Remotely sensing the effects of managed wildfire programs on Sierra Nevada meadows

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Geography: Resource Management and Environmental Planning

by

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Certification of Approval

I certify that I have read "Remotely sensing the effects of managed wildfire programs on Sierra Nevada meadows" by Logan Christopher Hansen, and that in my opinion this work meets the criteria for approving a thesis submitted in partial fulfillment of the requirement for the degree Master of Arts in Geography, Concentration in Resource Management and Environmental Planning at San Francisco State University.

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Abstract

Californian mixed-conifer ecosystems are overstocked and at risk of burning at high stand-replacing severity due to the confluence of a century of aggressive fire suppression and anthropogenic climate warming. Fire needs to be returned to the landscape, and naturally ignited wildfire managed for hazard reduction and ecological benefit is one important tool in accomplishing this. An understudied consequence of allowing naturally ignited fires to burn unabated in the Sierra Nevada is the possible post-fire proliferation of meadow ecosystems, with the managed wildfire program in Yosemite leading to a 160% increase in dense meadow area from 1972-2012. These SN meadows are capable of sequestering more carbon per acre than forests and are host to more biodiversity than any other ecosystem type in the state, making any change that they undergo deserving of close study. Another national park whose natural ecosystems have been the recipient of managed wildfire for over 60 years is Kings Canyon National Park. This thesis project uses remote sensing and object-based image analysis to differentiate between outcomes for frequently-burned versus fire-suppressed meadow ecosystems in a smally study area in Kings Canyon National Park. Meadow area in the study region from 1976-2020 has decreased by 36.56% in areas that have received no fire while decreasing by only 4.18% in areas that have burned at least once, lending credence to the hypothesis that managed wildfire is improving the health of Sierra Nevada subalpine and montane meadows.

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1. Introduction / Literature Review

California lawmakers and land managers face an uphill battle when it comes to maintaining the state's natural resources in the decades to come. Wildfire in the state has been an increasingly destructive force in recent years, with unprecedented losses to ecological resources and human infrastructure seen in consecutive fire seasons (Buechi et al. 2021), due to a confluence of anthropogenic climate warming and a century of aggressive fire suppression leaving ample fuels on the landscape for megafires to burn (Miller et al. 2012, Abatzoglou et al. 2016, Westerling 2016, Williams 2019). High-severity wildfire increased eightfold from 1985-2017 in the forests of the Western U.S, and this increase has been most notable in forests that have been subject to the greatest departure from historic fire return intervals (Smith et al. 2015). The scientific consensus is that aggressive reductions in wildfire fuels are needed. Recent studies have suggested that under likely future climate warming scenarios, as little as one fourth of the current aboveground live tree biomass in the state can persist in a stable state with the projected severity and extent of fires in the coming decades. (Bernal et al. 2022). Allowing naturally ignited fires to burn at mixed-severity in California's forests can contribute to a necessary reduction of tree basal area by limiting post-fire seedling establishment and contributing to successional pathways towards low-density forest and non-forest cover (Coop et al. 2020). Accepting a certain level of type conversion due to the presence of fire may be a difficult proposition for the state's decisionmakers to accept, due (among other concerns) to the high level of importance that mixed-conifer forests play in the state's carbon sequestration goals. Recent research suggests, however, that current forest carbon offset programs in the state may not only be unreliable as a tactic to reach net zero emission but may also be having adverse effects on forest ecosystem health and resiliency (Herbert et al. 2022, Williams et al. 2022). There is, additionally, potential for unexpected benefits from forest conversion in the form of post-fire increases in ecologically valuable non-forest vegetation. In the Sierra Nevada, one type of ecosystem that often arises after major fire disturbance is the wet meadow (White and Long 2018, Coop et al. 2020). Healthy wet meadows sequester carbon efficiently, filter water, attenuate flooding, support plant and animal biodiversity, and can beneficially control the timing of snowmelt water release (Ratliff et al. 1985, Purdy and Moyle 2006, Pope et al. 2015). The link between meadow establishment and the presence of wildfire has been studied relatively sparsely, and the argument has not yet widely been made that meadow restoration efforts could be effectively integrated into managed wildfire for fuels reduction. The literature review component of this thesis research is designed to posit and explore this argument, giving background on the ecological functions of Sierra Nevada meadows, the effect of shifting postcolonial fire regimes on these meadows, and how land managers can approach managed wildfire in a way that helps proliferate the extent of healthy meadows in the state.

1.1 Changing Fire Regimes and California Forest Carbon

In the pre-colonial era, California indigenous communities burned approximately 1.8 million hectares in the state per year, creating resilient and heterogeneous forests that had relatively low forest density, low aboveground live biomass, and high average pine dominance (Stephens et al. 2007, Bernal et al. 2022). In the wake of The Great Fires of 1910 that burned more than 3 million acres across North Idaho and Western Montana and killed 85 people, California fire officials began to take a more adversarial stance towards fire. 97% of all fires in the state were put out before they reached 120 hectares from 1920 to 2005 (Steel et al. 2015, Forest History Society). This departure from historic fire regimes has had several consequences for the composition of California's forests. One of these consequences is that the state's forests currently support 2.75 times more trees per acre than historic averages, a change that has led in many mixed-conifer stands to trees becoming drought-stressed and more likely to burn at high stand-replacing severity levels (Steel et al. 2015, Herbert et al. 2022). This increased density exists primarily in the form of small-diameter trees, and large trees in California forests have actually declined by over 50% from the 1930s to the 2000s (Bernal et al. 2022). Ponderosas and other California pines need frequent fire to keep shade-tolerant species such as incense cedar and white fir from crowding forest understories. This crowding creates vertical continuity of fuels, allowing fire to climb to the canopy and top-kill otherwise fire-resistant pine species that can struggle to outcompete other tree species during post-fire regeneration (Minnich et al. 1995, Steel and Ruth 2005, McIntire et al. 2015, Bernal et al. 2022).

A study of tree mortality in the southern Sierra Nevada found that from the years of 2011 to 2020, over 30% of the region's conifer forests transitioned to non-forest shrub-dominated ecosystems, with forest cover losses of 85% in high-density mature conifer stands due to drought, pests, and high-severity wildfire (Steel et al. 2022). Future projections of forest biomass suggest that a confluence of climate change and worsening fire seasons will lead to increasingly extreme reductions, even without intentional fuel removal. Under RCP8.5 warming, known as the "business as usual" climate warming scenario and characterized by continued high anthropogenic emissions, Bernal et al. predict that by the year 2069 California's forests will be capable of hosting in a stable configuration only 25% of the aboveground live biomass they current hold (Bernal et al. 2022). These extrapolations suggest that the state's forests could emit 860 million metric tons of CO_2 equivalent (total emissions from all gasses represented as their equivalent in CO_2 in terms of warming potential) over the next 50 years (Bernal et al. 2022). Coffield et al. (2021) in their review of 32 coupled climate models predicted a 28% loss of forest area in the state by the end of the century. Dass et al. (2018) use a process-based dynamic vegetation-terrestrial ecosystem model to show that wildfires may potentially contribute CO_2 equivalent emissions equal to 11-50% of 2030 CA carbon targets.

Fire scientists and managers have argued in recent years that the impacts of wildfire and climate warming on California forests have led to aspects of the Integrated Forest Management (IFM) component of the state's Cap-and-trade program becoming maladapted and out of sync with ecological realities. In their 2022 study, Herbert et al. describe how IFM projects encourage forestry practices that artificially inflate aboveground carbon estimates by planting trees in areas that may already be experiencing overstock. The authors explain that while many IFM projects are in fire-prone areas, these projects are not subject to standard fire mitigation practices. In their remote sensing comparison of IFM forest land and CAL FIRE-managed forest land they find that forests managed under carbon offset programs consistently exhibit less beneficial outcomes in terms of fire hazard and vegetation health when compared to forests managed by fire authorities. Herbert's concerns with carbon baselines that are often artificially established for the sake of carbon offset programs are represented elsewhere in the literature (Gifford 2020).

Furthermore, there is reason to believe that the insurance component of IFM carbon-offset problems is undercapitalized and represents an underestimation of the effects of wildfire on stable forest carbon. In an actuarial analysis of the various components of the “buffer” pool of carbon credits that exist in California’s cap-and-trade program to account for forests that are unexpectedly affected by disruptions like fire, pests, and drought, Badgley et al. (2022) found that 95% of the buffer pool that was designed to cover pyrogenic emissions through the end of the 21st century had already been depleted as of 2022. The state will very likely need to look to forms of carbon storage other than aboveground live tree carbon, and additionally will need to greatly increase the amount of treated acreage of forest land per year in order to allow for the extant tree carbon to persist in a stable state (Hurteau et al. 2019, Gifford 2020, Stephens et al. 2020, Bernal et al. 2022, Herbert et al. 2022). One alternative avenue of carbon storage exists in the state’s subalpine and montane meadows. The carbon sequestration potential of these meadow complexes has been historically ill-studied but is the recipient of increased research interest in recent years (Reed et al. 2021, Tangen and Bansal 2021).

1.2 Sierra Nevada Subalpine and Montane Meadows

Subalpine and montane meadows are wetland and semi-wetland areas that occur between approximately 2000-8000 m in elevation in the Sierra Nevada range (Ratliff 1985, Purdy and Moyle 2012, Gross and Coppoletta 2013). These meadow areas can return to a high level of ecological functioning after disturbance due to a confluence of water availability, low gradient, and abundant seedbanks, with water being the primary driver that separates classes of meadows from one another (Ratliff 1985, Norton et al. 2006). Depth to water table in a meadow system controls the extent to which soil redox reactions can occur and therefore is the most important predictor of meadow floristic properties (Purdy and Moyle 2006). Generally, hydric vegetation in

Sierra Nevada meadows occurs where the water Table is 0–40 cm below the surface and mesic vegetation predominates when the water Table is 20–80 cm below the surface. *Carex* species frequently dominate moist meadows while meadows with declining water tables may begin to be covered by junipers, annual grasses, and sagebrush (Purdy and Moyle 2006). Geomorphologically, subalpine and montane meadows frequently form where impermeable bedrock limits root zone water loss to percolation, in recessed areas of valleys allowing for ponding, or bordering streams (Ratliff 1985, Weixelman et al. 2011).

Less than 2% of the total land area of the Sierra Nevada and Lower Cascade Range is covered by meadows, but these meadow areas have an outsized impact (Norton et al. 2013). Freshwater wetlands (which wet meadows are classified as), due in large part to high soil moisture limiting microbial decay, can have carbon sequestration rates 30 to 50 times higher than forests, and wet subalpine and montane meadows are estimated to comprise anywhere from 12–31% of the Sierra Nevada soil organic carbon stocks (Norton et al. 2013, Reed et al. 2021, Tangen and Bansal 2021). Sierra Nevada meadow areas support more species of wildlife than any other land cover type, with particular importance for migratory bird species and amphibians (Purdy and Moyle 2006). Hydrologically intact (not incised or otherwise degraded, connected to surrounding floodplains) meadows can additionally contribute meaningfully to managing freshwater resources. The presence of meadows has been known to reduce spring streamflow in Sierra Nevada watersheds and increase summer streamflow, a shift that aligns well with when demand is highest for water downstream, as well as reduce water-borne sediment and contaminants (Hunt et al. 2018). The fact that Californian meadows have this kind of impact in the modern era is made all the more impressive by the fact that in the postcolonial area the state is estimated to have lost over 90% percent of the freshwater wetlands it once had (Garone 2011).

1.3 Degradation of Sierra Nevada Meadows

The meadow areas that still exist in California have nearly all been affected to some degree by human activity. Grazing, logging, recreation, and changes in disturbance regimes have led to as much as 70% of Sierra Nevada meadows being in a degraded state (Pope et al. 2015). Degraded meadows are characterized by shifts in vegetation away from hydric and towards mesic/xeric vegetation, incision of stream banks and reduction of hydrological connectivity to surrounding floodplains, increases in bank erosion, and reductions in net primary productivity (Viers et al. 2013, Vernon et al. 2019). There are significant consequences of meadow degradation when it comes to the ecosystem services a given meadow can provide. Carbon sequestration potential has been found to be lowered significantly in degraded meadows. Research done on carbon fluxes in 13 Sierra Nevada montane meadows found a wide range of carbon activity in these meadows, ranging from storing 577.6 ± 250.5 g C m^{-2} y^{-1} to releasing 391.6 ± 154.2 g C m^{-2} y^{-1} (Reed et al. 2021). One of the primary differences between meadows that were carbon sinks and those that were carbon sources was the presence of obligate wetland vegetation, supporting the notion that alterations to the water table of Sierra Nevada wet meadows can have significant impacts on carbon budgets (Reed et al. 2021).

One important mechanism of meadow degradation is meadow conifer encroachment. This process occurs when coniferous plant cover begins to grow in meadow peripheries, leading to a variety of alterations to meadow ecosystems including increases in vegetation water use, disruption of biogeochemical cycling, increases in bank instability, and promotion of xeric conditions (Lubetkin et al. 2017, Surfleet et al. 2019). A remote sensing analysis of 101 meadows in the Sierra Nevada found that over 70% of these meadows had some form of conifer recruitment while 40% were covered in conifers in 10% or more of their total area (Gross and Coppoletta 2013). The most common cause of conifer intrusion in the region's meadows is *Pinus contorta*, commonly known as the lodgepole pine. One study of the central Sierra Nevada found that 94% of conifers encroaching on meadows were lodgepoles, and that they dominated even when they were not the primary species in the surrounding forests (Lubetkin et al. 2017). Evergreens like the lodgepole pine transpire nearly year-long, as long as the soil they are rooting in is not frozen. When in meadow peripheries there is evidence that these evergreens can significantly lower the water table and reduce water access to meadow vegetation (Wagtendonk et al. 2018). Over time, the changes to meadow hydrogeomorphology encouraged by conifer encroachment can lead to complete vegetative succession. Modeling efforts using General Circulation Models have predicted that nearly all meadows that are currently experiencing some degree of conifer encroachment will have converted entirely to mixed-conifer ecosystems by the end of the century without intervention (Lubetkin et al. 2017).

