2018). Both historical and post-fire climatic conditions can influence moisture availability and temperature, which are critical for the survival and growth of conifer seedlings (Davis et al. 2018). Changes in these climatic factors, especially due to global warming, can alter the regeneration dynamics of conifer forests (Davis et al. 2018). Topographical features and soil conditions also contribute to the regeneration process by affecting local microclimates, which in turn influence seedling survival and growth (Shive et al. 2018). These factors include the physical landscape's slope and soil properties, which can modify microclimates around the seedlings (Shive et al. 2018). The physical characteristics of the landscape, such as slope, elevation, and soil properties, affect microclimates that in turn influence conifer regeneration (Shive et al. 2018). These topographic factors can create varying microenvironments that support different rates and patterns of forest recovery (Shive et al. 2018). For example, aspects and elevations that retain more moisture can be more conducive to regeneration. Other environmental variables, like elevation, can influence moisture and temperature conditions, which are vital for the establishment and survival of conifer seedlings (Kemp et al. 2015). These gradients can determine the distribution and abundance of conifer species across different areas within a forest (Kemp et al. 2015).

Given these complex interactions between abiotic and biotic conditions and the pressing need for nuanced forest management strategies, land managers must efficiently use resources by planting tree seedlings in large, high-severity burned patches while implementing preventative strategies to mitigate and limit large, high-severity burns. Such management practices are crucial for sustaining the ecological integrity and resilience of mixed conifer forests in the face of an uncertain future, ensuring the continued provision of essential ecosystem services and maintaining forest health and biodiversity (Collins and Roller 2013, Steel et al. 2022).

Reforestation Management Challenges

Forest Regeneration Methods encompass two primary approaches: Natural and Artificial Regeneration. Natural Regeneration allows a site to regrow without human intervention to improve site conditions or direct the trajectory of succession (Nunamaker and Valachovic 2007). This method depends on adequate seed production, successful germination, and seedling growth, which are all influenced by weather, site conditions, competition between species, predation, and chance (Nunamaker and Valachovic 2007, USFS 2021a). It is generally the least expensive option but is not always the most reliable and may result in a forest with an undesirable species composition. On the other hand, Artificial Regeneration involves deliberate efforts to regenerate a stand, typically through sowing seeds or planting seedlings (Baldwin et al. 2021). The standard method in California involves planting nursery-grown seedlings, which allows for control over spacing, species selection, and genetic composition (Nunamaker and Valachovic 2007, USFS 2021a, California Wildfire & Forest Resilience Task Force 2024). This method is particularly useful when natural regeneration is not feasible or yields unacceptable results. Artificial regeneration can be employed to ensure a desirable species composition, establish a stand with superior genetic traits, or enhance the survival chances of young trees in adverse environmental conditions (Nunamaker and Valachovic 2007, USFS 2021a, Knight et al. 2022).

Ecological restoration in fire-affected areas often requires managing for resilient forests that can adapt to future fires and climate conditions. This includes considering future ecological conditions and forest community structures in reforestation planning. Seed supply is also a critical factor, with a need for adequate seed production and genetically appropriate materials to support diverse and resilient forest regeneration (Nunamaker and Valachovic 2007). The reforestation pipeline in California encompasses a series of systematic steps crucial for restoring forest ecosystems, particularly in areas impacted by severe wildfires, pest infestations, and other disturbances that inhibit natural regeneration (Balloffet and Dumroese 2022, USFS 2022a, California Wildfire & Forest Resilience Task Force 2024). However, scaling this program faces several significant challenges. In 2020, total statewide seedling production was 28 million seedlings (California Wildfire & Forest Resilience Task Force 2024). It would take 14 years at the current rate of production to propagate enough seedlings to reforest al of the ~1.5 million acres of postfire reforestation need generated by the 2019-2021 wildfire seasons, with no capacity to address needs generated prior to the 2019 fire season or those resulting from future fires (California Wildfire & Forest Resilience Task Force 2024). Firstly, there is a pronounced capacity shortage within the state's forestry sector, which affects all stages of the reforestation process (Shaheen et al. 2021, Balloffet and Dumroese 2022, California Wildfire & Forest Resilience Task Force 2024). Additionally, financial constraints are prevalent, with inconsistent funding and insufficient financial resources hindering the ability to maintain ongoing reforestation efforts, especially for non-industrial landowners (California Wildfire & Forest Resilience Task Force 2024). Regulatory hurdles also pose significant barriers; while compliance with environmental regulations is essential, it often leads to delays and increases project costs (California Wildfire & Forest Resilience Task Force 2024). Biological and ecological challenges include issues like inadequate seed supply and the impacts of climate change on seed viability, which complicate seedling growth and survival in post-fire landscapes (California Wildfire & Forest Resilience Task Force 2024). Lastly, the existing infrastructure for nursery production is inadequate to meet the increasing demand for seedlings needed for extensive reforestation efforts (California Wildfire & Forest Resilience Task Force 2024).

The Forest Service faces a significant backlog of areas needing reforestation due to a lack of adequate resources (California Wildfire & Forest Resilience Task Force 2024). This issue has been somewhat addressed by the REPLANT Act, which aims to significantly boost funding by removing the cap on the Reforestation Trust Fund (Shaheen et al. 2021). The act supports the planting of 1.2 billion trees over ten years to cover nearly 4.1 million acres (Shaheen et al. 2021).

Wildfire alone causes 80% of reforestation needs on NFS lands. In 2020 and 2021, more than 2.5 million acres of NFS lands burned with high severity (Balloffet and Dumroese 2022). In addition to the 1.5 million acres, the USFS has already been identified as in need of active reforestation treatment (Balloffet and Dumroese 2022). The rapid escalation of major disturbances on NFS has outpaced the agency's capacity to treat the land as necessary (Balloffet and Dumroese 2022). Over the last decade, only 6% of the post-wildfire reforestation activities identified by the USFS were implemented (Balloffet and Dumroese 2022).

Geospatial Technology and Decision Support Tools

The Forest Service is tasked with integrating the best available science and technology to improve the efficiency and effectiveness of reforestation efforts (USFS 2021b, Balloffet and Dumroese 2022). This includes developing and applying new methodologies and tools for assessing reforestation needs and monitoring progress. There is also an emphasis on collaborative strategies and cross-boundary management to address the landscape-scale nature of forest ecosystems (USFS 2021b).

The Forest Service has already developed a suite of tools to help their staff plan effective management strategies including the forest management tool, Forest Vegetation Simulator (FVS). Its primary use cases include managing forest growth by predicting forest stand dynamics under different management scenarios, evaluating the impacts of management practices on forest composition and structure, estimating wildfire hazards, and assessing potential losses due to fires or pest outbreaks (Dixon 2024). FVS calculates forest regeneration through a detailed model that involves several options depending on the specific variant of the simulator being used (Dixon 2024). Some variants employ a full establishment model that actively models the densities of regeneration under various conditions (Dixon 2024). This includes options to manage ingrowth, sprouting, and the automatic tallying of new growth. The model enables users to specify whether natural regeneration or planting is simulated, and it can adjust for site-specific factors like species growth rates and environmental conditions (Dixon 2024). Other variants may use a partial establishment model where the user must input regeneration data (Dixon 2024). In both cases, detailed descriptions of the regeneration process must be specified in the model inputs to accurately simulate forest dynamics (Dixon 2024).

The USDA California Climate Hub also provides interested parties with access to a handful of geospatial decision support tools that are helpful in identifying priority areas for reforestation treatments and seed sourcing (USDA California Climate Hub). One such tool is the Forest Regeneration after Disturbance (PostCRPTool), which helps predict and understand forest recovery scenarios to inform reforestation strategies (USDA California Climate Hub). The Post-fire Restoration Prioritization Tool (PReP Tool) assists in allocating restoration resources efficiently by evaluating areas based on ecological and community risks (USDA California Climate Hub). The Climate-wise Reforestation Toolkit addresses the extensive tree mortality during the 2012-2016 California drought by providing resources for reforestation prioritization and assessing post-drought stand conditions (USDA California Climate Hub).

Additionally, the PReSET Reforestation Tool is designed for areas severely affected by wildfires, estimating the success rates of various reforestation strategies based on local conditions (USDA California Climate Hub). The Climate-adapted Seed Tool (CAST) and the Seedlot Selection Tool both focus on selecting seed sources that are resilient and adapted to current and future climatic conditions, ensuring long-term sustainability of reforestation efforts (USDA California Climate Hub). Finally, the Reforestation Hub offers an interactive map that provides data on potential new forest areas and their carbon storage capacities, supporting strategic planning for reforestation projects (USDA California Climate Hub). These tools collectively provide a comprehensive approach to reforestation that considers climate impacts, ecological data, and targeted restoration strategies, making them essential for resource managers.

Program and Policy Evaluation

Introduction

The resilience and regeneration of mixed conifer forests post-wildfire are of significant concern to the USFS, requiring the implementation of effective land management strategies. These strategies are designed to improve forest health, biodiversity, and ecosystem services, especially with the rising frequency of wildfire disturbances (USFS 2022a). The urgency to address these threats through effective reforestation efforts is greater than ever.

The importance of this analysis lies in its potential to influence policy and operational directions. Effective forest management and reforestation are not only critical for ecological health but also for the economic stability of regions dependent on forest goods and services. Moreover, these forests are integral to fire management strategies that protect human communities from devastating wildfires, which have become increasingly frequent and severe in recent years. Ultimately, this paper aims to provide a comprehensive overview of the state of reforestation efforts in the Sierra Nevada, offering valuable insights and recommendations that could guide policymakers, stakeholders, and practitioners in enhancing the resilience and sustainability of these critical ecosystems. The findings and recommendations will also be relevant to similar mixed conifer forest regions across the United States, contributing to broader national discussions on forest management and climate adaptation strategies.

Analysis of Current Policies

Federal reforestation policy is influenced by several major bills: the National Environmental Policy Act (NEPA), the National Forest Management Act of 1976, and the Repairing Existing Public Land by Adding Necessary Trees (REPLANT) Act 2021. The National Forest Management Act established many important federal natural resource programs, planning, and reporting processes. It specifically mandates prompt reforestation of disturbed forestland (Rep. Melcher 1976). The National Forest Management Act (NFMA) encompasses various stipulations concerning reforestation within the National Forest System. Key mandates include the maintenance of lands in "appropriate forest cover" as specified in 16 U.S.C. 1606 Sec. 4(d)(1), and the application of "sound silvicultural practices" according to 16 U.S.C. 1606 Sec. 6(m)(1). Additionally, the Act emphasizes the need for these lands to "provide for a diversity of plant and animal communities" (16 U.S.C. 1604 Sec. 6(g)(3)(B)). It also requires that reforestation surveys be conducted and reported in the first and third years following a reforestation effort. While the NFMA mandates prompt reforestation after timber harvests, it does not require the same following wildfires (California Wildfire & Forest Resilience Task Force 2024).