Many researchers have asserted that the prevalence of conifer encroachment in Sierra Nevada meadows can be attributed in part to the last century of highly aggressive fire suppression in California, though this is difficult to prove due to the lack of research on historic extents of meadow systems (Vankat 1977, Purdy and Moyle 2006, Gross and Coppoletta 2013). One of the most direct links between fire suppression and conifer encroachment was made by Norman and Taylor in their 2005 research "Pine forest expansion along a forest-meadow ecotone in northeastern California, USA”. In studying the changes in fire regime and conifer recruitment in areas surrounding 11 Sierra Nevada meadows, the researchers found that mean fire frequency in these areas decreased from 7.7 fires in the period of 1750-1849 to 0.3 in 1906-1996, with their general takeaway on conifer recruitment being that the extent of tree establishment was varied between meadows, but in every case followed the removal of fire. Conifer encroachment does seem to be reversible, as attempts at manually removing lodgepole pines from California meadows have yielded decreases in water table depth of 15cm (Viers et al. 2013).

1.4 Wildfire as Vehicle for Vegetative Succession/Meadow Restoration

While it is not particularly well-represented in the literature, there is evidence that, through removal of woody vegetation cover, wildfire can increase the extent of meadow systems and reverse conifer encroachment. As early as the 1980’s fire managers recognized that fire could potentially be used as a tool to control vegetative succession in meadow perimeters, including reducing the presence of woody plant cover, but asserted that too little was known about how fire functions in meadows to have it function as a reliable management technique. (Ratliff 1985). This latter sentiment is still partially true, although there are studies that can help us estimate the effectiveness of fire as meadow management technique. One of these studies involves the use of Google Earth Engine cloud computing, deriving mean Normalize Difference Vegetation Index (NDVI) values in the years following 1996’s Ackerson Fire in 26 montane meadows in the Upper Middle Tuolumne River sub-watershed (Soulard et al. 2016). Of these 26 meadows, 14 burned during the fire and 12 did not. Burned meadows exhibited a statistically lower mean NDVI from 1996-2012 when compared with unburned meadows, and this NDVI difference occurred primarily during the dormant season and nearly not at all during the growing season. The researchers argue that this suggests that the primary effect of mixed-severity fire in these meadows was to reduce the extent of evergreen vegetation in meadow boundaries. Fire in these 14 burned meadows appears to have created favorable conditions for herbaceous vegetation while reducing the extent of woody vegetation in meadow peripheries (Soulard et al. 2016).

A standout example of wildfire leading to expansion of meadow complexes is in the case of the Illilouette Creek Basin, a 150 km² area in the south of Yosemite State Park with a Mediterranean climate at 1800-3000 m elevation (Stephens 2021). Fire has been allowed to burn naturally when ignited in this region since 1972 with the implementation of its "Natural Fire Management Program". This return to a historically analogous fire regime has led to a number of changes in the region's ecological makeup. One such change is the increase of streamflow from the area, which can likely be attributed to a reduction in transpiration that results from thinning of forest cover (Rakhmatulina et al. 2019). Other changes include an increase of summer soil moisture by 30%, increase in plant and animal biodiversity, and (crucially for the purposes of this study) and increase of meadow area (Boisrame 2017). Specifically, sparse meadows increased by 200% from 1972 to 2012 and dense meadows (which includes wetlands/wet meadows) increased by 160% over the same period. A 2015 post-fire vegetation change study found that low and moderate-severity fire had little impact on the vegetative composition of the basin, with high-severity fire being primarily responsible for shifts away from conifer cover and towards shrub and meadow cover (Naranjo 2015). This is congruent with best available science on vegetative succession post-fire, which suggests that high-severity fire is often required to create fire-driven forest conversion in California ecosystems (Coop et al. 2020, Nemens et al.

2022). Attempts to use prescribed fire, which burns at low-to-moderate-severity, to combat conifer encroachment in meadows have found that this kind of fire removes lodgepole pines that are smaller in diameter than 20 cm but that there is little effect on larger trees (Frenzel 2012).

1.5 Integrated Considerations of Meadows into Wildfire Management

In recent years it has become increasingly clear that the post-1900 strategy of outright fire suppression in California has led to increases in fuels, unsustainable forest densification, loss of fire-adapted species, and increases in large and damaging fires (Scholl and Taylor 2010, Westerling 2016, Steel et al. 2018, Williams 2019). Loss of forest cover due to high-severity wildfire has been a source of consternation for forestry officials, as trees are of course critically important for ecology and carbon budgets, and for this reason reforestation has been a focal point post-fire (Nave et al. 2018). Recent modeling studies have concluded that under likely climate futures, California cannot sustain anywhere near the stocks of trees it currently holds in a stable state, and that increasing the presence of fire in the state's forests will be necessary to encourage fire-resilient heterogeneous forest ecosystems (Liang et al. 2016, Bernal 2022). Land managers will likely need to eventually accept fire-driven forest conversion on a large scale, and concentrating on the hydroecological benefits of increased meadow area post-fire is one way to ease this transition.

Forest Service ecologists have presented useful management recommendations for where to focus on reforestation after fire and where to accept and even encourage vegetative transitions. White and Long (2018) in particular provide a useful set of guidelines where reforestation is prioritized in areas that have long been covered by mixed-conifer vegetation and de-emphasized in areas that represent converted meadows. They mention the Illilouette Creek Basin by name and suggest that the increased prevalence of meadows in the basin should not be viewed as a large-scale type conversion but rather as a return to more resilient historic conditions. In bottomland riparian areas with relatively high water availability, high-severity fire (when it does occur) is likely to lead to transitions towards non-forest vegetation, and these forms of transition can potentially be viewed as restoration rather than as losses. The National Parks Service has developed a framework for adaptive natural resource management called Resist-Accept-Direct or RAD, an iterative loop-learning process that helps managers to recognize when and where ecosystem transformation may be ecologically acceptable or even necessary (Lynch et al. 2022). Increasing the operationalization of adaptive management tactics in state decision-making could add meaningfully to wildfire management strategies in ways that are ecologically beneficial for meadow ecosystems.

1.6 Potential Synergies for Managed Wildfire, Carbon, Water, and Meadow Health

Naturally ignited fires managed for ecological and hazard reduction benefit, frequently known in fire management circles as “managed wildfire” or “wildland fire use” (significant disagreements persist in the discipline on the correct term), offer important opportunities to supplement California’s fire and fuels plans (Wagtendonk 2007, Beasley and Ingalsbee 2021). Mechanical thinning of fuels from the state’s fire-starved ecosystems will play a continual role in necessary fuels reduction, but just under a quarter of the 10.7 billion acres in the Sierra Nevada Bioregion are accessible and available for this kind of thinning, as many of the overstocked forests in the region are in remote areas with steep or otherwise treacherous terrain (North et al.

2015). Prescribed burning is an excellent option for clearing crowded understories and has been found to be effective at reducing hazardous fuel layers in SN forests. Much like mechanical thinning, however, it is often infeasible in remote areas *and* can be costly and time consuming, as all prescribed burns must comply with National Environmental Policy Act (NEPA) or California Environmental Quality Act (CEQA) processes (Stephens et al. 2020, Beasley and Ingalsbee 2021). Managed wildfire is often the least resource-intensive and most efficient option available for returning fire to the landscape, as it does not involve the upfront costs and physical constraints associated with getting boots on the ground for lighting prescribed fire, and, due to the Federal Wildland Fire Management Policy, naturally ignited fires managed for resource benefit are not subject to lengthy NEPA or CEQA review (Beasley and Ingalsbee 2021). If managed wildfire is already being used in the coming decades in California to mitigate fire hazard and protect ecological resources, it is the argument of this thesis that increased research attention should be paid to how historically analogous fire regimes can and will affect the extent and ecological functioning of subalpine and montane meadows.

In the Illilouette Creek Basin, where fire has led to major increases in meadow area, effects on streamflow and soil moisture have been studied but soil carbon has yet to be thoroughly investigated. One of the few carbon studies that has been done in the ICB found that 50 years of managed wildfire reduced carbon stocks in the basin by approximately 25%, but this study gave no consideration to below-ground carbon, which we know can be a highly productive force for sequestration (Quintana 2018). There are approximately 10,000 km^2 of wilderness area in the Sierra Nevada that are climatically comparable to the ICB (Boisrame et al. 2018). Future studies that elucidate the potential water *and* carbon benefit in meadows that would result from returning fire to some or all of those comparable acres could help to “sell” the process of managed wildfire to skeptics. In their carbon analysis of 13 montane meadows, Reed et al. (2021) estimated that if all meadows in the Sierra Nevada sequestered carbon at the rates that hydrologically intact meadows do, they would store as much carbon annually as 6000 km^2 of forest. Connecting this kind of projection to managed wildfire, especially considering it has the potential to not only restore but increase the overall presence of meadow area, would be invaluable.

2. Study Area

Yosemite’s Illilouette Creek Basin, mentioned extensively in the review portion of this research, is not the only region in the Sierra Nevada home to over half a century of managed wildfire. The oldest natural fire management program in the state is found in Sequoia and Kings Canyon National Park (Kilgore 1972, Bancroft et al. 1983, Keeley et al. 2021). With the creation of the park in 1890, any and all fires that might have once been intentionally lit in the area by local indigenous land managers were made illegal, however concerns were quickly raised around the artificially inflated fuel levels that were created by fire suppression (Bancroft et al. 1983). These concerns and others are reflected in the landmark Leopold Report of 1963, spearheaded by A. Starker Leopold. This report advocated for management in the National Parks System that resembled as closely as possible the “natural” state of the ecosystems within them. This proposed management regime included encouraging wildfire to burn in the parks at levels congruent with historic fire regimes (Leopold et al. 1963, Kilgore 2007). Influenced by the Leopold Report and by contributions from other notable ecologists of the time like Harold Biswell, the sub-alpine and alpine areas (covering nearly 75% of the park’s extent) of SEKI were designated as a “let-burn zone" in 1968 (Kilgore and Briggs 1972, Keeley 2021). Over time a recognition of the passive tone implied by "let-burn" led to the terminology surrounding the program being changed to "prescribed natural fire" and subsequently to "wildland fire use" and finally "wildfires managed for resource benefit" (Kilgore 2007, Keeley 2021). From 1960-2017, an average of 4673 ha per million ha per year burned in SEKI through either prescribed burning or natural fire managed for resource benefit, the highest total in any park or national forest in the state (Keeley 2021). It is worth noting that the follow-through on managed wildfire for ecological benefit in SEKI has not been consistent. Political and regulatory pressure due to megafires has led to suppression efforts becoming recentered in the park's management for periods of the managed wildfire program's history (Botti and Nichols 1983, Botti and Nichols 2021). The legacy effects of managed wildfire in SEKI appear to vary greatly across the landscape and across vegetation types. A 2017 study found that frequently burned red fir forests in the park exhibited 29% lower tree carbon, frequently burned ponderosa and white fir-sugar pine forests exhibited 15% lower tree carbon density, while frequently burned jeffrey pine forests actually exhibited 40% *higher* tree carbon density (Lutz et al. 2017).

For this thesis research, the goal is to identify meadow complexes on either side of the "let-burn zone" in Kings Canyon National Park (the less well-studied of the two SEKI parks when it comes to post-fire vegetation dynamics, judging by the literature) and see how the extent and vegetation greenness of these complexes with disparate fire histories have changed since 1968. Kings Canyon National Park is a park covering 1,870 km^2 in the Southern Sierra Nevada, characterized by a Mediterranean climate with warm summers and cold winters, with the dominant soil type in the park being decomposed granite loam (Huntington and Akeson 1987, Stephenson 1988, Nesmith et al. 2010). Over 1200 individual plant species can be found within the park, with its vegetation zones broadly classified as (from lowest to highest elevation) foothills, montane forests, subalpine, and alpine (NPS 2023). Pre-colonial average fire return interval in the park varies by elevation and by dominant vegetation type, with a historic fire return interval of 4 years in ponderosa mixed conifer forests, 10 years in white fir mixed conifer forests, 30 years in red fire mixed conifer forests, 7 years in mid-elevation hardwood forests, 10 years in giant sequoia forests, and 187 years in subalpine conifer forests (Caprio and Lineback 2003). Overlaying a dataset containing shapefiles for all meadows in the Sierra Nevada provided by University of California, Davis, with an extent shapefile of Kings Canyon National Park provided by the Parks Service reveals that there are approximately 2,262 discrete meadow areas in the park (not a true count of meadow complexes in the park, since some complexes are made of multiple shapefiles). Dominant vegetation types in the park's meadows include conifer, riparian, hardwood, shrubland, grassland, and sparse.

Figure 1 depicts the 16.63 km^2 area chosen as the study area for this research, featuring a mix of meadows that have burned frequently since 1950 and meadows that have not burned at all over the same time period (see methods for more detail). Given these meadows' proximity to one another they were deemed useful comparisons for the purpose of this study, and the area was chosen as a possible study area. A freely available dataset combining the Sierra Nevada Multi-Source Meadow Polygons Compilation created by UC Davis with climatic variables collected by Albano et al. (2019) allows for comparison of important hydrogeomorphological variables in the study meadows. The dominant rock type for each of the 8 chosen meadow areas is granodiorite, with all meadows additionally sharing the soil series Bucking Humixerept as well as estimated k factor 0.15. Seven out of the eight meadows are designated as Riparian in vegetation type with one meadow designated as Conifer. Mean elevation of the meadows ranges from 2,223 m at the lowest to 3,008 m at the highest, putting them in the middle of the elevation range for subalpine Sierra Nevada meadows.

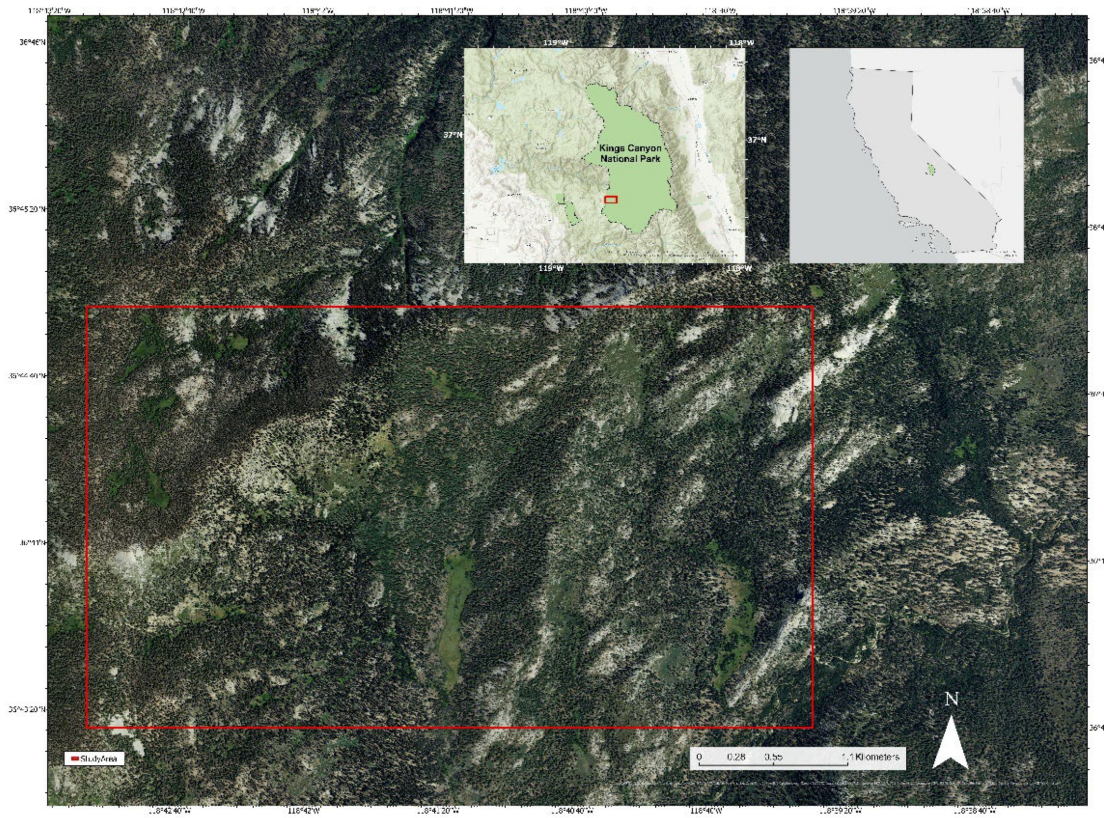

Figure 1. Study area, Kings Canyon National Park

30-year precipitation experienced by the meadows is relatively consistent across the study area, ranging from 893 mm 955 mm, however there are significant differences in the sizes of upstream catchment in the meadows as well as 30-year snow water equivalent, seen in figure

2 and table 1. Information on groundwater availability for these meadows is not available, a variable that directly determines the amount of meadow vegetation in a given ecosystem. With the understanding that some degree of change over time in meadow extent and functioning may be due to differences in the hydrogeomorphological and climatic variables discussed above, the 8 study meadows were accepted as useful for comparison due to their proximity, similarity in many important variables, and difference in fire history. Figure 3 shows historic extent of SEKI's "let-burn zone" as seen in Kilgore and Briggs (1972) and demonstrates that the study area for this research is directly proximal to this fire managemenet boundary. Altogether there were 7 fires larger than 15 acres that burned in the study area and whose perimeters overlapped with meadows in the last 60 years. These fires include the South Sentinel Fire of 1973, the Comanche fire of 1974, the Sugarloaf fire of 1977, the Sugarloaf fire of 1997, the Williams fire of 1999, the Williams fire of 2003, and the Sentinel fire of 2016 (See figure 4).

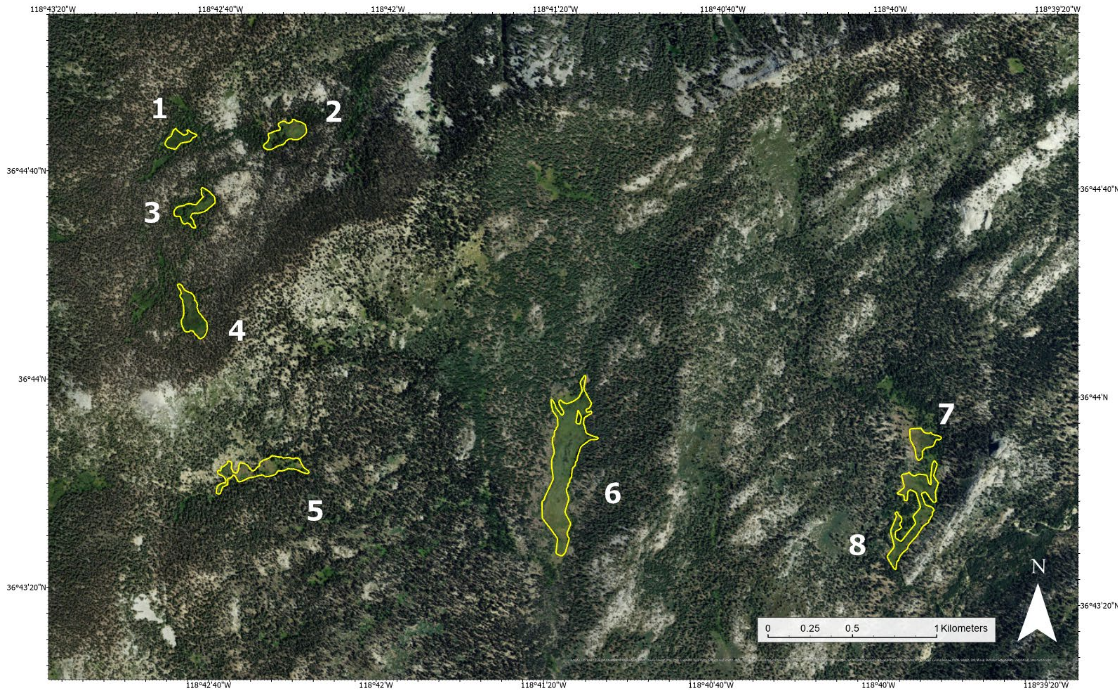

Figure 2. The 8 major meadow complexes in the study area, shapefiles courtesy of UC Davis's Sierra Nevada Multi-Source Meadow Polygons Compilation

	Mean Elevation (m)	Area of Upstream Catchment (sqkm)	Area of Meadow (Acres)	Dom. Soil Component	Dom. Rock Type	Mean 30-yr Precip (mm)	Mean 30-yr SWE (mm)
1	2914.19	57.37	2.78	Bucking	Granodiorite	955.12	633.89
2	2825.86	1786.37	5.91	Bucking	Granodiorite	953.71	629.46
3	2946.55	710.76	5.26	Bucking	Granodiorite	953.72	643.36
4	3008.13	233.87	6.85	Bucking	Granodiorite	959.90	652.25
5	2768.76	891.43	9.87	Bucking	Granodiorite	946.81	634.70
6	2446.84	3451.59	31.77	Bucking	Granodiorite	918.45	540.97
7	2239.44	2839.63	4.32	Bucking	Granodiorite	898.24	383.51
8	2222.55	3739.90	14.83	Bucking	Granodiorite	893.17	374.56

Table 1. Hydrogeomorphological qualities of major meadows in study area, data from Albano et al. 2019 (outliers, as defined by author, highlighted in red).

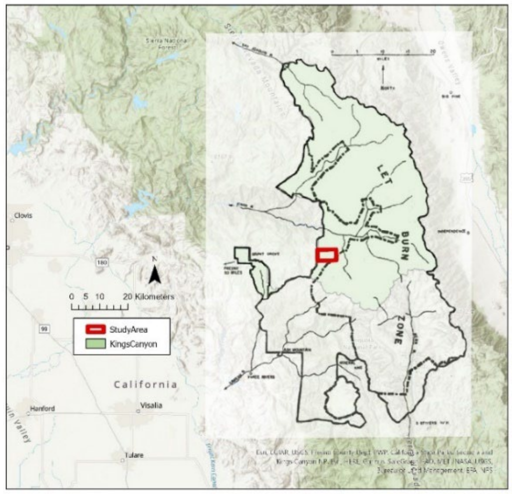

Figure 3. Georeferenced depiction of the SEKI "let-burn zone" as seen in Kilgore and Briggs 1972, demonstrating proximity of study area to border of fire use boundary

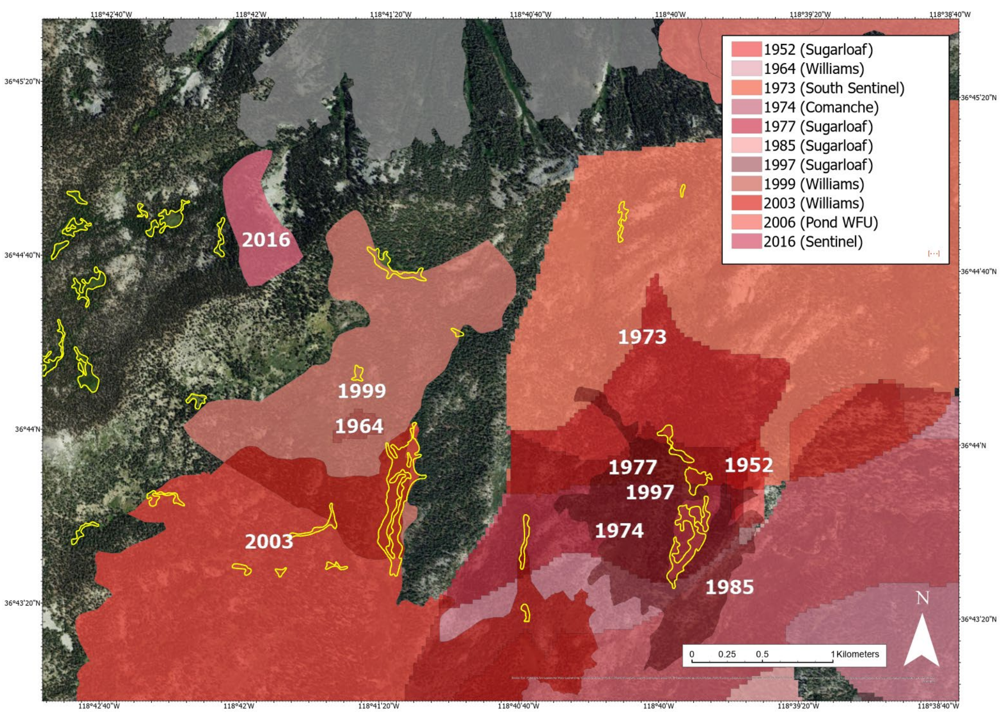

Figure 4. Fire history of study area 1950-2023, with meadows in study area in yellow as defined by the National Parks Service SEKI Vegetation Inventory

3. Methods

3.1 Object-Based Image Analysis Meadow Classification

For exploration of the study area of Kings Canyon National Park in the interest of finding adjoining meadow systems with differing fire histories over the past 60 years, a number of shapefiles were needed. These include a shapefile of the perimeter of Kings Canyon National Park retrieved from the NPS, a shapefile of all fire perimeters in California in recorded history retrieved from CAL FIRE, and a shapefile of all meadows in the Sierra Nevada retrieved from UC Davis. These shapefiles were imported into QGIS, and their areas of overlap led to the identification of the area shown in figure 1, totaling approximately 16.63 km^2 in extent and featuring 4 large meadow systems that have not burned since 1950 and 4 large meadow systems that have burned at least once since 1950.

The detailed vegetation classification in this study necessitated the use of high resolution imagery. This meant that satellite data like that provided by Landsat, which offers a 30 m spatial resolution, was not an option. Imagery with fine spatial resolution covering nearly the entire time period of the managed wildfire program in Kings Canyon National Park is freely available through the USGS in the form of National Agriculture Imagery Program (NAIP) images, National High Altitude Photography (NHAP) images, and Aerial Photo Single Frames from other programs. Aerial photos from 1976, 1987, 1998, 2005, 2010, and 2020 were retrieved. All images were taken around the same time of year, June to early August, to coincide with the growing season. The 2020, 2010, and 2005 images were accessed from NAIP and therefore came pre-orthorectified at 1m spatial resolution with green, blue, and infrared bands. The other three images came from NHAP or other older programs, all at 1 m spatial resolution, one in color-infrared (1987) and the other two in black and white panchromatic (1976, 1998). These three images needed to be georeferenced and orthorectified before being useful for vegetation classification purposes. Orthorectification of these images was achieved through ERDAS Imagine's georeferencing capabilities. Control points were identified using the pre-processed 2020 NAIP as a reference, and the georeferencing algorithm was completed with the help of camera calibration information from each image as well as a 10 m DEM file of the study area, both accessed through the USGS.