The National Environmental Policy Act (NEPA) plays a significant role in guiding the U.S. Forest Service's post-fire rehabilitation strategies (Broussard and Whitaker 2009). NEPA requires the U.S. Forest Service to assess the environmental consequences of their proposed actions, leading to more robust methods for evaluating risks associated with different forest management practices (Fairbrother and Turnley 2005). Under NEPA, the U.S. Forest Service prepares the most Environmental Impact States of any federal agency (Broussard and Whitaker 2009).

The REPLANT Act was signed into law as part of the landmark Infrastructure Investment and Jobs Act of 2021. The act provides a clear mandate for the USFS to address reforestation needs on national forest lands and increases the amount of funding for this issue. The act removes the cap on the Reforestation Trust Fund, effectively increasing funding from $30 million to $123+ million by directing all wood product tariffs to the fund (Shaheen et al. 2021). The USFS is directed to develop a 10-year plan and cost estimate to address the backlog of replanting needs on national forest lands by 2031 (Balloffet and Dumroese 2022). Notably, the bill specifically prioritizes forestland that is unlikely to naturally regrow on its own. The primary objective of the REPLANT Act is to reforest 4.1 million acres of land by planting 1.2 billion trees over a 10-year period (Shaheen et al. 2021). However, the amount of land on backlog grows yearly with subsequent wildfires. The Forest Service acknowledges that professional capacity and staffing shortages are significant limiting factors in enacting the mandated 10-year plan (Balloffet and Dumroese 2022). As defined by the USFS, the management problem was born out of two decades of sharp declines in Forest Service harvest and reforestation activity alongside a 40% reduction in the workforce, which impacted the agency's ability to monitor and report on forestlands and substantial increase in wildfire activity (Balloffet and Dumroese 2022). The agency clearly states a need for an increase in the number of non-fire professionals within the Forest Service to work on reforestation and early stand tending as well as administrative tasks (e.g. HR, finance, engineering, etc.) (Balloffet and Dumroese 2022). The Forest Service must also comply with several Congressional reporting mandates. The REPLANT Act may contribute to improved and timely data collection, analysis, interpretation, planning, and implementation of reforestation activities.

As mandated by the REPLANT Act, The Forest Service published a National Reforestation Strategy in 2022 to address the backlog of reforestation needs on National Forest System (NFS) lands and to prepare for future needs (USFS 2022a). The strategy outlines goals, objectives, and an overall framework for tackling the issue of reforestation but does not provide specific actions. National and regional 10-year implementation plans are still being developed. Reforestation programs conduct activities including planting, seeding, and other activities that promote the natural regeneration of forests. Over the last 5 fiscal years, the USFS has reforested, on average, 190,000 acres every year, with 60,000 related to tree planting and the remaining 130,000 covering other activities (USFS 2022a). However, there is conflicting information on the amount of being treated every year. According to the California Wildfire & Forest Resilience Task Force, between 2010 and 2020, the USDA Forest Service (USFS) reforested an average of 11,646 acres per year (California Wildfire & Forest Resilience Task Force 2024). Furthermore, the treatment of acres impacted by high-severity fires decreased over a five-year period (36.6% between 2010 and 2014 compared to 7.8% between 2015 and 2020) (California Wildfire & Forest Resilience Task Force 2024). Regardless, treating less than 200,000 acres every year is not sufficient to address the over 3,000,000 acres mandated by the REPLANT Act.

The Forest Service's strategic vision is to reforest at "the right place, at the right time, with the right species, and at appropriate scales" (USFS 2022a). Guiding principles include (1) leading with science and technology, (2) strengthening internal resources and capacity, and (3) partnering and collaborating to accelerate and amplify success. These principles are in line with the stated needs of the Forest Service, which is primarily related to developing a skilled internal workforce and establishing partnerships where the site is necessary to scale reforestation activities. Traditional approaches to reforestation, including grid planting, are not efficient or scalable enough to address the current backlog (USFS 2023). Therefore, the Forest Service must adopt new technologies and science to meet its objectives. The 2022 strategy outlines six goals ranging from defining specific needs, specifying shared agency and partnership priorities, and expanding the capacity of their workforce.

Goal One. The first goal emphasizes the importance of promptly assessing and reporting reforestation needs following disturbances (USFS 2022a). The Forest Service leverages a robust array of existing assessments and reporting procedures, highlighting the potential to enhance these through the timely evaluation of impacts on ecosystem services. Additionally, the strategy mentions CALFIRE's Fire and Resource Assessment Program (FRAP), which conducts comprehensive inventories of California rangelands periodically. The document recognizes the complexities involved in determining whether a forest will recover naturally and suggests that remote sensing and new technologies could improve assessment efficiency.

Goal Three. This third goal addresses the need to expand reforestation workforce capacity, seed production, nursery capacity, and related infrastructure (USFS 2022a). It specifically notes that seedling production must quadruple to meet growing reforestation demands, underlining the scale of increase required to sustain effective reforestation efforts (USFS 2022a). The reforestation pipeline represents maybe the most substantial bottleneck for the Forest Service and its partners to scale (California Wildfire & Forest Resilience Task Force 2024). All the resources already dedicated to analysis, planning and monitoring are worth very little without a supply of scientifically informed seeds or saplings to plant on-site.

Goal Four. Through Objective 4C, goal four advocates for the use of innovative approaches to scale up reforestation efforts and enhance monitoring systems (USFS 2022a). It underscores the necessity to continue acknowledging the variety of ecosystem services provided by forested landscapes in reforestation planning (USFS 2022a). Additionally, the strategy points to adaptive management as essential for long-term success, relying on continuous monitoring to adapt and refine reforestation practices over time (USFS 2022a).

Goal Five. Goal five stresses the inclusion of future forest management activities, such as stand tending, in the design of reforestation projects (USFS 2022a). It details specific actions like thinning and prescribed fires, which are crucial for developing the desired canopy structure and species composition (USFS 2022a). These practices are vital for both naturally regenerating forests and those requiring assisted regeneration.

Published in 2015, the USFS Region 5 leadership team outlined the high-level intentions before their land management strategies (USFS 2015). Although now almost 5 years old, the intentions speak to the long-term commitment of the Forest Service to enhancing the ecological resilience and sustainability of forestlands in the Pacific Southwest Region. The leadership intent emphasizes the importance of maintaining ecological resilience to ensure that ecosystems can adapt to natural disturbances and threats, which are increasingly exacerbated by climate change and human activity (USFS 2015). A key component of the strategy is the commitment to the sustainable delivery of ecosystem services, including but not limited to water and air purification, climate regulation, and biodiversity conservation (USFS 2015). Specifically, regarding reforestation, the intent mentions the importance of reforesting areas affected by wildfires as a critical aspect of the restoration strategy. This includes implementing suitable stand maintenance activities that are aligned with project goals and site conditions to ensure the retention and sustainability of forest resources and carbon sequestration over the long term (USFS 2015).

Review of Funding Mechanisms

Reforestation efforts on federal lands in the Sierra Nevada benefit from a robust combination of federal funding, private investments, and non-profit contributions (U.S. Senate Committee on Appropriations 2024). Each year, Congress allocates funding to the Forest Service for various activities, including forest management, rehabilitation, and reforestation (U.S. Senate Committee on Appropriations 2024). This funding is part of the federal budget process and is subject to approval by both the House and Senate. As part of the Fiscal Year 2024 Appropriations, the Wildfire Suppression Operations Reserve Fund was allocated $2.65 billion to ensure the Forest Service and the Department of the Interior have sufficient resources when fire activity exceeds the usual suppression funding (U.S. Senate Committee on Appropriations 2024). This is critical for managing large-scale fire events on federal lands (U.S. Senate Committee on Appropriations 2024).

Key federal initiatives include the Infrastructure Investment and Jobs Act (H.R. 3684, Public Law 117–58), which allocates $225 million over five years for burned area recovery projects on National Forests and an additional $400 million to the Department of Interior for ecosystem restoration projects on both public and private land (California Wildfire & Forest Resilience Task Force 2024). The REPLANT Act, integrated within the same legislative framework, significantly increases the resources available by removing the annual cap on the Reforestation Trust Fund, directly impacting reforestation efforts on National Forest System lands (Shaheen et al. 2021). The Restoration Trust Fund is specifically designated for reforestation and rehabilitation efforts on National Forest lands. It is primarily funded through a portion of the receipts from timber sales, certain import duties, and other dedicated sources (California Wildfire & Forest Resilience Task Force 2024). The fund is used to plant trees, improve forest health, and restore ecosystems affected by fires, insects, and diseases. The USDA Farm Service Agency Emergency Forest Restoration Program also supports forest health restoration across these federal territories following natural disasters (California Wildfire & Forest Resilience Task Force 2024).

Figure 2: General timeline of main USFS post-fire recovery processes (USFS 2022b)

Adding to these federal efforts, private investments and non-profit contributions play crucial roles. Sierra Pacific Industries, with financial support from CAL FIRE, is setting up a new nursery in Siskiyou County (California Wildfire & Forest Resilience Task Force 2024). This facility is expected to produce millions of seedlings each year, significantly enhancing the reforestation capacity in the region, including federal lands (California Wildfire & Forest Resilience Task Force 2024). Furthermore, the non-profit organization American Forests collaborates with CAL FIRE and the US Forest Service through the California Reforestation Pipeline Partnership. This initiative aims to streamline and accelerate reforestation processes, addressing various challenges and ensuring effective recovery and management of forest ecosystems (California Wildfire & Forest Resilience Task Force 2024). Together, these diverse funding streams and partnerships facilitate a comprehensive approach to managing and restoring forest health on federal lands in the Sierra Nevada.

Evaluation of Forest Service Programs

Emergency Response Programs

Within the first three years after a fire, the Forest Service adheres to a post-fire recovery program dictated by strict implementation timelines and systematic emergency assessments. After three years, local authorities manage the long-term rehabilitation of burned areas. The damages resulting from wildfires are addressed in stages: suppression repair, emergency stabilization, rehabilitation, and restoration and recovery. Burned Area Emergency Response (BAER) is the first major assessment to occur once a fire is extinguished (USFS 2022b). Burned Area Emergency Response (BAER) is a program used by various U.S. federal agencies, including the Forest Service, to rapidly assess and respond to post-wildfire conditions with the goal of protecting life, property, and critical natural and cultural resources (USFS 2021a). The BAER program focuses on emergency stabilization rather than long-term recovery, aiming to manage immediate threats posed by land conditions following a wildfire. A Burned Area Report is a rapid assessment of burned watersheds by a cross-functional Rapid Assessment Team (RAT). The intention is to identify post-wildfire threats to human life, safety, property, infrastructure, and critical natural or cultural resources on federal lands. BAER is also responsible for implementing emergency soil stabilization treatments before the next major storm. Importantly, forests have one year after containment to implement BAER treatments with available funding. Treatments BAER might apply to a burned landscape include mulching, seeding, installation of erosion and water run-off control structures along roads and trails, temporary barriers to protect recovering areas, removal of dangerous debris or other safety hazards, and installation of warning signs.