For the meadow classification portion of this study, an object-based image analysis (OBIA) approach was selected. In this kind of analysis an image is initially broken up into objects consisting of homogenous adjoining pixels, and classes can subsequently be applied to each object. The advantages of an OBIA approach include that textural and contextual variables can be used in the classification process, whereas pixel-based techniques rely predominantly on spectral information. Because the images to be processed in this study provided varying degrees of spectral information (both multi-band and single-band), OBIA classification was deemed appropriate and effective. Each orthorectified image was imported into Trimble eCognition and segments were created using the software's "multiresolution segmentation" algorithm that relies on a pairwise region merging technique. The best results for this algorithm were found, through a process of trial and error, to be scale parameter 45, shape parameter 0.15, and compactness parameter 0.5.

eCognition allows for the creation of multiple-threshold image classification where each image object is assigned a classification based on a unique set of spectral, textural, and contextual conditions. Conditions were added for each individual image iteratively until meadow area was as cleanly delineated from non-meadow area as possible. This delineation was verified by a combination of cross-referencing the thresholded classification results with the meadow extents indicated by a 2018 vegetation inventory of the park and close visual examination of each high-resolution image / comparison to the other images. Different sets of conditions were used for each image, which was necessary due to the differences in quality and availability of spectral information for each image. Examples of spectral variables of image objects that were used for threshold classification include the mean, median, min, max, and standard deviation of total brightness, red, green, and NIR band values, as well as calculated NDVI and Normalized Difference Water Index (NDWI) values. Examples of textural variables include mean and contrast of the gray-level co-occurrence matrix (GLCM) and Grey Level Difference Vector (GLDV) image object values. A tendency towards over-estimation of meadow extent across the study area was identified in the threshold classification outputs, so a contextual limit of 125 meters from the vector file indicating the 2018 meadow vegetation extent was added to each image's classification algorithm.

3.2 OBIA Accuracy Assessment and TWI Validation

Once the threshold classification algorithms were finalized, an accuracy assessment was produced. Using QGIS, 200 random sample points were generated within the boundaries of each of the 6 aerial images, and each point was determined to represent either meadow or non-meadow area through careful visual inspection and cross-reference to official NPS vegetation inventories as well as the other aerial images. These sample shapefiles were then imported into eCognition using the "convert thematic layer to samples" function, and the samples were compared against the results of each image's unique classification algorithm through the creation of confusion matrices. Each segmented image was then improved through limited manual reclassification aided by close visual inspection and photo interpretation, and another accuracy assessment was completed for the manually improved classification using the same accuracy assessment methods as for the initial classification, with new sample points (See table 1).

To further validate the results of the final meadow classification, a topographic wetness index (TWI) raster was calculated based on slope values derived from a USGS 10-meter DEM of the study area and using QGIS's Flow Accumulation and Raster Calculator functions. The equation used to derive the TWI raster was **ln ((Contributing Area Raster * DEM pixel size) / tan (Slope Raster in Radians))**. TWI calculations were invented as a way to use topography to approximate moisture availability and can be used to predict areas where wetlands are likely to occur. This makes TWI rasters useful as a way to visualize if classified meadows appear in areas where they would likely have enough water to support meadow vegetation (Grabs et al. 2009, Dosskey and Qiu 2011). Figure 5 shows an example of a classified meadow shapefile overlaid on the TWI raster. Close visual inspection of the meadow outputs for each image showed that all meadow areas that were found in eCognition were in direct proximity to high TWI areas. Using QGIS's Zonal Statistics function, average TWI for the 8 major meadows in the study area as defined by the Sierra Nevada Multi-Source Meadow Polygons Compilation was calculated. The average TWI in the 8 distinct meadow shapefiles ranged from 12.5 to 15, with no significant difference between TWI in the frequently burned meadows and the fire suppressed meadows.

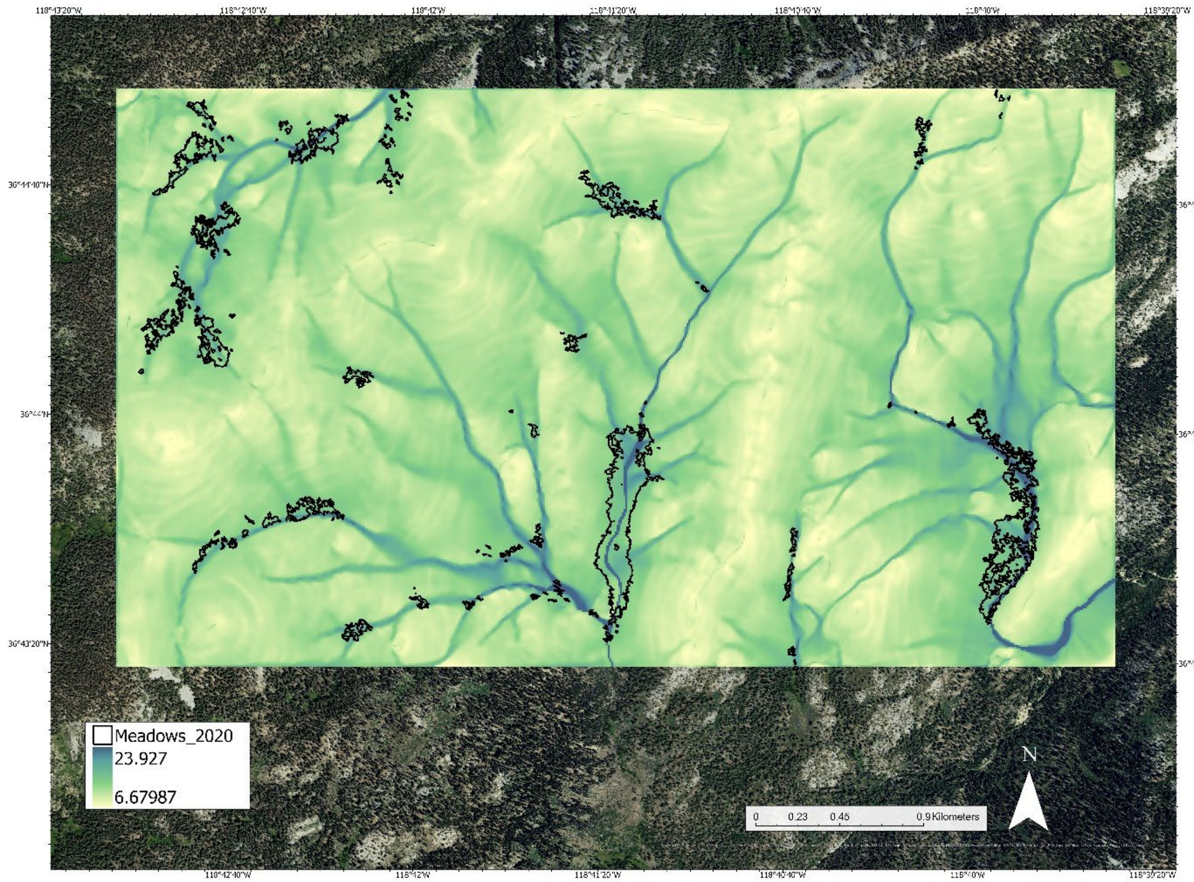

Figure 5. Classified meadow areas from the 2020 NAIP image overlaid onto a Topographic Wetness Index raster of the study area

4. Results

4.1 Change in Meadow Area, Fire vs. No Fire

Accuracy for meadow classification, as determined by the accuracy assessment methods described in the previous section, was relatively consistent across aerial images, with an overall accuracy range of 0.98-0.99 and a Kappa range of 0.86-0.96 (see table 2). According to the classification results, total meadow extent in the study area decreased from 520,221 m^2 in 1976 to 433,729 m^2 in in 2020, an overall 16.63% decrease. Controlling for meadow area that burned at least once since 1950 by clipping each aerial image's classified meadow shapefiles to a shapefile of all historic fire perimeters reveals that meadow area within the perimeter of at least one fire decreased from 320,288 m^2 in 1976 to 306,885 m^2 in 2020, a 4.18% decrease, while meadow area that did not overlap with any fire perimeters decreased from 199,934 m^2 in 1976 to 126,843 m^2 in 2020, a 36.56% decrease (See figure 6).

	Conditional Classification		**Conditional Classification + Manual Classification**	
	Overall Accuracy	Kappa	Overall Accuracy	Kappa
1976	0.98	0.86	0.99	0.91
1987	0.95	0.56	0.99	0.96
1998	0.98	0.86	0.99	0.93
2005	0.98	0.79	0.99	0.9
2010	0.99	0.87	0.98	0.94
2020	0.98	0.83	0.98	0.86

Table 2. Accuracy assessment results for eCognition meadow classification algorithm pre and post manual classification

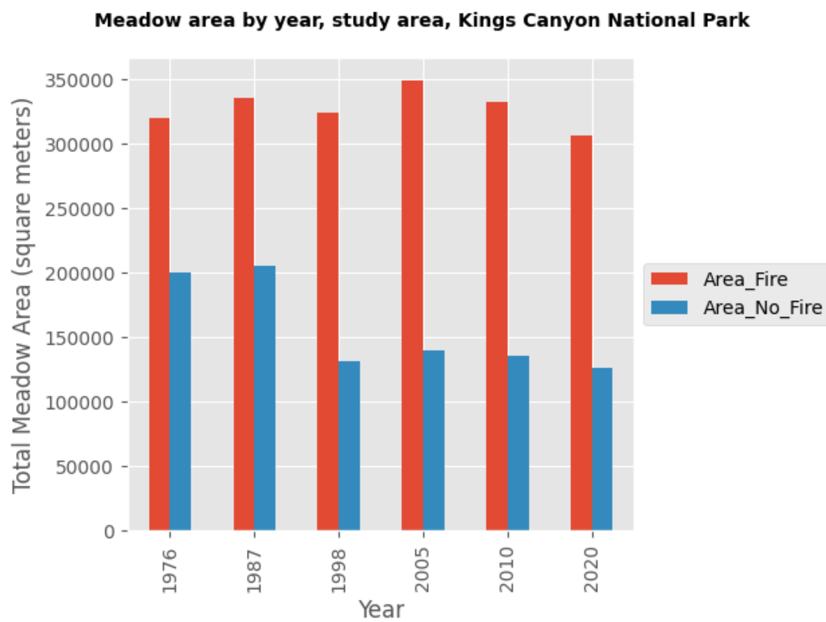

Figure 6. Change in meadow area over time, burnt versus unburnt meadows

4.2 Fire Perimeter Analysis

To more directly connect instances of fire in study area meadows to change in meadow extent, the perimeters of each of the 7 major fires that occurred in the region were clipped to the classified meadow results of each of the 6 aerial images. Trends in meadow area within these fire perimeters can be seen in figure 7. In the perimeter of the 1973 South Sentinel Fire that burned 3,746,762 m^2 of the study area, meadow area increased in the years post-fire from 28,406 m^2 in 1976 to 34,279 m^2 in 1987 to 49,558 m^2 in 1998, decreasing steadily in subsequent years. Similar trends can be seen in the perimeters of the Comanche Fire of 1974 covering 2,371,877 m^2 and the Sugarloaf Fire of 1977 covering 2,598,312 m^2, with meadow area in their perimeters growing steadily from 1976 to 1998 and decreasing until 2020, although in the perimeters of all three fires the amount of meadow area in 2020 exceeds the amount of meadow area in 1976. Meadow area increased substantially from 16,728 m^2 in 1987 to 33,060 m^2 in 1998 in the perimeter of the Sugarloaf Fire of 1997, with considerable decreases in the subsequent years. In the cases of both the Williams Fires of 1999 and 2003, meadow area in the fire perimeters had decreased from 1976 to 1998, with post-fire meadow area increasing to around 1976 levels by 2005 and remaining stable in the decade and a half to come. Meadow presence in the perimeter of the 2016 Sentinel Fire disappeared completely in the years of 1998 and 2010, with a 2,322 m^2 recovery in 2020 the wake of the 2016 fire event. Only one fire perimeter exhibited lower meadow area at any point post-fire than pre-fire, the 1997 Sugarloaf Fire perimeter, while meadows in unburnt areas decreased by 36.56% from 1976-2020, as mentioned previously. Worth noting is that some of these perimeter areas represent surface that burned more than once over the study period. Figure 8 shows the change in meadow area over time in areas of overlap between fire perimeters, controlling for areas with two or more overlapping fire perimeters and areas with three or more overlapping fire perimeters.

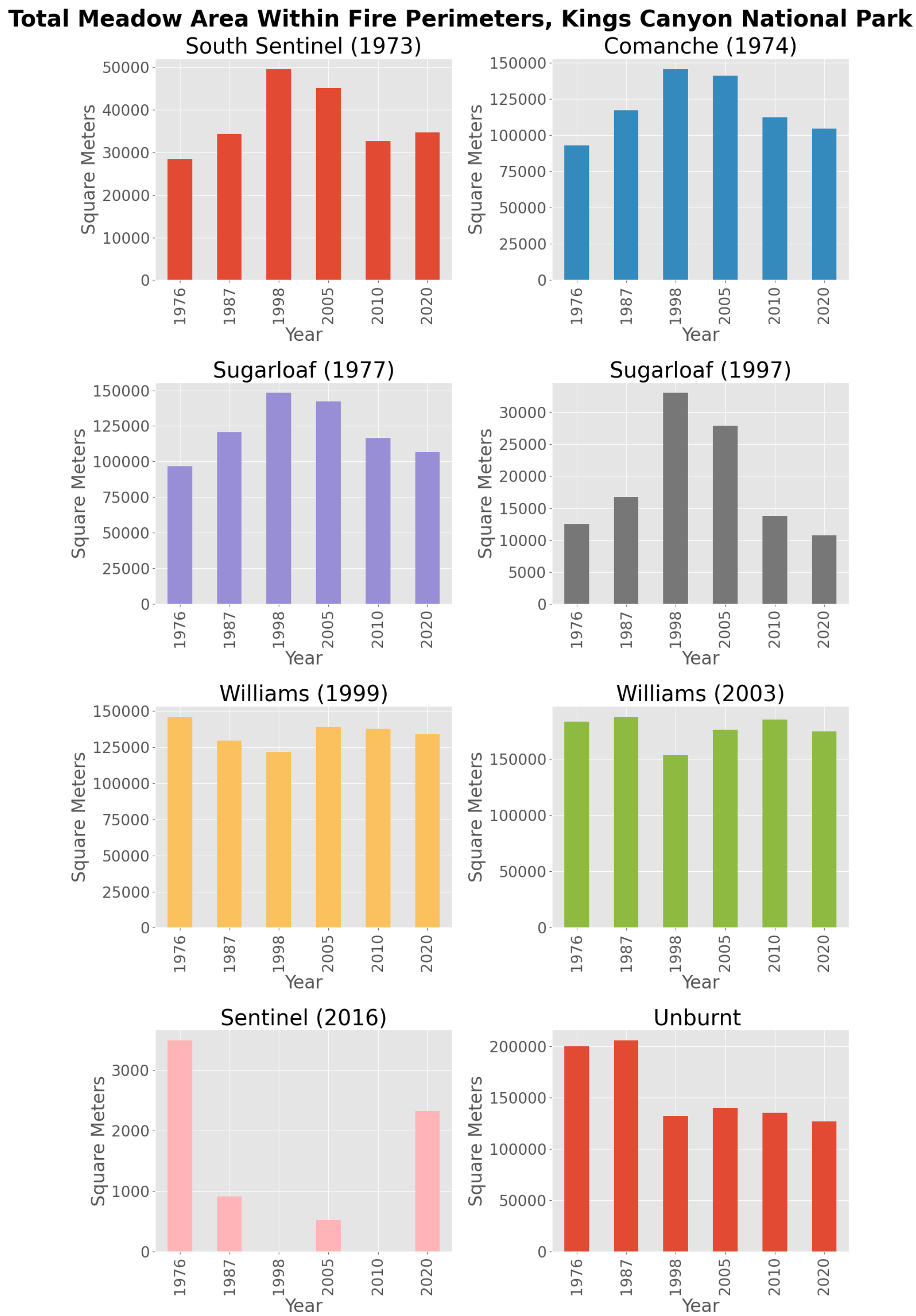

Figure 7. Change in meadow area over time, separated by perimeters of major fires in the study area. Years of each fire indicated to allow for analysis of potential change in meadow extent post-fire due to wildfire-initiated vegetation transition.

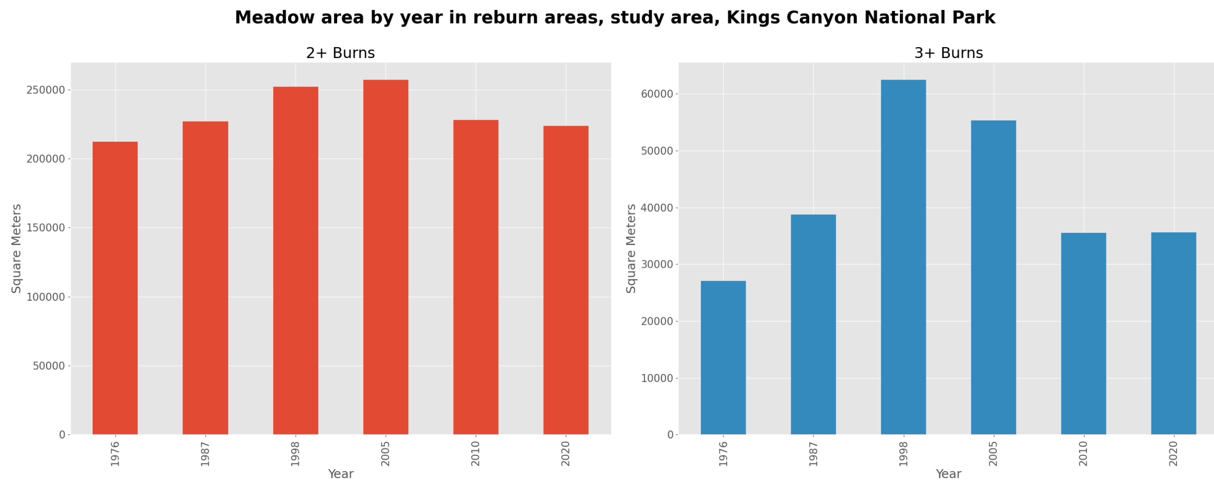

Figure 8. Change in meadow area over time, areas with multiple overlapping fire events during the study period. In the 3+ burn areas, fires occurred in 1973 (South Sentinel Fire), 1974 (Comanche Fire), 1977 (Sugarloaf Fire), and 1997 (Sugarloaf Fire)

4.3 Fire Return Interval Departure Analysis

One final way to interpret the results of the meadow classification is to stratify change in meadow area not simply by whether or not a fire occurred in that meadow or how many fires occurred, but by how frequently a meadow burned in the study period relative to how frequently it was estimated to have burned under precolonial fire regimes. This information exists in the form of the 2020 Fire Return Interval Departure (FRID) database for Sequoia and Kings Canyon National Parks hosted by the Department of the Interior. FRID was developed as a method of quantifying change in fire frequency in a given region over time to provide managers with information when prioritizing treatments. In the case of the dataset used for this research FRID was determined based on dendrochronological samples from fire-scarred trees and from relevant literature, which includes testimony from indigenous cultural leaders on the historic burning practices of the region's native tribes (Stephens et al. 2007, Safford and Water 2014). In the SEKI dataset areas were categorized as FRD class 1-4 representing extremity of departure from precolonial fire frequency, with 1 being the most fire deprived and 4 being most similar in fire regime to precolonial conditions. Overlapping the FRID shapefile with the classified meadows areas reveals that since 1972, meadow extent in FRID 1 areas has historically been scant in the study area, peaking at 309 m^2 in 1987, but does appear to have decreased with only 69 m^2 of meadow coverage in 2020. Meadow extent in FRID 3 areas (there were no FRID 2 areas in the study area) decreased from 154,066 m^2 in 1976 to 118,334 m^2 in 2020, with extent in FRID 4 areas remaining more stable, increasing from 348,102 m^2 in 1976 to 360,481 m^2 by 2005 before reducing in extent to 304,375 m^2 by 2020.

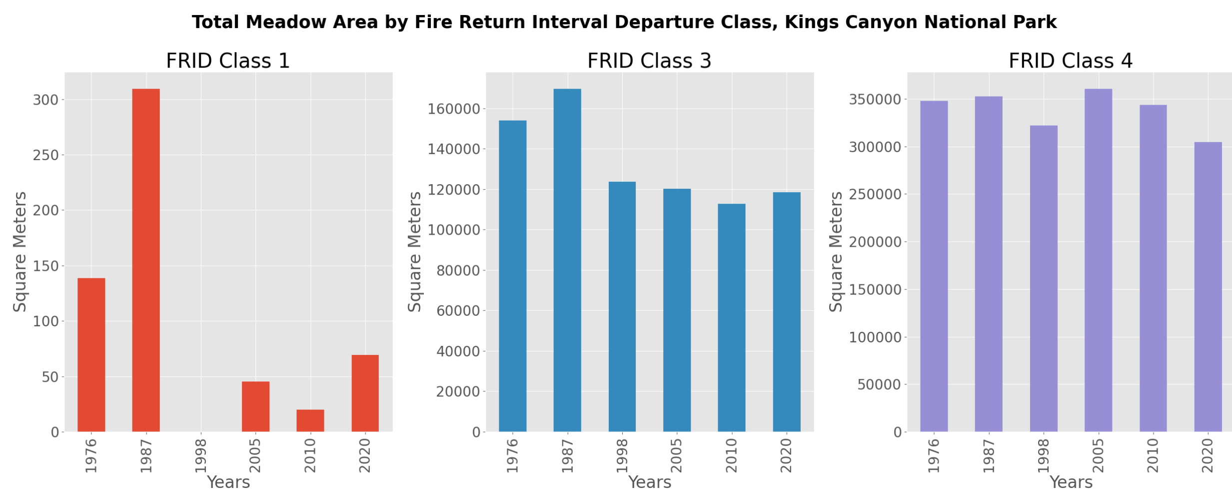

Figure 9. Change in meadow area over time, stratified by FRID class.

5. Discussion

5.1 Evidence for Managed Wildfire Increasing Meadow Area

In the approximately 16 km^2 area chosen as the study area for this research, there is evidence that fire regimes resembling pre-settlement levels contributed to higher meadow extent in burned areas when compared to fire-suppressed areas. Meadows that did not overlap with any fire perimeters since 1950 exhibited consistent reduction in extent over the study period, while meadows that overlapped with at least one fire perimeter shrunk at a slower rate and even increased in extent at certain temporal scales. This result is somewhat consistent with the findings of research in the Illilouette Creek Basin, which revealed increases of meadows area of 200% from 1972-2012 due to the presence of wildfire-initiated vegetation conversion (Boisrame et al. 2017, Saska et al. 2020). In the ICB, the proposed explanation for how wildfire led to increased meadow area over time was the reduction in evapotranspiration (ET) initiated by the removal of woody forest vegetation leading to higher water availability for meadow vegetation. If the meadow extent trends in Kings Canyon seen in this research can indeed be attributed to the presence of wildfire, it is likely in large part due to this same process. In a 2020 study investigating the hydrological impacts of 625 large fires in the SN from 1985 to 2018, ET reductions were found to be 265 mm yr^{-1} in the first year after a fire and 169 mm yr^{-1} in the next 15 years, with most significant reductions seen in dense mid-elevation forests (Ma et a. 2020). In the ICB specifically, frequent fire reducing forest cover by 20% is hypothesized to have contributed directly to higher streamflow and summer soil moisture in the basin when compared to surrounding areas (Boisrame et al. 2018, Saska et al. 2020, Rakhmatulina et al. 2021, Stephens et al. 2021). A study in the 125 km^2 Sugarloaf Creek Basin in Kings Canyon National Park expected to find similar vegetation change and increased soil moisture to that seen in the ICB. Instead, researchers found that lower productivity and relatively low fire frequency in the basin led to “greater stability in vegetation over time and a more muted hydrologic response to managed wildfire” when compared to the ICB (Stevens et al. 2020).

While no region of the study area for this research experienced anything like the 200% proliferation of meadow area seen in the ICB, the 31.58% increase in meadow area from 1976-2020 in meadows that burned three or more times stands in stark contrast to the 36.56% reduction in area in unburned meadows. This difference alligns with the theory that the meadow trends seen in this study area can be attributed at least in part to reduction in woody vegetation. Many studies have found that multiple consecutive fires are necessary to achieve conversion from forest to non-forest vegetation in the SN (White and Long 2019, Nemens et al. 2022, Paudel et al. 2022). The fires in question in the 3+ burn areas all occurred between 1973-1997, and from 1976-1998 meadow extent in those areas actually increased by 130.88%, the most marked increase seen in any of the meadow change analyses (See figure 8). This research suggests that if these reburn areas continued to burn / otherwise be treated in the years following 1998 that meadow extent would have stabilized at levels to closer to its maximum in the study period, or perhaps would have even continued to increase due to more persistent reduction of woody plant cover in meadow peripheries.

A more qualitative approach to analyzing the imagery used for the meadow classification in this study is useful for concretely visualizing the vegetation transition result suggested by trends in meadow area. One particular areas stood out as imagery was being visually inspected for manual reclassification, shown in figure 10. This figure represents the Northeastern boundary of a meadow close to the center of the study area that burned in 1999 and 2003. Comparing the 1998 image to the 2020 image shows an apparent reduction in tree cover and increase in bare soil and downed trees over time. While the classification component of this research does not account for change in forest cover due to the infeasabilty in rectifying the quality differences between images, this qualitative comparison shows an example of how fire has led to a decrease in woody vegetation cover in the peripheries of meadows that would likely increase water availability and suitable conditions for meadow vegetation. According to a National Parks Service SEKI Vegetation Inventory shapefile, the trees adjacent to this meadow are largely lodgepole pine. This species contributes to meadow conifer encroachment more than any other tree variety in the SN. Removal of lodgepole pines from meadow peripheries has been found to locally decrease depth to water table, an important predictor of the presence of meadow vegetation (Viers et al. 2013, Lubetkin et al. 2017). A 1984 study of Ellis Meadow, a meadow at 2,790 m elevation a mere 2,100 m from the study area in Kings Canyon, found that a 1977 lightning-ignited fire killed many lodgepole pine saplings in the forest / meadow boundary and contributed to increased presence of hydric vegetation in the meadow in the 5 years following the fire (DeBennedeti and Parsons 1984). These findings give credence to the hypothesis that the increase in meadow extent found in burned regions of this thesis research's study area is due in large part to the reversal of conifer encroachment.

Figure 10. Aerial images in 1998 (left) and 2020 (right) of study meadow that burned in 1999 and 2003, showing apparent long-term reduction in lodgepole pine cover

5.2 Limitations and Sources of Error

The biggest source of uncertainty in the classification of meadow areas for this research is the difference in quality between NAIP, NHAP, and assorted aerial photo single frame images retrieved from the USGS. While hypothetically a 1 m resolution was achieved for each of the 6 images through the orthorectification process in ERDAS Imagine, there are visual aberrations and imperfections in the older images. In particular, the NHAP image from 1998 had several areas that were partially obscured by what appeared to be lens distortion. Another issue with the images collected for this study is that while they are all from the same time of year, there is no way to be certain that they were taken at the same time of day, making shadows a potential source of error in meadow classification. Figure 11 shows a swipe created on ArcGIS Pro that exhibits the difference in the appearance of shadow coverage between the 1976 image and the 2020 image. The features seen in this swipe may also be a function of the difference in image quality between the two aerial images.