The next program to take effect is the Burned Area Rehabilitation (BAR) program. The Burned Area Rehabilitation (BAR) program is an initiative by the U.S. Forest Service designed to restore natural landscapes that have been affected by wildfires. The program focuses on immediate post-fire actions intended to protect soil from erosion, repair damaged plant systems, prevent invasive plant species from entering the area, and restore habitats suitable for wildlife. The BAR program operates under the guidelines set by the National Environmental Policy Act (NEPA), ensuring that all rehabilitation activities are conducted with consideration for environmental impacts and with opportunities for public input and involvement. BAR processes are not focused on emergency actions critical to human safety and infrastructure. Actions implemented under this program must be taken within three years of wildfire containment. BAR treatments intend to repair or improve lands unlikely to recover naturally or repair/replace minor infrastructure and facilities. Actions include restoring burned habitat, reforestation, planting and seeding, replacing burned fences, interpreting cultural sites, treating noxious weed infestations, and installing signs.

Post-Fire Restoration Framework

The USFS recognized that it has relied on conventional land management techniques and that to meet management objectives, a new framework for post-fire management must be developed that takes a more holistic approach to environmental management (USFS 2021a). Historically, environmental stressors such as fire suppression practices, coupled with anthropogenic impacts and climate variations, have led to significant ecological alterations (Stevens-rumann, Camille and Morgan 2016, Abatzoglou and Williams 2016, Stevens-Rumann and Morgan 2019). These include shifts in disturbance regimes that have escalated the frequency and severity of wildfires, necessitating a reassessment of forest management and restoration practices (Skinner and Chang 1996, Abatzoglou and Williams 2016).

Moreover, forest managers are tasked with reconciling multifaceted and occasionally divergent objectives ranging from public safety to biodiversity conservation (USFS 2021a). Traditional frameworks may not effectively integrate these goals within the current environmental context. There is an increasing emphasis on ecological restoration aimed at enhancing ecosystem services like carbon sequestration, water purification, and habitat conservation (de Groot et al. 2010, Vogler et al. 2015, Fernandez et al. 2023). Additionally, the framework seeks to adapt to climatic changes that influence fire regimes and forest ecosystems (USFS 2021a). Incorporating the latest scientific research and aligning it with practical management strategies is fundamental to ensuring that restoration efforts are grounded in empirical evidence and are responsive to ecological dynamics (de Groot et al. 2010). The framework is designed to guide the restoration of terrestrial ecosystems post-wildfire, focusing on long-term sustainability and ecological integrity (USFS 2021a). It entails a reevaluation of conventional management goals, the integration of scientific insights into practical applications, and an adaptation to ongoing environmental transformations, particularly those driven by climate variability (USFS 2021a).

General Technical Reports (GTRs) are publications that address a wide range of topics related to forest management, ecology, and conservation. These reports provide detailed information, research findings, and guidance on various aspects of forestry, aimed at supporting forest managers, researchers, and policymakers in their work (USFS 2021a). In the context of the North Complex fire, a General Technical Report (GTRs) was published that analyzed the North Complex fire in the context of other recent fires in the area utilizing this post-fire restoration framework. This GTR270 assessment did go as far as to recommend specific actions for the burn sites included in the analysis, rather its purpose was solely to identify areas in which to prioritize restoration activities (Bovee 2022).

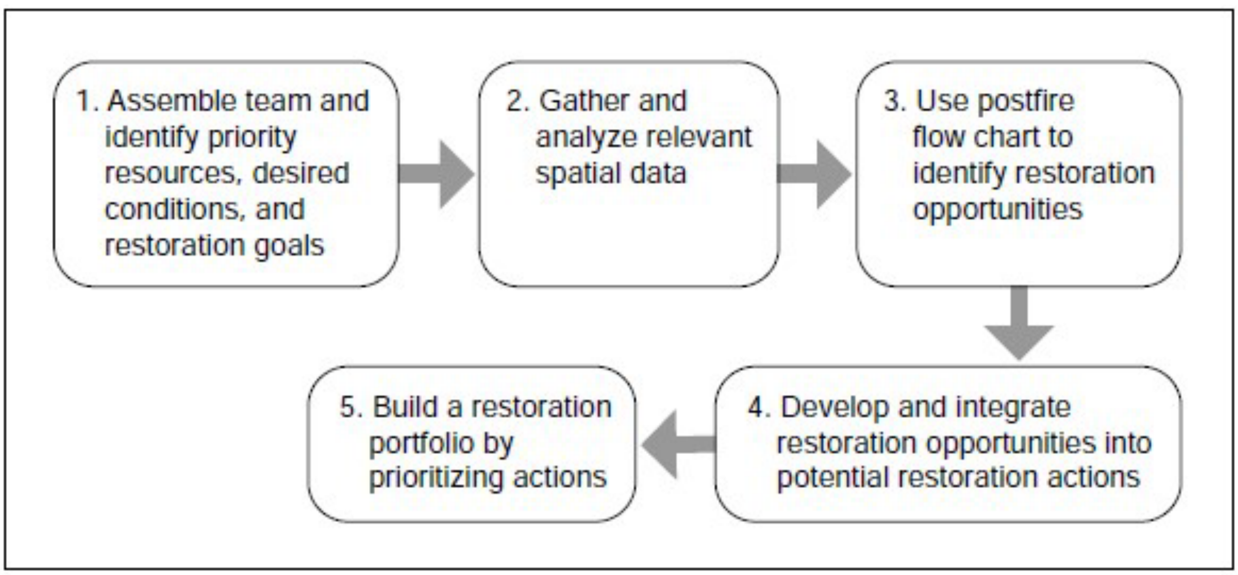

Figure 3: Process diagram from the USFS postfire restoration framework (USFS 2021a)

The process outlined in this framework consists of five stages, which are (1) assembling a team and identifying priority resources and desired conditions, (2) gathering and analyzing relevant spatial data (see chapter 3), (3) using a postfire flowchart to identify restoration opportunities, (4) developing and integrating a list of potential management actions that take advantage of these

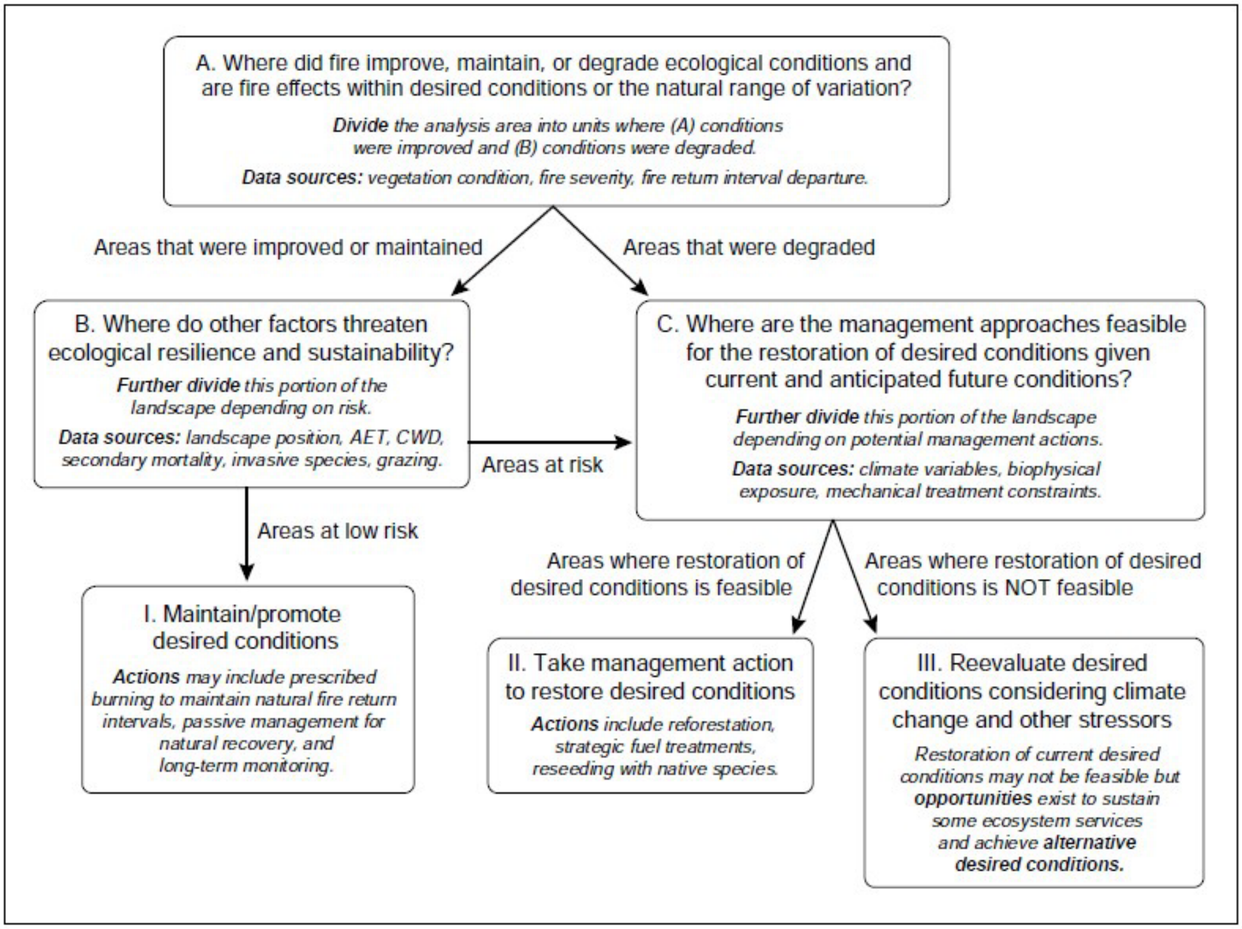

Figure 4: postfire flowchart from USFS postfire restoration framework representing step three of the process diagram in figure 3 (USFS 2021a)

opportunities, and (5) building a portfolio of potential restoration actions and prioritizing these actions based on timing, feasibility, opportunity cost, and level of integration (USFS 2021a). The initial step involves assembling a multidisciplinary team of specialists who bring diverse expertise to the restoration effort (USFS 2021a). In the second step, the team collects and analyzes relevant spatial and non-spatial data to assess the current condition of the ecosystem and predict future conditions (USFS 2021a). Then, using the information and insights gained from the data analysis, the team uses a structured decision-making tool, in the form of a flowchart, to identify and categorize restoration opportunities (USFS 2021a). Once restoration opportunities have been identified, the fourth step involves developing specific management actions tailored to these opportunities (USFS 2021a). The final step involves prioritizing the proposed restoration actions based on criteria such as ecological impact, feasibility, cost-effectiveness, and alignment with long-term management goals (USFS 2021a).

The postfire flowchart functions as a structured decision tool, facilitating the identification and categorization of restoration opportunities based on an evaluation of ecological conditions and the impacts of fire (USFS 2021a). The process begins with an assessment of the fire's effects on the landscape, determining areas where ecological conditions have either improved, remained stable, or degraded (USFS 2021a). This initial categorization helps in understanding the spatial variability of fire impacts and in identifying zones where natural recovery processes may be sufficient or where human intervention may be necessary (USFS 2021a).

Subsequent steps in the flowchart involve a deeper analysis of these categorized areas. For areas where ecological conditions have improved or are stable, the flowchart guides users to consider maintaining or enhancing these conditions through minimal interventions or targeted management practices, such as prescribed burns or selective replanting (USFS 2021a). This approach is informed by the recognition that some fire-affected areas may benefit from fire's natural role in ecosystem dynamics (USFS 2021a). Conversely, for areas where conditions have degraded, the flowchart prompts further investigation into factors that might threaten ecological resilience and sustainability (USFS 2021a). This includes evaluating additional stressors such as invasive species, altered hydrological conditions, or ongoing climatic changes.

Based on this analysis, restoration actions are tailored to address specific vulnerabilities and to promote recovery towards desired ecological states (USFS 2021a). The flowchart incorporates considerations of management feasibility and potential future conditions, assessing whether restoration efforts can realistically achieve the desired ecological outcomes (USFS 2021a). Where conditions are unlikely to support traditional restoration goals, the framework may suggest reevaluating and possibly adjusting these goals to align with more feasible, future-oriented objectives (USFS 2021a). This tool ensures that restoration efforts are not only reactive but are also proactive in fostering landscapes that are resilient and sustainable in the face of future disturbances.

Geospatial Analysis

Introduction

The North Complex Fire of 2020 burned 197,372 acres of Plumas National Forest along with 120,796 acres of the surrounding area (Bovee 2022). It was part of the more significant 2020 California wildfire season, which saw numerous wildfires burning across the state due to a combination of dry conditions, high temperatures, and occasional strong winds. The North Complex Fire started on August 17, 2020, due to lightning strikes. It quickly grew, fueled by dry vegetation and challenging terrain. The fire spread rapidly at its peak, prompting evacuations in several communities and threatening thousands of structures. The fire resulted in multiple fatalities and destroyed hundreds of homes and other buildings. It also caused significant environmental damage, consuming thousands of acres of forest land and wildlife habitat. The North Complex Fire was fully contained in late October 2020 after burning for over two months. Characteristic of recent wildfire trends in California, a large portion of the area burned at high severity, which has been proven to reduce the likelihood of natural conifer regeneration (Williams et al. 2019, Wang et al. 2022, Sterner et al. 2022) This geospatial analysis utilizes various analytical methods to evaluate to what extent burned areas of Plumas National Forest are regenerating in each of the three years since the fire was extinguished, as well as quantifying the impact this fire and the Forest Service's management post-fire has had on the ecosystem services provided by this landscape.

Study Area

The study area is restricted to the perimeter of the North Complex Fire as of October 2020 when the fire was extinguished. The NCF burned primarily within the boundaries of the Plumas National Forest, which occupies over 1 million acres of mountainous terrain in the northern Sierra Nevada in Plumas National Forest (Plumas National Forest). However, to provide a thorough assessment of regeneration and ecosystem services requires an analysis of the entire burn site, not just the federal lands which were affected. The forest spans multiple counties, including Plumas, Butte, Sierra, and Lassen. The western end of the forest directly borders Lake Oroville Reservoir and the Oroville Dam.

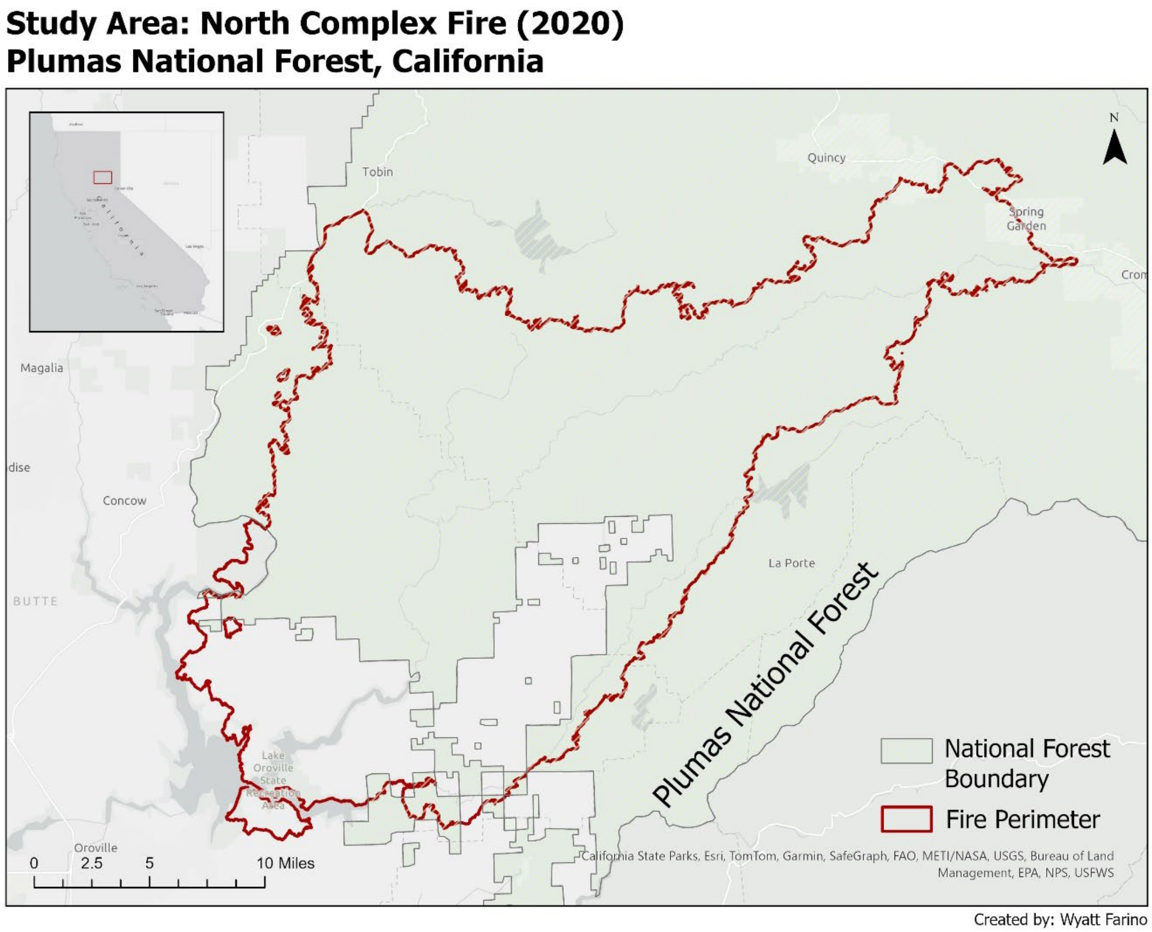

Figure 5: map displaying the final perimeter of the North Complex Fire. The boundaries of the Plumas National Forest are overlayed for reference.

Data and Methods

InVEST Model

InVEST® is a set of free, open-source software models aimed at mapping and assessing the value of ecosystem services crucial for human well-being (Stanford University et al. 2024). The models were developed by the Natural Capital Project at Stanford University, a collaboration of interdisciplinary researchers representing reputable organizations worldwide, including The Nature Conservancy and the World Wildlife Foundation (Stanford University et al. 2024). These services include the provision of goods (like food), life-support processes (such as water purification), and life-enhancing conditions (like beauty and recreational opportunities) (Stanford University et al. 2024). Despite the significance of these services, they are often poorly understood and inadequately monitored, leading to rapid degradation (Stanford University et al. 2024). InVEST offers a multi-service, modular design that aids various entities, including governments, non-profits, and corporations, manage natural resources effectively (Stanford University et al. 2024). Quantitating tradeoffs between different management choices helps identify areas where investment in natural capital can benefit human development and conservation (Stanford University et al. 2024). The toolset covers terrestrial, freshwater, marine, and coastal ecosystems, and additional tools to assist in data processing and visualization (Stanford University et al. 2024).

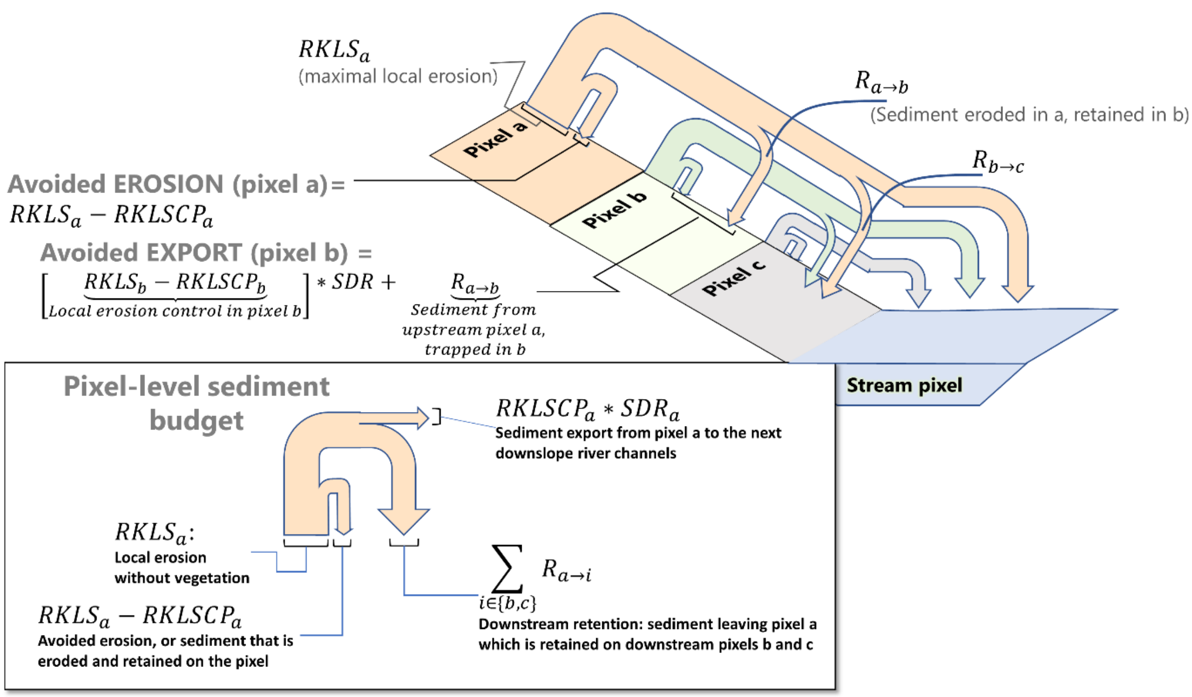

Figure 6: Illustration of sediment erosion and deposition processes, their spatial interconnectedness and how the model represents them all (Stanford University et al. 2024).