While the meadows on either side of Kings Canyon's "let-burn zone" were chosen due to their proximity making them useful to compare, these meadows do not share all hydrogeomorphological attributes, as seen in figure 2 and table 1. Differences in baseline groundwater availability and aquifer geometry, important components of Sierra Nevada meadow vegetation health, were not available for the study meadows (Ciruzzi and Lowry 2017, Hunt et al. 2018). In the classification process there may also be user error. Given that no true ground truthing was possible and comparison between meadow images was used in part for validation, there may have been a classification bias towards classifying areas as meadow that appeared as meadow in images from previous years.

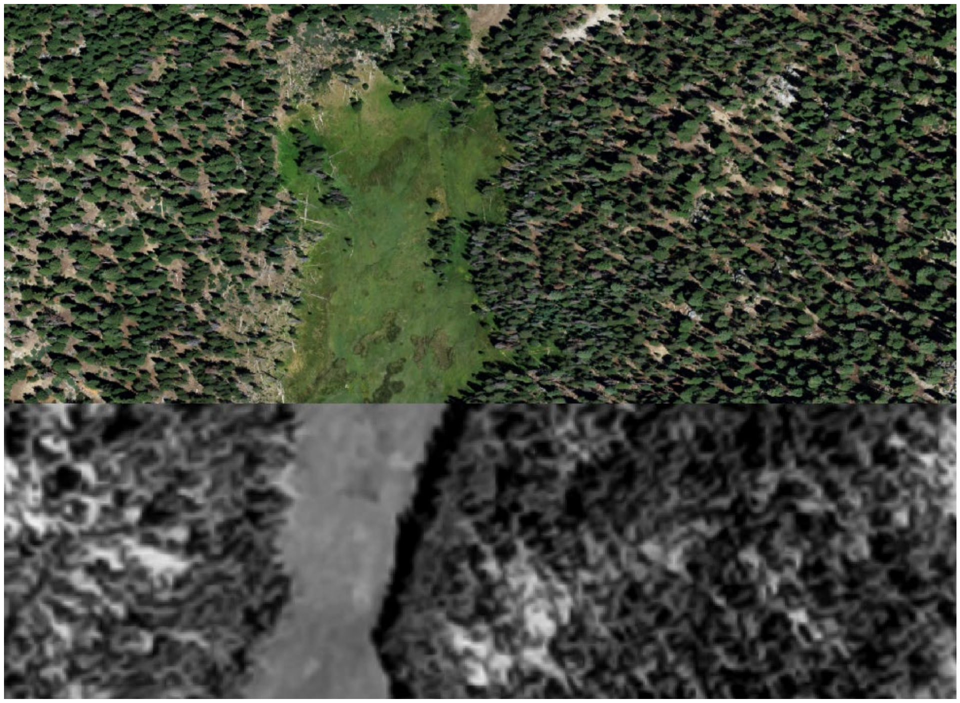

Figure 11. Differences in presence of shadow in study meadow, 1976 (bottom) and 2020 (top)

6. Conclusion

The results of the classification done for this study suggest that, over the last 60+ years, meadows in the study area that burned due to managed wildfire in King's Canyon National Park's "let-burn zone" experienced greater stability in their extent over time than nearby fire-suppressed meadows. This effect was likely achieved through fire limiting woody vegetation presence in meadow peripheries, reducing transpiration and providing higher water access to meadow vegetation. These results are consistent with what limited previous research exists on the role that fire plays in forming the forest-meadow boundary in the Sierra Nevada. As managed wildfire continues to be used as a tool for fuels reduction and ecosystem restoration in California in the decades to come, land managers and government agencies should be open to the possibility of new meadows being created through fire-driven vegetation type conversion and extant meadows increasing in size. New metrics should be designed to determine which fire-suppressed forest areas in the SN may have once represented meadow areas, based on historic fire regime reconstructions as well as topographic and climatic variables (White and Long 2019).

Fire may not always be a positive presence in SN meadow ecosystems, and fire alone may not always be enough to provide conditions for meadows to thrive. Tree and shrub cover being lost all at once due to high-severity fire has been found to cause large volumes of early snowmelt contributing to extreme erosion in downstream meadows. (Kattleman 1996). Meadow vegetation burning at high severity under uncharacteristically dry conditions can lead to higher likelihood of incision and channel degradation, lowering the water table and reducing the stable presence of meadow vegetation, a possibility that will become more likely due to continued climate warming (Ratliff 1985, Westerling 2016, Vernon et al. 2019). The Sugarloaf Creek Basin experienced managed wildfire over approximately the same period as the Illilouette Creek Basin, yet saw very little increase in meadow area, emphasizing the fact that basin characteristics can influence the extent to which fire can encourage meadow restoration/succession. Increased research attention should be paid to what forms of post-fire activities in burnt areas can contribute to the long-term presence of ecologically valuable non-forest vegetation. Mixed-severity fire may at times do very little on its own to combat conifer encroachment and encourage stable meadow presence, and treatments other than fire such as mechanical tree removal may be necessary to see the desired results (Frenzel 2012, White and Long 2019). Wildfire will likely restore some meadows unassisted by human activity, and other areas may need additional attention in the form of restoration techniques such as building beaver dam analogues, planting willows on streambanks (which both stabilizes banks and promotes beaver occupancy), and pond-and-plug (Pope et al. 2015, Vernon et al. 2019, Yarnell et al. 2019). With more research, the capabilities of managed wildfire as a catalyst for subalpine and montane meadow proliferation and stabilization can be realized. These fire-indebted meadows will provide habitat for wildlife, beneficially control streamflow, improve water quality, and store carbon efficiently for years to come.

References

Albano, Christine M., Meredith L. McClure, Shana E. Gross, Wesley Kitlasten, Christopher E. Soulard, Charles Morton, and Justin Huntington. "Spatial Patterns of Meadow Sensitivities to Interannual Climate Variability in the Sierra Nevada." *Ecohydrology* 12, no. 7 (October 2019). https://doi.org/10.1002/eco.2128.

Aragoneses, Elena, and Emilio Chuvieco. "Generation and Mapping of Fuel Types for Fire Risk Assessment." *Fire* 4, no. 3 (September 2021): 59. https://doi.org/10.3390/fire4030059.

Ashok, Amgoth, Hari Ponnamma Rani, and K. V. Jayakumar. "Monitoring of Dynamic Wetland Changes Using NDVI and NDWI Based Landsat Imagery." *Remote Sensing Applications: Society and Environment* 23 (August 1, 2021): 100547. https://doi.org/10.1016/j.rsase.2021.100547.

Badgley, Grayson, Freya Chay, Oriana Chegwidden, Joseph Hamman, Jeremy Freeman, and Danny Cullenward. "California's Forest Carbon Offsets Buffer Pool Is Severely Undercapitalized." *Frontiers in Forests and Global Change* 5 (August 1, 2022): 930426. https://doi.org/10.3389/ffgc.2022.930426.

Bancroft, L., T. Nichols, D. Parsons, D. Graber, B. Evison, and Jan van Wagtendonk. "Evolution of the Natural Fire Management Program at Sequoia and Kings Canyon National Parks," 1983.

Bernal, Alexis A., Scott L. Stephens, Brandon M. Collins, and John J. Battles. "Biomass Stocks in California's Fire-Prone Forests: Mismatch in Ecology and Policy." *Environmental Research Letters* 17, no. 4 (March 2022): 044047. https://doi.org/10.1088/1748-9326/ac576a.

Bixler, R. Patrick, Rebecca S. Epanchin-Niell, Mark W. Brunson, Ryan D. Tarver, Benjamin A. Sikes, Meredith McClure, and Clare E. Aslan. "How Social and Ecological Characteristics Shape Transaction Costs in Polycentric Wildfire Governance: Insights from the Sequoia-Kings Canyon Ecosystem, California, USA." *Ecology and Society* 28, no. 1 (March 1, 2023). https://doi.org/10.5751/ES-13834-280134.

Boisramé, Gabrielle F. S., Sally E. Thompson, Maggi Kelly, Julia Cavalli, Kate M. Wilkin, and Scott L. Stephens. "Vegetation Change during 40years of Repeated Managed Wildfires in the Sierra Nevada, California." *Forest Ecology and Management* 402 (October 15, 2017): 241–52. https://doi.org/10.1016/j.foreco.2017.07.034.

Boisramé, Gabrielle, Sally Thompson, and Scott Stephens. "Hydrologic Responses to Restored Wildfire Regimes Revealed by Soil Moisture-Vegetation Relationships." *Advances in Water Resources* 112 (February 2018): 124–46. https://doi.org/10.1016/j.advwatres.2017.12.009.

Botti, Stephen J. "THE YOSEMITE AND SEQUOIA-KINGS CANYON PRESCRIBED NATURAL FIRE PROGRAMS 1968-1978," n.d., 19.

Botti, Steve, and Tom Nichols. "National Park Service Fire Restoration, Policies versus Results: What Went Wrong." *Parks Stewardship Forum* 37, no. 2 (2021). https://doi.org/10.5070/P537253241.

Buechi, Hanna, Paige Weber, Sarah Heard, Dick Cameron, Andrew J. Plantinga, Hanna Buechi, Paige Weber, Sarah Heard, Dick Cameron, and Andrew J. Plantinga. "Long-Term Trends in Wildfire Damages in California." *International Journal of Wildland Fire* 30, no. 10 (August 20, 2021): 757–62. https://doi.org/10.1071/WF21024.

Campbell, Anthony D., Temilola Fatoyinbo, Sean P. Charles, Laura L. Bourgeau-Chavez, Joaquim Goes, Helga Gomes, Meghan Halabisky, et al. "A Review of Carbon Monitoring in Wet Carbon Systems Using Remote Sensing." *Environmental Research Letters* 17, no. 2 (February 2022): 025009. https://doi.org/10.1088/1748-9326/ac4d4d.

Caprio, Anthony, and Pat Lineback. "Pre-Twentieth Century Fire History of Sequoia and Kings Canyon National Parks: A Review and Evaluation of Our Knowledge." *Association for Fire Ecology Misc. Publ. No. 1* 1 (January 1, 2003): 180–99.

Ciruzzi, Dominick M., and Christopher S. Lowry. "Impact of Complex Aquifer Geometry on Groundwater Storage in High-Elevation Meadows of the Sierra Nevada Mountains, CA." *Hydrological Processes* 31, no. 10 (2017): 1863–75. https://doi.org/10.1002/hyp.11147.

Coffield, Shane R., Kyle S. Hemes, Charles D. Koven, Michael L. Goulden, and James T. Randerson. "Climate-Driven Limits to Future Carbon Storage in California's Wildland Ecosystems." *AGU Advances* 2, no. 3 (2021): e2021AV000384. https://doi.org/10.1029/2021AV000384.

Collins, Brandon M., and Gary B. Roller. "Early Forest Dynamics in Stand-Replacing Fire Patches in the Northern Sierra Nevada, California, USA." *Landscape Ecology* 28, no. 9 (November 2013): 1801–13. http://dx.doi.org/10.1007/s10980-013-9923-8.

Coop, Jonathan D, Sean A Parks, Camille S Stevens-Rumann, Shelley D Crausbay, Philip E Higuera, Matthew D Hurteau, Alan Tepley, et al. "Wildfire-Driven Forest Conversion in Western North American Landscapes." *BioScience* 70, no. 8 (August 2020): 659–73. https://doi.org/10.1093/biosci/biaa061.

Coppoletta, Michelle, Kyle E. Merriam, and Brandon M. Collins. “Post-Fire Vegetation and Fuel Development Influences Fire Severity Patterns in Reburns.” *Ecological Applications* 26, no. 3 (2016): 686–99.

Dass, Pawlok, Benjamin Z. Houlton, Yingping Wang, and David Warlind. “Grasslands May Be More Reliable Carbon Sinks than Forests in California.” *Environmental Research Letters* 13, no. 7 (July 2018): 074027. https://doi.org/10.1088/1748-9326/aacb39.

DeBenedetti, Steven H., and David J. Parsons. “Postfire Succession in a Sierran Subalpine Meadow.” *The American Midland Naturalist* 111, no. 1 (1984): 118–25. https://doi.org/10.2307/2425549.

Dosskey, Michael G., and Zeyuan Qiu. “Comparison of Indexes for Prioritizing Placement of Water Quality Buffers in Agricultural Watersheds1.” *JAWRA Journal of the American Water Resources Association* 47, no. 4 (2011): 662–71. https://doi.org/10.1111/j.1752-1688.2011.00532.x.

Dwire, Kathleen A., and J. Boone Kauffman. “Fire and Riparian Ecosystems in Landscapes of the Western USA.” *Forest Ecology and Management*, The Effect of Wildland Fire on Aquatic Ecosystems in the Western USA., 178, no. 1 (June 3, 2003): 61–74. https://doi.org/10.1016/S0378-1127(03)00053-7.

Frenzel, Erik. “Using Prescribed Fire to Restore Tree-Invaded Mountain Meadows: A Case Study from the Lake Tahoe Basin, California and Nevada USA,” 2012.

Garone, Philip. *The Fall and Rise of the Wetlands of California’s Great Central Valley*. 1st ed. University of California Press, 2011. https://www.jstor.org/stable/10.1525/j.ctt1pp4f6.

Gifford, Lauren. "'You Can't Value What You Can't Measure': A Critical Look at Forest Carbon Accounting." *Climatic Change* 161, no. 2 (July 1, 2020): 291–306. https://doi.org/10.1007/s10584-020-02653-1.

Grabs, T., J. Seibert, K. Bishop, and H. Laudon. "Modeling Spatial Patterns of Saturated Areas: A Comparison of the Topographic Wetness Index and a Dynamic Distributed Model." *Journal of Hydrology* 373, no. 1 (June 30, 2009): 15–23. https://doi.org/10.1016/j.jhydrol.2009.03.031.