InVEST models utilize spatial data as inputs and outputs, offering results in either biophysical or economic terms (Stanford University et al. 2024). Users can choose the spatial resolution of their analysis, ranging from local to global scales (Stanford University et al. 2024). These models are built on production functions that predict how ecosystem structure changes affect ecosystem services' flow and value (Stanford University et al. 2024). The modular tool allows users to select specific ecosystem services for analysis (Stanford University et al. 2024). The Sediment Delivery Ratio (SDR) model is leveraged in this analysis to quantify and map overland sediment generation and delivery to stream networks based on land use and land cover classifications (Stanford University et al. 2024). The SDR model requires data inputs that inform key indicators of soil conditions. Digital Elevation Model (DEM) serves as the foundational layer, providing elevation values necessary for deriving flow direction, flow accumulation, stream definition, and slope characteristics. Land Use/Land Cover (LULC) data are crucial as they influence soil loss and sediment deposition, requiring an accompanying table that specifies class codes and descriptions for each LULC category. Rainfall Erosivity Index (R) and Soil Erodibility Factor (K) are raster files that represent the impact of rainfall and the susceptibility of soil to erosion, respectively. These factors are measured in terms of the energy and intensity of rainfall and the soil's propensity to detach and transport. The model also requires a watersheds vector file that delineates the boundaries of watersheds or sub-watersheds, where sediment export calculations are performed. A biophysical table, typically in CSV format, includes parameters such as management factors (usle_c and usle_p), soil loss tolerance (tol), and sediment retention coefficients (sdr_max and ic_0), which are associated with each LULC class. Threshold Flow Accumulation values further refine the model by defining the slope at which overland flow starts and the cell count threshold for stream initiation.

For the Digital Elevation Model (DEM), the process began by merging two SENTINAL-2 images into a single raster using the Mosaic to New Raster tool. This composite raster was then clipped to the boundaries defined by the fire perimeter. Following the guidelines in the InVEST documentation, a 1 km buffer was created around the fire perimeter to ensure that the edges of the study area were included in the model calculations, which is critical for capturing all relevant hydrological processes.

Table 1: all required inputs to the InVEST Sediment Delivery Ratio (SDR) model, the file type, respective sources, and description of the data.

Input	File Type	Source	Description
Digital Elevation Model	raster	USGS	Raster of elevation used to calculate slope, define streams, and trace
Rainfall erosivity index (R)	raster	EPA	Raster indicating average annual rainfall intensity.
Soil Erosivity (K)	raster	USDA	Raster of erodibility values for different soil types.
Land use/land cover	raster	SENTINAL-2	this is the baseline for which the ecosystem should theoretically recover
Watersheds	vector	USGS	Vector layer containing polygons of the sub-watersheds that define the area of analysis contributing to a particular point of interest.
Biophysical Table (usle_c)	csv	(Panagos et al. 2015)	A table mapping each LULC code to biophysical properties of that LULC class. Cover-management factor for the USLE.
Biophysical Table (usle_p)	csv	InVEST	A table mapping each LULC code to biophysical properties of that LULC class. Support practice factor for the USLE.
Threshold Flow Accumulation	numeric	InVEST	The number of upslope pixels that must flow into a pixel before it is
Borselli K Parameter	numeric	InVEST	Calibration parameter that define the relationship between the index of connectivity and the sediment delivery ratio (SDR).
Borselli IC0 Parameter	numeric	InVEST	Calibration parameter that define the relationship between the index of connectivity and the sediment delivery ratio (SDR).
Maximum SDR Value	ratio	InVEST	The maximum SDR value that a pixel can have.
Maximum L Value	numeric	InVEST	The maximum allowed value of the slope length parameter (L) in the LS

The soils data preparation involved handling both global and national datasets. The global erosivity data, already formatted correctly for the InVEST model, was simply clipped to the fire perimeter's extent. For the Soil Survey Geographic Database (SSURGO), the erodibility factor values required a unit conversion, being multiplied by 0.1317 to match the model's requirements. The national dataset was then clipped to the same extent, converted to TIFF format, and processed through a lookup operation to extract the adjusted erodibility factors into a new generic TIFF file. Additionally, this dataset required reprojection to align with the rest of the geodatabase, ensuring spatial consistency across all data inputs.

For the InVEST model application, the model was initially run using the pre-burn image and classification to establish a baseline. Unexpectedly high initial results prompted a series of calibrations to refine the model's accuracy. According to the InVEST documentation, adjustments began with the Borselli K parameter, altered by ±10% to test its impact on the results, which proved minimal. Subsequently, the Threshold Flow Accumulation parameter was modified to better align the modeled stream network with actual hydrological observations. Further adjustments were made to the values for the cover-management factor by class, utilizing the ranges provided in the documentation. After these calibrations, the model was run for subsequent years included in the study. Finally, the analysis concluded with calculating the percent difference in sediment export (sed_export.tif) across the years studied, quantifying the changes in sediment dynamics over time.

Land Classification

The raster files for this analysis were sourced from Sentinal-2 due to the high resolution of the image products available to the public. The analysis of Sentinel-2 composite images for classifying land use and land cover, particularly focusing on the regeneration of conifer forests post-wildfire, utilizes the maximum likelihood classification model to generate a classified raster within the fire perimeter. Maximum Likelihood Classification (MLC) in ArcGIS Pro employs statistical techniques to classify land cover by analyzing the probability that pixel values belong to various predefined classes (ESRI). This method operates on the principles of normal distribution and Bayesian decision making. In practice, it starts with the selection of training samples that are used to gather essential statistics, such as mean vectors and covariance matrices, about each class. These statistics are stored in a signature file which is then used to assess each pixel in the dataset. The classification assigns each pixel to the class where it fits best based on the highest probability of membership.

Individual Sentinal-2 images available for the dates before and after the North Complex fire only covered half of the study area. Initially, the 'Mosaic to New Raster' function was utilized to merge two images, completing the study area's coverage. This was followed by the 'Clip Raster' operation to reduce the study area to a more manageable size. A new schema relevant to the land use and land cover (LULC) classifications was then created to facilitate precise categorization.

The next step involved using Classification Tools, specifically the Training Sample Manager, to manually identify elements within the image that corresponded to each class within the schema. After defining these training samples, signatures were created encapsulating the statistical characteristics of each class. These signatures served as the foundation for training the Maximum Likelihood Classification model.

With the model trained, the classification process was executed to categorize the land cover. To refine this classification, spectral signatures of the sample data were charted to analyze the effectiveness of the training samples. This analysis guided decisions on which samples could be bundled together and which required removal for improved classification accuracy.

The model was subsequently re-trained using the optimized set of training samples and the raster was classified again. The results of this classification were compared against ground observations obtained from composite imagery. This iterative process was repeated, enhancing the model's accuracy with each cycle, until the classification results closely aligned with other observations. The trained sample was then used to classify the images from subsequent years (2021, 2022, 2023). The final classified raster layers allow for the tracking of conifer forest regeneration post-wildfire. The output raster files from the classification model in ArcGIS Pro are in .crf format, which the InVEST model does not support. Therefore, each land classification raster was exported and clipped to change the type to TIFF files.

Burn Severity

The Normalized Burn Ratio (NBR) is a remote sensing index derived from satellite data, utilizing near-infrared (NIR) and short-wave infrared (SWIR) wavelengths to evaluate the condition of vegetation and the severity of burns (Parsons et al. 2010). The index is calculated using the formula:

$$NBR = \frac{(NIR - SWIR)}{(NIR + SWIR)}$$

This calculation is based on the principle that healthy vegetation reflects more NIR and less SWIR, whereas burned areas or bare soil show the opposite pattern, which results in lower NBR values indicating greater burn severity (Parsons et al. 2010). Sentinal-2 bands 8 and 12 are leveraged in this calculation, as they represent NIR and SWIR (SentinelHub).

An extension of this measure, the differenced Normalized Burn Ratio (dNBR), is computed by subtracting the post-fire NBR value from the pre-fire NBR value, expressed as:

$$dNBR = NBR_{pre-fire} - NBR_{post-fire}$$

The dNBR quantifies the change in land cover and vegetation by providing a numerical value that reflects the extent of burn damage, where higher values suggest more severe burns (La- et al.). These indices are integral to assessing the impacts of wildfires on land cover, aiding in the identification of burn severity over large areas and facilitating effective post-fire management strategies to mitigate potential secondary effects such as erosion and flooding (Parsons et al. 2010). The output rasters were subsequently reclassified in order to extract insights as to how much of the study area burned at what specific severity classes.

Conifer Regeneration Probability

A suite of forest regeneration tools was developed for the USDA California Climate Hub. The Forest regeneration after disturbance (PostCRPTool) was leveraged in this analysis to assess whether regeneration was occurring in the areas deemed most likely to successfully regenerate. The tool predicts the probability of post-fire conifer regeneration based on various scenarios of postfire precipitation and seed production (Stewart, Joseph et al. 2021). The model was originally trained on a postfire regeneration dataset that is comprised of mainly low-moderate-elevation portions of the northern Sierra, southern Cascades, and Klamath regions (Stewart, Joseph A. E. et al.). The most recent version of the tool (version 0.22), which was utilized in this analysis, was subsequently trained on a larger dataset to improve the predictive accuracy of the model.

The tool requires a shapefile of the fire perimeter and a raster of burn severity (RdNBR) provided by the RAVG website. The predictions are then generated in a new raster file that can be downloaded. The tool is intended to help resource managers prioritize areas to focus their reforestation resources.

In a comparative analysis between two rasters—one representing land classification with various classes and the other depicting the probability of forest regeneration—initial steps involved ensuring that both datasets shared the same spatial resolution, coordinate system, and extent. This alignment was essential for accurate comparison and was achieved using tools for resampling and coordinate system adjustment.

To focus on areas with high potential for forest regeneration, the probability raster was reclassified. Values between 80 and 100, indicating a high likelihood of regeneration, were coded as 1, representing suitable conditions, while all other values were coded as 0. Similarly, the land classification raster underwent reclassification to isolate forested land, coding the class representing forest as 1 and other classes as 0.

The core of the analysis involved the application of the Raster Calculator tool to multiply the two reclassified rasters. This multiplication highlighted areas that were both classified as forest and had a high probability of regeneration. The output raster from this operation thus identified cells with a value of 1 as zones meeting both critical criteria.

Visualization techniques were then applied to the resultant raster to enhance the clarity and interpretability of the data. Areas fulfilling the dual criteria were distinctly marked, facilitating immediate visual assessment. Moreover, the areas corresponding to the high probability of regeneration within forested regions were quantified using the Summarize Raster tool, which aggregated the areas of all pixels marked as 1. Finally, the summarized results were exported to Excel and displayed in a stacked bar chart.

U.S. Forest Service Activity

The Activity Silviculture Timber Stand Improvement (SilvTSI) dataset focuses on activities aimed at improving forest vegetation, such as release, weeding, cleaning, precommercial thinning, pruning, and fertilization (U.S. Forest Service 2024a). These activities are integral to the Forest Service's silviculture program, funded through budget allocations and tracked using the Forest Service Activity Tracking System (FACTS) within the Natural Resource Manager (NRM) applications suite (U.S. Forest Service 2024a). Although the dataset aims to portray areas where these activities have been accomplished, it is noted that not all activities are currently captured due to the optional reporting of spatial data by Forest Service units (U.S. Forest Service 2024a). As reporting requirements and compliance enhance, the dataset is expected to improve in comprehensiveness and quality (U.S. Forest Service 2024a).

This Activity Silviculture Reforestation (SilvReforestation) dataset represents activities related to establishing forest vegetation, including planting, seeding, site preparation for natural regeneration, and certification of natural regeneration without site preparation (U.S. Forest Service 2024b). Like SilvTSI, these activities are part of the silviculture program and are recorded in the

FACTS database. The dataset aims to showcase areas where these reforestation activities are executed, contributing to the agency's performance metrics (U.S. Forest Service 2024b). However, like the Timber Stand Improvement dataset, the completeness of the data may vary due to the current optional nature of spatial data reporting by Forest Service units (U.S. Forest Service 2024b).

Results & Discussion

Pre-fire landscape

Immediately preceding the fire, the study area consisted of approximately 183,107 acres (or 57%) of forest, followed by live (20%) and dead grass (10%). The proportion of forest cover increases when you consider the presence of already dead trees, which accounted for 22,991 acres (or 7%) of total land cover within the fire perimeter. Dead trees are prevalent in the study area because five large fires burned on portions Plumas National Forest between 2017 and 2020 (Bovee 2022). In total, these five fires burned 292,648 acres of Plumas National Forest (Bovee 2022).

Burn Severity

142,211 acres (or 45%) of the study area burned at least moderate-high to high severity. Furthermore, the size of the high severity patches are large, which has been shown to negatively impact conifer regeneration (Stevens-rumann, Camille S. et al. 2017, Stevens-Rumann and Morgan 2019, Williams et al. 2019, Wang et al. 2022, Sterner et al. 2022).

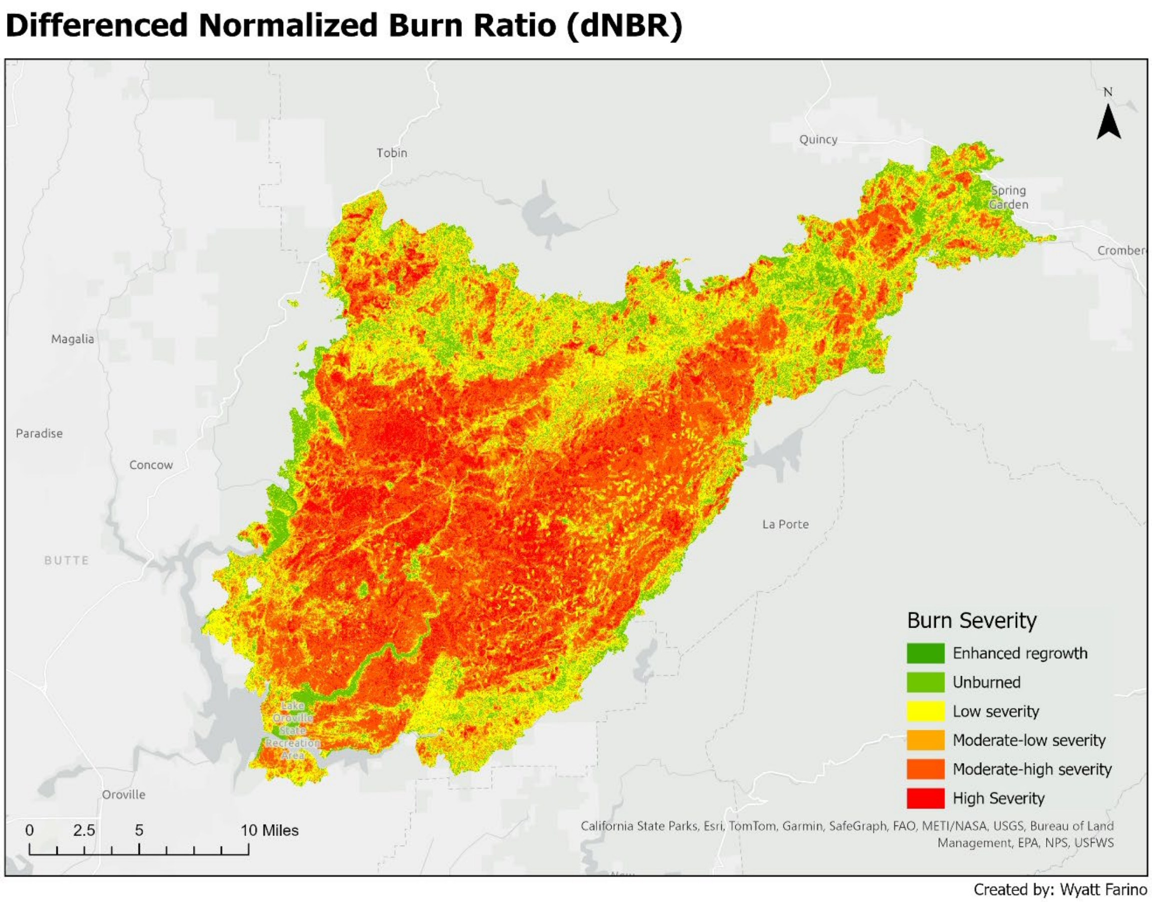

Figure 7: visualization of differenced normalized burn ration (dNBR). A standard measure of burn severity leveraged by the USFS.

Conifer Regeneration Probability

The projected probability of conifer regeneration is lowest in areas that burned with high severity. 53% of the burned area has at least a 50% chance of regenerating. The majority of which are in the northern and eastern ends of the study area.

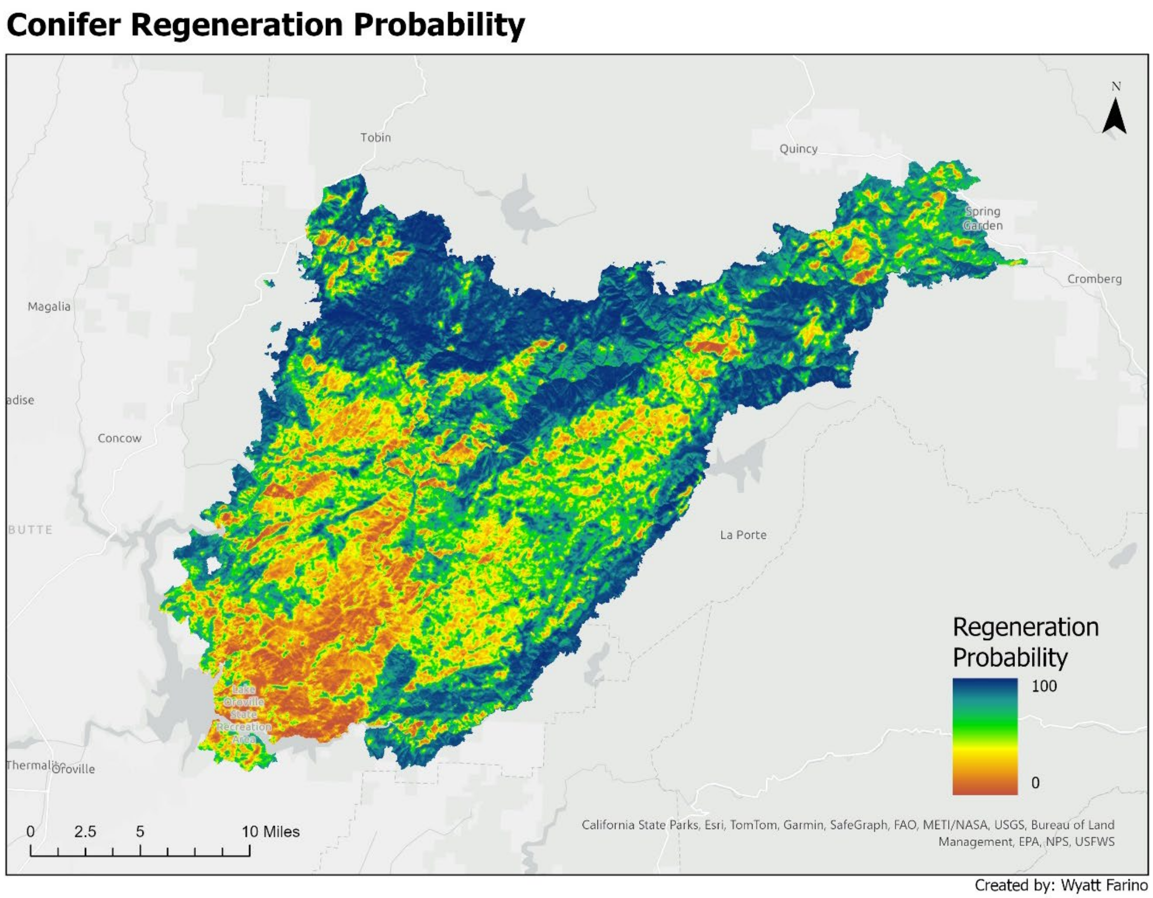

Figure 8: map of the probability of conifer regeneration probability produced by the PostCRPTool.

Land cover change over time

Initially, in August 2020, the landscape predominantly featured forest, constituting 57% of the area, and live grass, covering 20%. The land classification model indicates that the burned area surged to 59%, significantly diminishing forest cover from 57% down to 19%. Live grass was also reduced to just 2%. As the landscape began to recover, the data shows a reduction in the burned area to 37%, alongside a notable continued decline in forest cover to only 5% of the study area, accompanied by an increase in grass cover to 47% combined.

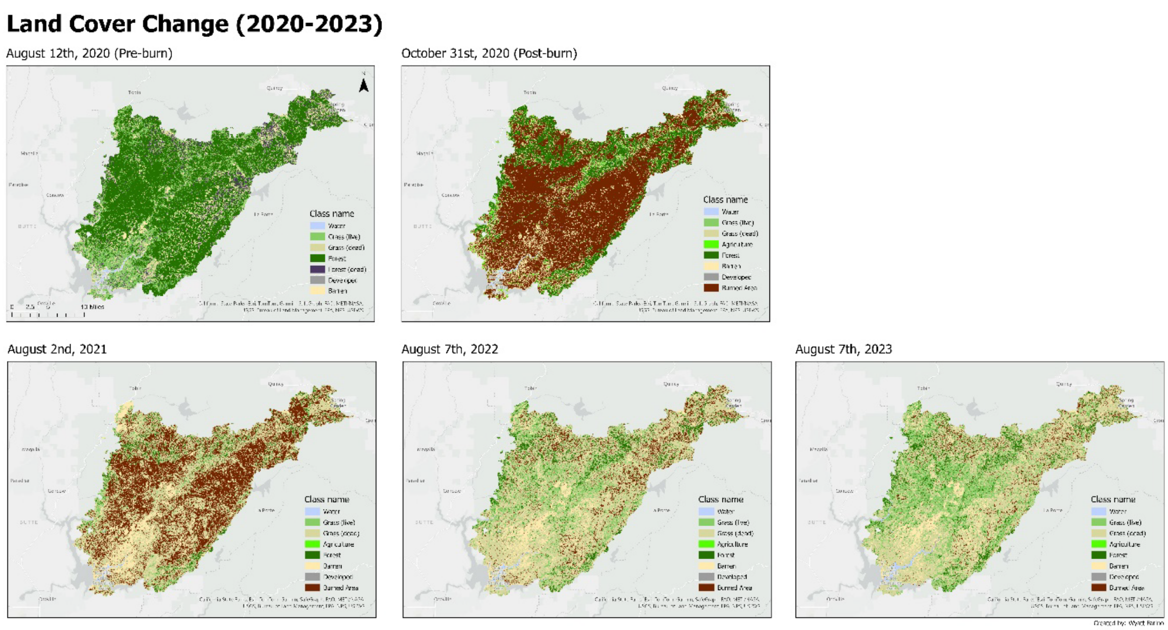

Figure 9: maps tracking changes in land cover and land use immediately before, after, and then in the three years post-fire.