Gross, Shana, and Michelle Coppoletta. "Historic Range of Variability for Meadows in the Sierra Nevada and South Cascades," n.d.

Guo, Meng, Jing Li, Chunlei Sheng, Jiawei Xu, and Li Wu. "A Review of Wetland Remote Sensing." *Sensors (Basel, Switzerland)* 17, no. 4 (April 5, 2017): 777. https://doi.org/10.3390/s17040777.

Herbert, Claudia, Barbara K. Haya, Scott L. Stephens, and Van Butsic. "Managing Nature-Based Solutions in Fire-Prone Ecosystems: Competing Management Objectives in California Forests Evaluated at a Landscape Scale." *Frontiers in Forests and Global Change* 5 (2022). https://www.frontiersin.org/articles/10.3389/ffgc.2022.957189.

Hinshaw, Sarah, and Ellen Wohl. "Quantitatively Estimating Carbon Sequestration Potential in Soil and Large Wood in the Context of River Restoration." *Frontiers in Earth Science* 9 (2021). https://www.frontiersin.org/article/10.3389/feart.2021.708895.

Hird, Jennifer N., Evan R. DeLancey, Gregory J. McDermid, and Jahan Kariyeva. "Google Earth Engine, Open-Access Satellite Data, and Machine Learning in Support of Large-Area

Probabilistic Wetland Mapping.” *Remote Sensing* 9, no. 12 (December 2017): 1315. https://doi.org/10.3390/rs9121315.

Hunt, Luke J.H., Julie Fair, and Maxwell Odland. “Meadow Restoration Increases Baseflow and Groundwater Storage in the Sierra Nevada Mountains of California.” *JAWRA Journal of the American Water Resources Association* 54, no. 5 (2018): 1127–36. https://doi.org/10.1111/1752-1688.12675.

Huntington, Gordon L., and Mark A. Akeson. “Soil Resource Inventory of Sequoia National Park, Central Part, California,” September 1, 1987. https://escholarship.org/uc/item/2x96d3sn.

Jackson, Breeanne K., S. Mažeika P. Sullivan, Breeanne K. Jackson, and S. Mažeika P. Sullivan. “Influence of Wildfire Severity on Geomorphic Features and Riparian Vegetation of Forested Streams of the Sierra Nevada, California, USA.” *International Journal of Wildland Fire* 29, no. 7 (March 31, 2020): 611–17. https://doi.org/10.1071/WF19114.

Kattelman, R., M. Embury. Riparian areas and wetlands. Sierra Nevada Ecosystem Project, Final Report to Congress; 1996

Keeley, Jon E., Anne Pfaff, Anthony C. Caprio, Jon E. Keeley, Anne Pfaff, and Anthony C. Caprio. “Contrasting Prescription Burning and Wildfires in California Sierra Nevada National Parks and Adjacent National Forests.” *International Journal of Wildland Fire* 30, no. 4 (February 4, 2021): 255–68. https://doi.org/10.1071/WF20112.

Kennedy, Brian, Alec Tyson, and Cary Funk. “Americans Divided Over Direction of Biden’s Climate Change Policies.” *Pew Research Center Science & Society* (blog), July 14, 2022.

https://www.pewresearch.org/science/2022/07/14/americans-divided-over-direction-of-bidens-climate-change-policies/.

Kilgore, Bruce M. "Fire Management in the National Parks: An Overview," (1972), 13.

Kilgore, Bruce M. "Origin and History of Wildland Fire Use in the U.S. National Park System." *The George Wright Forum* 24, no. 3 (2007): 92–122.

Kobziar, Leda N., and Joe R. McBride. "Wildfire Burn Patterns and Riparian Vegetation Response along Two Northern Sierra Nevada Streams." *Forest Ecology and Management* 222, no. 1 (February 15, 2006): 254–65. https://doi.org/10.1016/j.foreco.2005.10.024.

Lee, Steven. "Detecting Wetland Change through Supervised Classification of Landsat Satellite Imagery within the Tunkwa Watershed of British Columbia, Canada," n.d., 59.

Lee, Steven R., Eric L. Berlow, Steven M. Ostoja, Matthew L. Brooks, Alexandre Génin, John R. Matchett, and Stephen C. Hart. "A Multi-Scale Evaluation of Pack Stock Effects on Subalpine Meadow Plant Communities in the Sierra Nevada." *PLOS ONE* 12, no. 6 (June 13, 2017): e0178536. https://doi.org/10.1371/journal.pone.0178536.

Liang, Shuang, Matthew D. Hurteau, and Anthony LeRoy Westerling. "Response of Sierra Nevada Forests to Projected Climate–Wildfire Interactions." *Global Change Biology* 23, no. 5 (2017): 2016–30. https://doi.org/10.1111/gcb.13544.

Liang, Shuang, Matthew D. Hurteau, and Anthony LeRoy Westerling. "Potential Decline in Carbon Carrying Capacity under Projected Climate-Wildfire Interactions in the Sierra Nevada." *Scientific Reports* 7, no. 1 (May 25, 2017): 2420. https://doi.org/10.1038/s41598-017-02686-0.

Liu, Qionghuan, Yili Zhang, Linshan Liu, Zhaofeng Wang, Yong Nie, and Mohan Kumar Rai. "A Novel Landsat-Based Automated Mapping of Marsh Wetland in the Headwaters of the Brahmaputra, Ganges and Indus Rivers, Southwestern Tibetan Plateau." *International Journal of Applied Earth Observation and Geoinformation* 103 (December 1, 2021): 102481. https://doi.org/10.1016/j.jag.2021.102481.

Loheide, Steven P., Richard S. Deitchman, David J. Cooper, Evan C. Wolf, Christopher T. Hammersmark, and Jessica D. Lundquist. "A Framework for Understanding the Hydroecology of Impacted Wet Meadows in the Sierra Nevada and Cascade Ranges, California, USA." *Hydrogeology Journal* 1, no. 17 (2009): 229–46. https://doi.org/10.1007/s10040-008-0380-4.

Lubetkin, Kaitlin C., Anthony LeRoy Westerling, and Lara M. Kueppers. "Climate and Landscape Drive the Pace and Pattern of Conifer Encroachment into Subalpine Meadows." *Ecological Applications* 27, no. 6 (2017): 1876–87. https://doi.org/10.1002/eap.1574.

Lubetkin, Kaitlin Cantelow. "Extent and Causes of Conifer Encroachment into Subalpine Meadows in the Central Sierra Nevada." UC Merced, 2015. https://escholarship.org/uc/item/8f4273z4.

Lumbierres, Maria, Pablo F. Méndez, Javier Bustamante, Ramón Soriguer, and Luis Santamaría. "Modeling Biomass Production in Seasonal Wetlands Using MODIS NDVI Land Surface Phenology." *Remote Sensing* 9, no. 4 (April 2017): 392. https://doi.org/10.3390/rs9040392.

Lutz, James A., John R. Matchett, Leland W. Tarnay, Douglas F. Smith, Kendall M. L. Becker, Tucker J. Furniss, and Matthew L. Brooks. "Fire and the Distribution and Uncertainty of Carbon Sequestered as Aboveground Tree Biomass in Yosemite and Sequoia & Kings Canyon National Parks." *Land* 6, no. 1 (March 2017): 10. https://doi.org/10.3390/land6010010.

Lydersen, Jamie M., and Brandon M. Collins. "Change in Vegetation Patterns Over a Large Forested Landscape Based on Historical and Contemporary Aerial Photography." *Ecosystems* 21, no. 7 (November 2018): 1348–63. https://doi.org/10.1007/s10021-018-0225-5.

Lynch, Abigail J, Laura M Thompson, John M Morton, Erik A Beever, Michael Clifford, Douglas Limpinsel, Robert T Magill, et al. "RAD Adaptive Management for Transforming Ecosystems." *BioScience* 72, no. 1 (January 1, 2022): 45–56. https://doi.org/10.1093/biosci/biab091.

Ma, Qin, Roger C. Bales, Joseph Rungee, Martha H. Conklin, Brandon M. Collins, and Michael L. Goulden. "Wildfire Controls on Evapotranspiration in California's Sierra Nevada." *Journal of Hydrology* 590 (November 1, 2020): 125364. https://doi.org/10.1016/j.jhydrol.2020.125364.

McIntyre, Patrick, James Thorne, Christopher Dolanc, Alan Flint, Lorraine Flint, Maggi Kelly, and David Ackerly. "Twentieth-Century Shifts in Forest Structure in California: Denser Forests, Smaller Trees, and Increased Dominance of Oaks." *Proceedings of the National Academy of Sciences* 112 (January 21, 2015). https://doi.org/10.1073/pnas.1410186112.

Miller, Jay D., Brandon M. Collins, James A. Lutz, Scott L. Stephens, Jan W. van Wagtendonk, and Donald A. Yasuda. "Differences in Wildfires among Ecoregions and Land Management Agencies in the Sierra Nevada Region, California, USA." *Ecosphere* 3, no. 9 (2012): art80. https://doi.org/10.1890/ES12-00158.1.

Minnich, Richard A., Michael G. Barbour, Jack H. Burk, and Robert F. Fernau. "Sixty Years of Change in Californian Conifer Forests of the San Bernardino Mountains." *Conservation Biology* 9, no. 4 (1995): 902–14.

Nahlik, A. M., and M. S. Fennessy. "Carbon Storage in US Wetlands." *Nature Communications* 7, no. 1 (December 13, 2016): 13835. https://doi.org/10.1038/ncomms13835.

Naranjo, Miguel A. "Characterizing and Modeling Post-fire Vegetation Change in The Illilouette Creek Basin". (2015)

National Parks Service. "Plants - Sequoia & Kings Canyon National Parks (U.S. National Park Service)." Accessed June 3, 2023. https://www.nps.gov/seki/learn/nature/plants.htm.

Nave, Lucas E., Grant M. Domke, Kathryn L. Hofmeister, Umakant Mishra, Charles H. Perry, Brian F. Walters, and Christopher W. Swanston. "Reforestation Can Sequester Two Petagrams of Carbon in US Topsoils in a Century." *Proceedings of the National Academy of Sciences* 115, no. 11 (March 13, 2018): 2776–81. https://doi.org/10.1073/pnas.1719685115.

Nemens, Deborah G., Kathryn R. Kidd, J. Morgan Varner, and Brian Wing. "Recurring Wildfires Provoke Type Conversion in Dry Western Forests." *Ecosphere* 13, no. 8 (2022): e4184. https://doi.org/10.1002/ecs2.4184.

Nesmith, Jonathan C. B., Kevin L. O'Hara, Phillip J. van Mantgem, and Perry de Valpine. "The Effects of Raking on Sugar Pine Mortality Following Prescribed Fire in Sequoia and Kings Canyon National Parks, California, USA." *Fire Ecology* 6, no. 3 (December 2010): 97–116. https://doi.org/10.4996/fireecology.0603097.

Norman, Steven P., and Alan H. Taylor. "Pine Forest Expansion along a Forest-Meadow Ecotone in Northeastern California, USA." *Forest Ecology and Management* 215, no. 1 (August 25, 2005): 51–68. https://doi.org/10.1016/j.foreco.2005.05.003.

North, Malcolm, April Brough, Jonathan Long, Brandon Collins, Phil Bowden, Don Yasuda, Jay Miller, and Neil Sugihara. "Constraints on Mechanized Treatment Significantly Limit Mechanical Fuels Reduction Extent in the Sierra Nevada." *Journal of Forestry* 113, no. 1 (January 18, 2015): 40–48. https://doi.org/10.5849/jof.14-058.

Norton, Jay B, William R Horwath, and Kenneth W Tate. "Soil Carbon and Land Use in Upper Montane and Subalpine Sierra Nevada Meadows," n.d.

Norton, Jay B., Hayley R. Olsen, Laura J. Jungst, David E. Legg, and William R. Horwath. "Soil Carbon and Nitrogen Storage in Alluvial Wet Meadows of the Southern Sierra Nevada Mountains, USA." *Journal of Soils and Sediments* 14, no. 1 (January 1, 2014): 34–43. https://doi.org/10.1007/s11368-013-0797-9.

Osborne, Todd Z., Leda N. Kobziar, and Patrick W. Inglett. "Fire and Water: New Perspectives on Fire's Role in Shaping Wetland Ecosystems." *Fire Ecology* 9, no. 1 (April 2013): 1–5. https://doi.org/10.4996/fireecology.0901001.

Paudel, Asha, Michelle Coppoletta, Kyle Merriam, and Scott H. Markwith. "Persistent Composition Legacy and Rapid Structural Change Following Successive Fires in Sierra

Nevada Mixed Conifer Forests." *Forest Ecology and Management* 509 (April 1, 2022): 120079. https://doi.org/10.1016/j.foreco.2022.120079.

Pope, K. L., D. S. Montoya, J. N. Brownlee, J. Dierks, and T. E. Lisle. "Habitat Conditions of Montane Meadows Associated with Restored and Unrestored Stream Channels of California." *Ecological Restoration* 33, no. 1 (March 1, 2015): 61–73. https://doi.org/10.3368/er.33.1.61.

Prasai, Ritika, T. Wayne Schwertner, Kumar Mainali, Heather Mathewson, Hemanta Kafley, Swosthi Thapa, Dinesh Adhikari, Paul Medley, and Jason Drake. "Application of Google Earth Engine Python API and NAIP Imagery for Land Use and Land Cover Classification: A Case Study in Florida, USA." *Ecological Informatics* 66 (December 1, 2021): 101474. https://doi.org/10.1016/j.ecoinf.2021.101474.

Purdy, Sabra E, and Peter B Moyle. "Mountain Meadows of the Sierra Nevada," (2006): 54.

Quintana, Camila. "Changing aboveground carbon from fire suppression to natural fire regime", (2018).