By August 2022, grass continues to dominate the landscape. Although forest cover begins increasing in 2022 and 2023, grass now accounts for 72% of the burned area, indicating the potential for type conversion away from forest land. By the third-year post-fire, in August 2023, burn scars are still visible on the landscape. These observations underscore the capacity of high-severity wildfires to clear areas for grass species to quickly colonize the burned area.

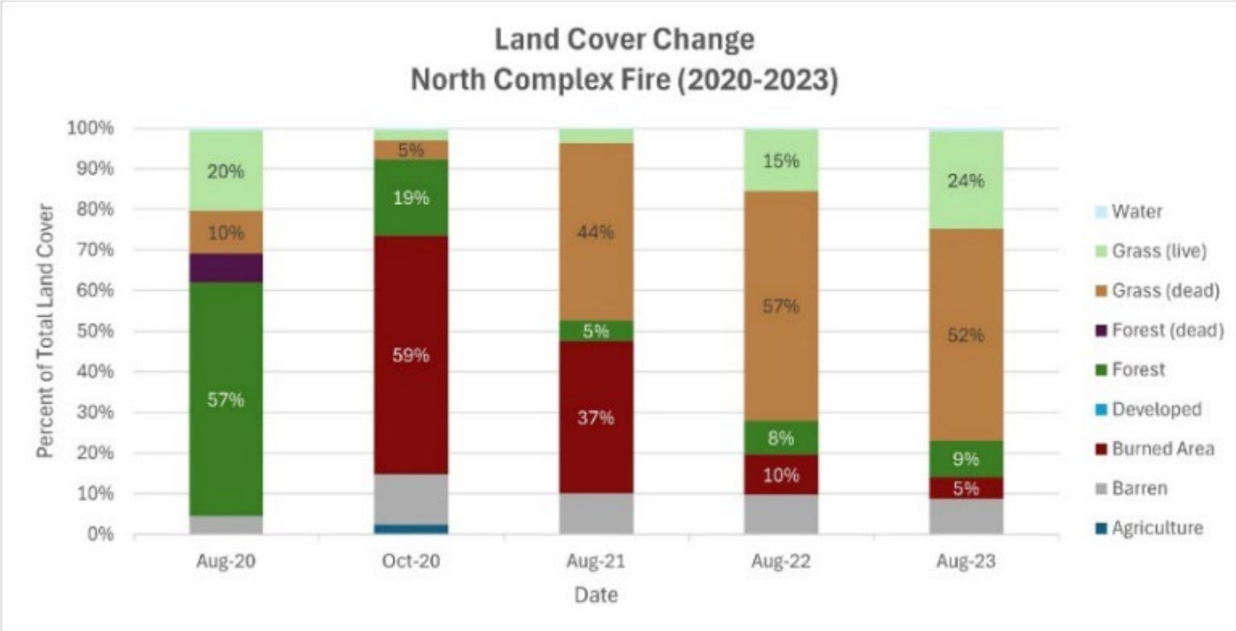

Figure 10: visualization of the distributions of total land cover by classification and year.

When comparing the land cover as of August 2023 against the areas modeled to have a greater than 50% change of regenerating, only 7% of that intersection is forestland. This is sort of disparity is concerning. The PostCRPTool's intended use case is to inform potential reforestation efforts, but this analysis indicates that relatively high probability areas are not regenerating naturally. It does appear that, three years post-fire, areas of low burn severity are more likely to be forestland than moderate or high severity areas. However, it's likely that other climatic and abiotic are influencing the regeneration of conifers including slope, aspect, and amount of precipitation.

Impact on ecosystem services

The Sediment Delivery Ratio (SDR) InVEST model was used to produce estimations of the impact that the North Complex Fire had on critical ecosystem services in the area. The burn site is comprised of very steep valleys with high risk of erosion and debris flow during subsequent precipitation or snowmelt. If any invasive non-native plant species were introduced during

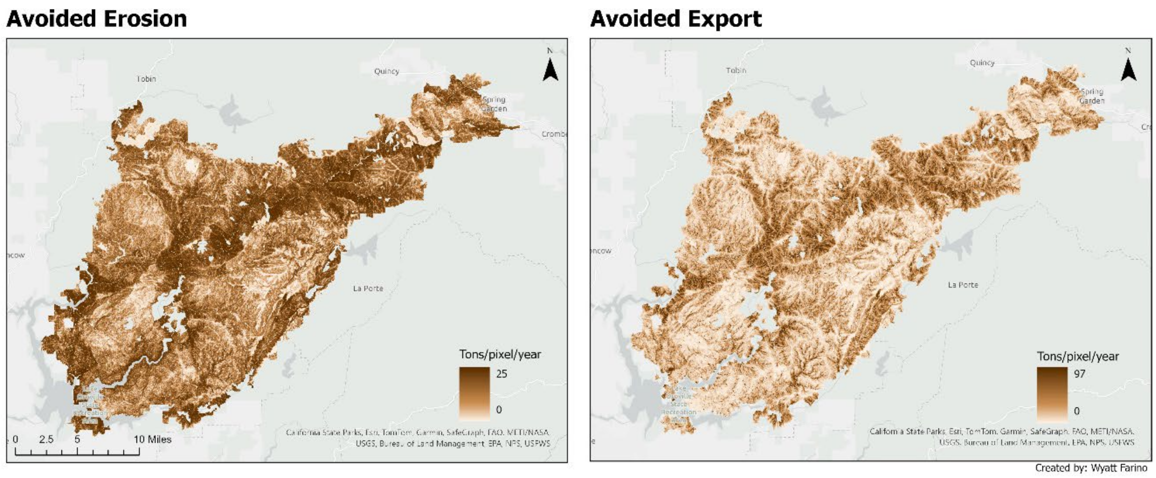

Figure 11: Maps of avoided erosion and export outputs produced by the InVEST Sediment Delivery Ratio (SDR) model.

suppression activities, these species would likely take advantage of the disturbance associated with the fire and displace native vegetation, degrade habitat function, and lower ecosystem stability (USDA Forest Service 2020). The probability of non-native invasive species expansion in these areas is likely and the consequence is major, resulting in a high to very high risk to native plant communities (USDA Forest Service 2020).

Avoided Erosion and Export indicators produced by the model may be used to identify places in the landscape that trap/retain sediment, which supports local soil resources and downstream water quality. Figure 9 shows that the main river valley that runs through the center of the burn site is critical to maintaining soils levels under vegetation can recover and stabilize those areas. A comparison of modeled sediment export between pre-fire 2020 land cover and post-fire conditions in 2023 resulted in an overall 15% increase in the amount of sediment exported from the burned area. The greatest increases occurred along the central river valley and at the main drainage point into the Oroville reservoir. However, results varied greatly by watershed. Eight sub-watersheds within the boundaries of the Plumas National Forest experienced net-positive impacts on sediment export. These watersheds are located along the north-west and south-east exteriors of the study area. The watersheds also overlap with relatively low severity burn areas.

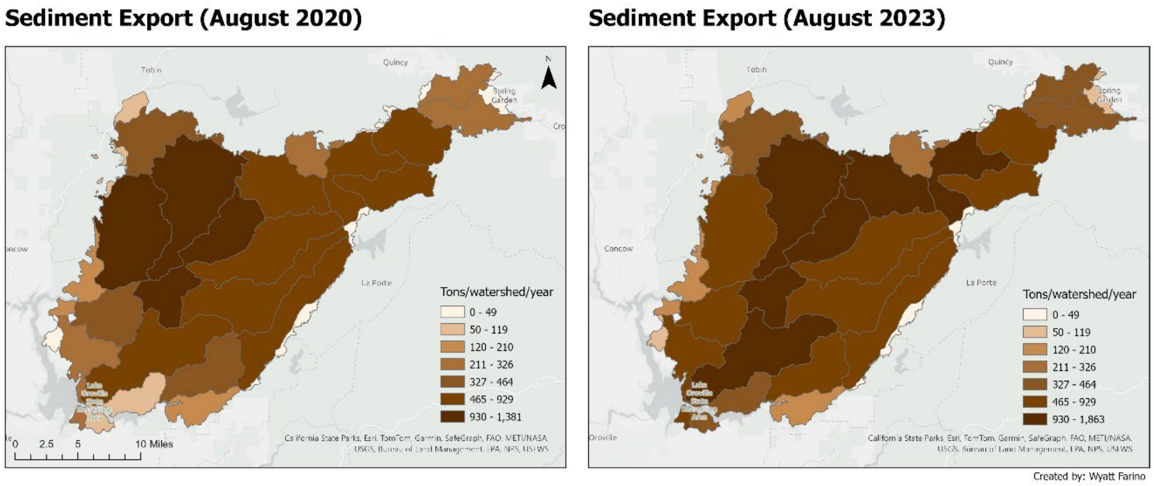

Figure 12: Maps of total sediment export outputs produced by the InVEST Sediment Delivery Ratio (SDR) model based on the pre-fire August 2020 landscape and land classification of three years post-fire.

According to the Burned Area Report produced by the BAER program in the immediate aftermath of the fire, 2.1% ($53,150) of requested funds allocated to actual land treatments, all of which are related to invasive species management (USDA Forest Service 2020). Since 2020, the Forest Service has completed reforestation activities on just 230.7 acres of the study area (U.S. Forest Service 2024b). This amounts to 0.16% of the total area (142,211 acres) that burned at high severity.

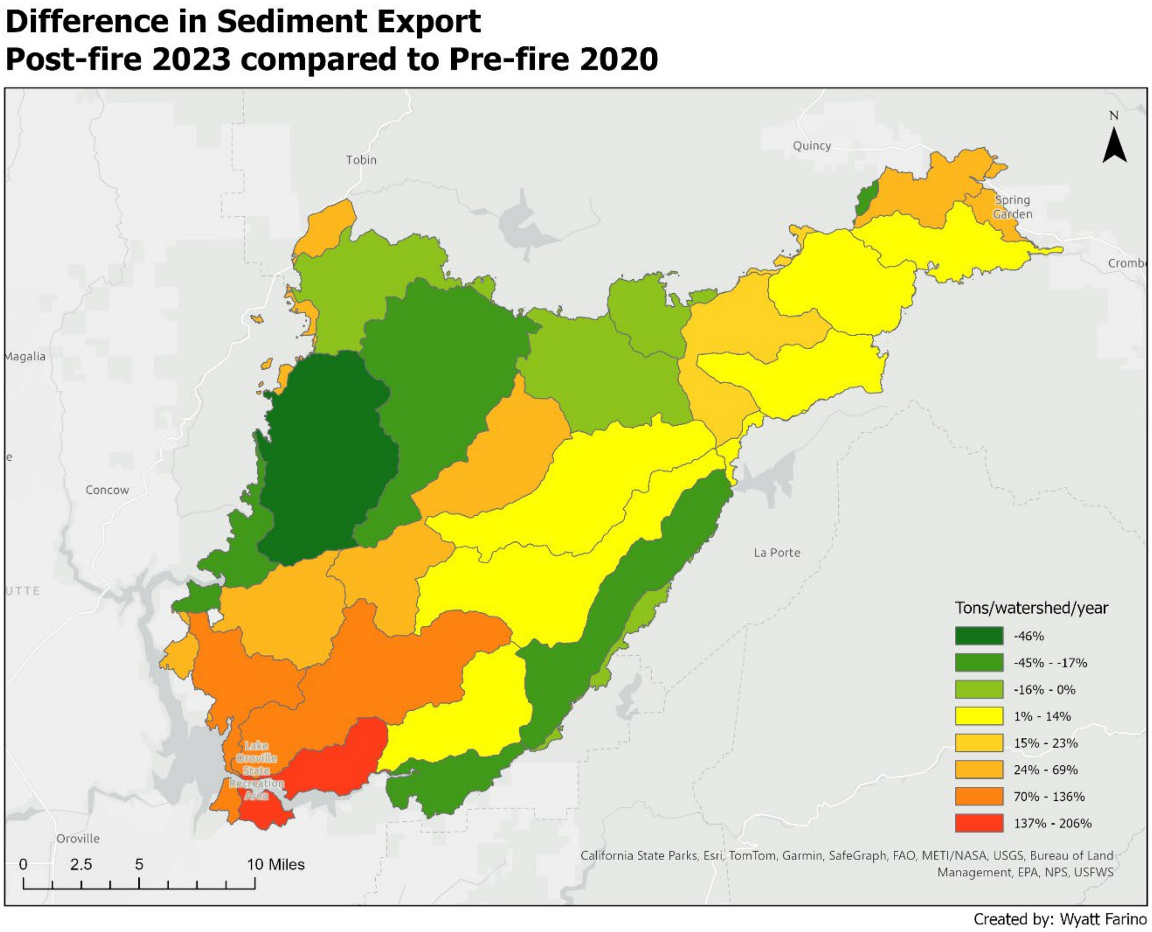

Figure 13: Map comparing the modeled total sediment export. Areas in green represent watersheds that experienced reduced exports. Conversely, those in yellow, orange, and red experienced increased sediment exports.

Conclusions

Some level of type conversion must be acceptable. Climate change is notably driving species range shifts, which, coupled with historical fire regime reintroductions, affects forest composition and cover (Coop et al. 2020). These changes are often seen as a necessary adaptation to maintain ecosystem functionality in a changing climate (Coop et al. 2020). The adaptation of ecosystems to altered conditions sometimes involves transitions from one forest type to another, such as from pine to aspen or to non-forest types like grasslands or shrublands (Coop et al. 2020). These transformations are primarily driven by climate change effects on pre- and post-fire tree population dynamics (Coop et al. 2020). Factors such as warmer, drier conditions can stress trees, increase mortality, and predispose forests to fire-induced mortality or conversion (Coop et al. 2020). For example, severe droughts linked to climate change have already triggered significant tree die-offs, hastening these conversions by eliminating potential seed sources and increasing dead fuels (Coop et al. 2020).

In some cases, restoring pre-fire forest conditions may not be feasible or desirable due to climatic changes (USFS 2021a). This has led to reconsiderations of what constitutes 'desired conditions' in forest management (USFS 2021a). Particularly in areas prone to high-severity fires and lower elevation forests with limited regenerative potential, type conversion might be a more viable option (USFS 2021a). Transitioning to hardwood-dominated vegetation, for instance, could maintain or even enhance ecosystem services such as wildlife habitat, soil nutrient status, and watershed integrity despite significant shifts in forest structure (USFS 2021a).

Systematically assessing, on a site-by-site basis, whether an affected area is worthy of reforestation investment is an essential skill the Forest Service must develop in the coming years. Advances in remote sensing technology and geospatial analysis provide the Forest Service with opportunities to standardize and scale the identification of likely successful areas for conifer regeneration. Models like the Forest Vegetation Simulator that quantify the value of various ecosystem services in relation to various management scenarios should continue to be developed and improved upon. While some in their current state may not be ready for widespread adoption, this represents an area of opportunity for integration with existing Forest Service processes to aid in assessing tradeoffs between different land treatments.

Substantial amounts of funding for reforestation at the state and federal levels have become available over the last four years, beginning with the passing of the Infrastructure Investment and Jobs Act of 2021. However, reforesting 4.1 million acres as mandated in the REPLANT Act is a substantial challenge for the Forest Service. The agency is currently not staffed at the levels necessary to treat millions of acres of National Forest (California Wildfire & Forest Resilience Task Force 2024). Developing a skilled workforce will take time, and therefore arming their staff with scalable science-informed tools will be crucial to their success.

The Forest Service's 10-year is comprehensive, addressing the entire lifecycle of forests from seed collection to long-term management. Adoption and development of new geospatial and remote sensing technology is critical to scaling treatment to millions of acres of National Forest System land. Collaboration across various agencies and levels of government, including federal, state, local, tribal, and private partners is important to implementing effective landscape scale reforestation activities. Substantial investments in resources, including workforce development and the reforestation pipeline are necessary to meet the increasing demands of reforestation. This includes expanding nursery capacity, increasing seed production, and enhancing the skills and size of the reforestation workforce.

The Postfire Restoration Framework does a great job of breaking down the important questions any land manager should ask themselves while planning restoration actions (USFS 2021a). The GTR270 assessment produced in 2021 by the Region 5 Ecology team was thorough (Bovee 2022). They identified specific regions that should be prioritized for reforestation and other restoration activities. However, follow through on part of Region 5 to implement the recommendation treatments is lacking according to the analysis of FACTS datasets. This is why long-term monitoring is essential for executing adaptive management strategies the Forest Service intends to adopt as part of their 10-year strategic plan. Tracking the progression of post-fire succession will allow the Forest Service to more effectively manage the land to meet their stated objectives.

The North Complex fire of 2020 was the catalyst for a substantial shift in the composition of vegetation. As of August 2023, grass comprised 72% of land cover while forest accounted for just 9% of total land cover. While it's expected that it will take time for a forest to recover, the land classification results show a concerning trend of increasing grassland establishment with little forest regeneration. The PostCRPTool predicted over half the burned area has a greater than 50% chance of regenerating, but three years post-fire, only 7% of that area is forest cover. Most of the forest regeneration that has occurred in the three years post-fire lies within areas that burned with low severity. This underscores the inverse relationship between burn severity and probable conifer regeneration. In addition, patches of high-severity burn are large (exceeding 100 acres), further reducing the likelihood of natural regeneration (Bovee 2022).

The high proportion of forestland that burned at moderate to high severity during the North Complex Fire necessitates intervention by the Forest Service to ensure the long-term stability of conifer forests in Plumas National Park. The GTR270 assessment produced by the Region 5 Ecology program puts forth an in-depth analysis of the North Complex and prior fires in the area, recommending specific areas within the North Complex fire perimeter that are suitable for reforestation activity. The available literature and data regarding Forest Service BAER and BAR activity in response to this fire is limited. No clear rationale was uncovered for the lack of investment in reforestation activities given the evident need for such treatments. This sort of gap in analysis and execution is concerning. Extrapolate this example in Plumas National Forest across the nation and hundreds of thousands of acres of scientifically validated land is going untreated. This is exactly the sort of gap the Forest Service should be focused on closing to hit their mandated reforestation targets.

Quantifying the value of ecosystem services and analyzing the impacts of various reforestation treatments will help land managers make better informed decisions about where to invest resources. The suite of decision support tools provided by the USDA California Climate Hub, in conjunction with a model that many InVEST provides can provide meaningful insights into what areas within a fire perimeter are likely good investments of reforestation resources. However, each tool is a separate entity requiring unique inputs which makes it more difficult to generate cohesive insights. In addition, while the Forest Vegetation Simulator is a robust tool capable of modeling the composition of forest stands long into the future, it's overly complicated for casual users to use effectively. Integrating these decision support tools into a single platform while tapping into the ability of FVS to model future forest regeneration on a fine spatial scale is a worthwhile effort given the potential for improving reforestation treatment planning.

Recommendations

Greater focus on ecological impacts during initial emergency assessments (BAER and BAR). The Burned Area Report sets the foundation for restoration activities. Little is spent on reforestation land treatments during the initial three years post-fire in which emergency response is primarily responsible for managing the burn site. More standardized reporting on the status of ecosystem services early in the recovery process may help establish greater continuity between the Forest Service's recovery management stages.

Adopt adaptive management strategies to curtail type conversion. Particularly, long-term monitoring is necessary to ensure the stability of forest ecosystems. GIS can play a large role in terms of efficiency gains for the agency. The FACTS database is a solid foundation for providing long-term records of land treatments. However, considerable resources across federal and state agencies are allocated to periodic assessments of forest inventory and other natural resources and assets. Further investment and research is recommended to apply remote sensing technology to automatically track successional stages of forests and alert stakeholders to problematic developments in species or vegetation composition.

The timing of interventions, such as replanting, should be informed by weather conditions and seasonal variations. This ensures that the treatments are compatible with the natural cycles and conditions most conducive to successful regeneration. For instance, understanding the specific requirements of different species during the BAER assessments can guide when and how to plant effectively to ensure high survival rates and successful establishment based on soil conditions and other local conditions.

Consolidate available models and decision support tools to provide Forest Service staff with the capability to craft more comprehensive and targeted reforestation strategies and action plans. The Forest Vegetation Simulator (FVS) is a complex application that requires expert knowledge of its inputs and outputs to be used effectively. The most difficult but potentially impactful asset to land managers is to understand how the land treatments they chose to implement will play out in the decades to come. A lot of these capabilities are already available in desperate sources and applications but need a more user-friendly interface that's housed within a single application.

In conclusion, the Forest Service has invested considerable resources into the development of a well-informed and comprehensive strategy to reforest millions of acres of the National Forest System. The 10-year strategy put forth in 2022 by the agency is comprehensive, but specific actions by region have yet to be determined. The challenges mixed conifer forests in the northern

Sierra Nevada are substantial and multi-faceted but not unsolvable. The Forest Service has already developed numerous resources and processes to address the issue of regeneration in the face of climate change. Technology is imperfect but must play a central role in the continued standardization and scaling of the Forest Service reforestation program. In the context of the North Complex Fire of 2020, this research has demonstrated how land management activities impact the regeneration of conifer forests and the associated ecosystem services. This geospatial analysis is repeatable with other fires given its reliance on existing federal and publicly available datasets.

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