Rakhmatulina, Ekaterina, Gabrielle Boisramé, Scott L. Stephens, and Sally Thompson. "Hydrological Benefits of Restoring Wildfire Regimes in the Sierra Nevada Persist in a Warming Climate." *Journal of Hydrology* 593 (February 1, 2021): 125808. https://doi.org/10.1016/j.jhydrol.2020.125808.

Ratliff, Raymond D. *Meadows in the Sierra Nevada of California: State of Knowledge*. U.S. Department of Agriculture, Forest Service, Pacific Southwest Forest and Range Experiment Station, (1985).

Reed, Cody C. “Soil Carbon Dynamics in Montane Meadows of the Sierra Nevada and Southern Cascade Mountain Ranges.” Ph.D., University of Nevada, Reno. Accessed April 13, 2022. https://www.proquest.com/docview/2480222730/abstract/82B4835AF4024792PQ/1.

Reed, Cody C., Amy G. Merrill, W. Mark Drew, Beth Christman, Rachel A. Hutchinson, Levi Keszey, Melissa Odell, et al. “Montane Meadows: A Soil Carbon Sink or Source?” *Ecosystems* 24, no. 5 (August 2021): 1125–41. https://doi.org/10.1007/s10021-020-00572-x.

Rideout, Douglas B., and Yu Wei. “A Probabilistic Landscape Analysis Supporting the Management of Unplanned Ignitions at Sequoia and Kings Canyon National Parks.” *Journal of Sustainable Forestry* 32, no. 5 (July 4, 2013): 437–55. https://doi.org/10.1080/10549811.2012.760470.

Roche, Leslie M., Anthony T. O’Geen, Andrew M. Latimer, and Danny J. Eastburn. “Montane Meadow Hydropedology, Plant Community, and Herbivore Dynamics.” *Ecosphere* 5, no. 12 (2014): art150. https://doi.org/10.1890/ES14-00173.1.

Roganda, M. S., Sigit Heru Murti, and Wirastuti Widyatmanti. “Mapping the Distribution of Natural Ecosystems on Peatlands through Vegetation Using the Object-Based Image Analysis (Obia) Method in Bangko District, Rokan Hilir Regency, Riau.” *IOP Conference Series: Earth and Environmental Science* 1047, no. 1 (July 2022): 012017. https://doi.org/10.1088/1755-1315/1047/1/012017.

Sabat-Tomala, Anita, Edwin Raczko, and Bogdan Zagajewski. “Comparison of Support Vector Machine and Random Forest Algorithms for Invasive and Expansive Species

Classification Using Airborne Hyperspectral Data." *Remote Sensing* 12, no. 3 (January 2020): 516. https://doi.org/10.3390/rs12030516.

Safford, Hugh D., and Kip M. Van De Water. "Using Fire Return Interval Departure (FRID) Analysis to Map Spatial and Temporal Changes in Fire Frequency on National Forest Lands in California." Albany, CA: U.S. Department of Agriculture, Forest Service, Pacific Southwest Research Station, 2014. https://doi.org/10.2737/PSW-RP-266.

Saksa, Phil C., Martha H. Conklin, Christina L. Tague, and Roger C. Bales. "Hydrologic Response of Sierra Nevada Mixed-Conifer Headwater Catchments to Vegetation Treatments and Wildfire in a Warming Climate." *Frontiers in Forests and Global Change* 3 (2020). https://doi.org/10.3389/ffgc.2020.539429.

Scholl, Andrew E., and Alan H. Taylor. "Fire Regimes, Forest Change, and Self-Organization in an Old-Growth Mixed-Conifer Forest, Yosemite National Park, USA." *Ecological Applications* 20, no. 2 (2010): 362–80. https://doi.org/10.1890/08-2324.1.

Sekhon, Jasjeet S. "Multivariate and Propensity Score Matching Software with Automated Balance Optimization: The **Matching** Package for *R*." *Journal of Statistical Software* 42, no. 7 (2011). https://doi.org/10.18637/jss.v042.i07.

Silverman, Nicholas L., Brady W. Allred, John Patrick Donnelly, Teresa B. Chapman, Jeremy D. Maestas, Joseph M. Wheaton, Jeff White, and David E. Naugle. "Low-Tech Riparian and Wet Meadow Restoration Increases Vegetation Productivity and Resilience across Semiarid Rangelands." *Restoration Ecology* 27, no. 2 (2019): 269–78. https://doi.org/10.1111/rec.12869.

Smith, O., and H. Cho. "AN OPEN-SOURCE CANOPY CLASSIFICATION SYSTEM USING MACHINE-LEARNING TECHNIQUES WITHIN A PYTHON FRAMEWORK." *The International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences* XLVI-4/W2-2021 (August 19, 2021): 175–82. https://doi.org/10.5194/isprs-archives-XLVI-4-W2-2021-175-2021.

Soulard, Christopher E., Christine M. Albano, Miguel L. Villarreal, and Jessica J. Walker. "Continuous 1985–2012 Landsat Monitoring to Assess Fire Effects on Meadows in Yosemite National Park, California." *Remote Sensing* 8, no. 5 (May 2016): 371. https://doi.org/10.3390/rs8050371.

Steel, Zachary L., Gavin M. Jones, Brandon M. Collins, Rebecca Green, Alexander Koltunov, Kathryn L. Purcell, Sarah C. Sawyer, et al. "Mega-Disturbances Cause Rapid Decline of Mature Conifer Forest Habitat in California." *Ecological Applications* n/a, no. n/a (2022): e2763. https://doi.org/10.1002/eap.2763.

Steel, Zachary L., Hugh D. Safford, and Joshua H. Viers. "The Fire Frequency-Severity Relationship and the Legacy of Fire Suppression in California Forests." *Ecosphere* 6, no. 1 (2015): art8. https://doi.org/10.1890/ES14-00224.1.

Stephens, Scott L., and Lawrence W. Ruth. "Federal Forest-Fire Policy in the United States." *Ecological Applications* 15, no. 2 (2005): 532–42.

Stephens, Scott L., Robert E. Martin, and Nicholas E. Clinton. "Prehistoric Fire Area and Emissions from California's Forests, Woodlands, Shrublands, and Grasslands." *Forest Ecology and Management* 251, no. 3 (November 2007): 205–16. https://doi.org/10.1016/j.foreco.2007.06.005.

Stephens, Scott L., Sally Thompson, Gabrielle Boisramé, Brandon M. Collins, Lauren C. Ponisio, Ekaterina Rakhmatulina, Zachary L. Steel, Jens T. Stevens, Jan W. van Wagtendonk, and Kate Wilkin. "Fire, Water, and Biodiversity in the Sierra Nevada: A Possible Triple Win." *Environmental Research Communications* 3, no. 8 (August 2021): 081004. https://doi.org/10.1088/2515-7620/ac17e2.

Stephens, Scott L, A LeRoy Westerling, Matthew D Hurteau, M Zachariah Peery, Courtney A Schultz, and Sally Thompson. "Fire and Climate Change: Conserving Seasonally Dry Forests Is Still Possible." *Frontiers in Ecology and the Environment* 18, no. 6 (2020): 354–60. https://doi.org/10.1002/fee.2218.

Stephenson, Nathan L. "Climatic Control of Vegetation Distribution: The Role of the Water Balance." *The American Naturalist* 135, no. 5 (May 1990): 649–70. https://doi.org/10.1086/285067.

Surfleet, Christopher, Thomas Sanford, Gregory VanOosbree, and John Jasbinsek. "Hydrologic Response of Meadow Restoration the First Year Following Removal of Encroached Conifers." *Water* 11, no. 3 (March 2019): 428. https://doi.org/10.3390/w11030428.

Swetnam, Thomas W., Christopher H. Baisan, Anthony C. Caprio, Peter M. Brown, Ramzi Touchan, R. Scott Anderson, and Douglas J. Hallett. "Multi-Millennial Fire History of the Giant Forest, Sequoia National Park, California, USA." *Fire Ecology* 5, no. 3 (December 2009): 120–50. https://doi.org/10.4996/fireecology.0503120.

Tangen, Brian A., and Sheel Bansal. "Soil Organic Carbon Stocks and Sequestration Rates of Inland, Freshwater Wetlands: Sources of Variability and Uncertainty." *Science of The*

Total Environment 749 (December 20, 2020): 141444. https://doi.org/10.1016/j.scitotenv.2020.141444.

Theobald, David M. "A General Model to Quantify Ecological Integrity for Landscape Assessments and US Application." *Landscape Ecology* 28, no. 10 (December 1, 2013): 1859–74. https://doi.org/10.1007/s10980-013-9941-6.

Uhran, Bergit, Lisamarie Windham-Myers, Norman Bliss, Amanda M. Nahlik, Eric T. Sundquist, and Camille L. Stagg. "Improved Wetland Soil Organic Carbon Stocks of the Conterminous U.S. Through Data Harmonization." *Frontiers in Soil Science* 1 (2021). https://www.frontiersin.org/article/10.3389/fsoil.2021.706701.

USDA. "Official Series Description - BUCKING Series." Accessed June 3, 2023. https://soilseries.sc.egov.usda.gov/OSD_Docs/B/BUCKING.html.

Vankat, John L. "Fire and Man in Sequoia National Park." *Annals of the Association of American Geographers* 67, no. 1 (1977): 17–27.

VAN WAGTENDONK, JAN W., JO ANN FITES-KAUFMAN, HUGH D. SAFFORD, MALCOLM P. NORTH, and BRANDON M. COLLINS. "Sierra Nevada Bioregion." In *Fire in California's Ecosystems*, edited by JAN W. VAN WAGTENDONK, JO ANN FITES-KAUFMAN, NEIL G. SUGIHARA, SCOTT L. STEPHENS, ANDREA E. THODE, and KEVIN E. SHAFFER, 2nd ed., 249–78. University of California Press, 2018. http://www.jstor.org/stable/10.1525/j.ctv1wxrxh.19.

Vanderhoof, Melanie K., Todd J. Hawbaker, Casey Teske, Andrea Ku, Joe Noble, and Josh Picotte. "Mapping Wetland Burned Area from Sentinel-2 across the Southeastern United

States and Its Contributions Relative to Landsat-8 (2016–2019).” *Fire* 4, no. 3 (September 2021): 52. https://doi.org/10.3390/fire4030052.

Viers, J.; Purdy, S.; Peek, R.; Fryjoff-Hung, A.; Santos, N.; Katz, J.; Emmons, J.; Dolan, D.; Yarnell, S. *Montane Meadows in the Sierra Nevada: Changing Hydroclimatic Conditions and Concepts for Vulnerability Assessment*; Center for Watershed Sciences Technical Report (CWS-2013-01); University of California: Davis, CA, USA, 2013; 63p

Vernon, Marian E., Brent R. Campos, and Ryan D. Burnett. “Effects of Livestock Grazing On The Ecology Of Sierra Meadows: A Review of The Current State of Scientific Knowledge To Inform Meadow Restoration And Management.” *Environmental Management* 69, no. 6 (June 2022): 1118–36. https://doi.org/10.1007/s00267-022-01634-7.

Vernon, M. E., B. R. Campos, and R. D. Burnett. “A guide to climate-smart meadow restoration in the Sierra Nevada and southern Cascades”. Point Blue Contribution. (2019)

Wagtendonk, Van, and Jan W. “The History and Evolution of Wildland Fire Use.” *Fire Ecology* 3, no. 2 (December 2007): 3–17. https://doi.org/10.4996/fireecology.0302003.

Weixelman, D. A., B. Hill, D. J. Cooper, E. L. Berlow, J. H. Viers, S. E. Purdy, A. G. Merrill, and S. G. Gross. “Meadow Hydrogeomorphic Types for the Sierra Nevada and Suuthern Cascade Ranges in California - A Field Key”. (2011): Page 34 in U. S. D. o. Agriculuture, editor. U.S. Department of Agriculture, Forest Service, Pacific Southwest Region, Vallejo, CA.

Wells, Adam G., Seth M. Munson, Steven E. Sesnie, and Miguel L. Villarreal. “Remotely Sensed Fine-Fuel Changes from Wildfire and Prescribed Fire in a Semi-Arid Grassland.” *Fire* 4, no. 4 (December 2021): 84. https://doi.org/10.3390/fire4040084.

White, Angela M., and Jonathan W. Long. “Understanding Ecological Contexts for Active Reforestation Following Wildfires.” *New Forests* 50, no. 1 (January 2019): 41–56. https://doi.org/10.1007/s11056-018-9675-z.

Williams, A. Park, John T. Abatzoglou, Alexander Gershunov, Janin Guzman-Morales, Daniel A. Bishop, Jennifer K. Balch, and Dennis P. Lettenmaier. “Observed Impacts of Anthropogenic Climate Change on Wildfire in California.” *Earth's Future* 7, no. 8 (August 1, 2019): 892–910. https://doi.org/10.1029/2019EF001210.

Williams, A. Park, Ben Livneh, Karen A. McKinnon, Winslow D. Hansen, Justin S. Mankin, Benjamin I. Cook, Jason E. Smerdon, et al. “Growing Impact of Wildfire on Western US Water Supply.” *Proceedings of the National Academy of Sciences* 119, no. 10 (March 8, 2022): e2114069119. https://doi.org/10.1073/pnas.2114069119.

Xie, Yichun, Anbing Zhang, and William Welsh. “Mapping Wetlands and <I>Phragmites</I> Using Publically Available Remotely Sensed Images.” *Photogrammetric Engineering & Remote Sensing* 81, no. 1 (January 1, 2015): 69–78. https://doi.org/10.14358/PERS.81.1.69.

Youngstrum, Gavin. “TREE MORTALITY ANALYSIS OF GIANT SEQUOIA GROVES IN SEQUOIA AND KINGS CANYON NATIONAL PARK,” August 2021. https://repository.arizona.edu/handle/10150/661332.