# FINAL REPORT

## Title: Outcomes Prioritization on Fuel Treatment Placement in Extreme Fire Weather in 3 CFLRP Landscapes

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# Table of Contents

# List of Tables

# List of Figures

# List of Abbreviations

AGC – Aboveground Carbon
BAU – Business as usual
CA - California

DFFS - Dynamic Fire and Fuels System
FIA – Forest Inventory Analysis
FL - Florida
FRP – Fire rotation period
NECN – Net Ecosystem Carbon & Nitrogen
OR - Oregon
SSURGO - Soil Survey Geographic Database
USDA – United States Department of Agriculture
USGS – United States Geological Survey

# Keywords

Collaborative Forest Landscape Restoration Program
Osceola National Forest
Malheur National Forest
Dinkey Creek watershed
Fuel treatments
Wildland fire
Prescribed fire
Carbon
Extreme fire weather
LANDIS-II
Landscape simulation modeling
Forest disturbance

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# Abstract

Active forest management practices for reducing fire risk and enhancing forest integrity have become necessary in many U.S. forests. The risks of inaction and escalating costs of continued fire suppression far outweigh the risks of implementation. If the goal is to maximize the long-term efficacy of treatments, then creating and maintaining a more fire-resilient forest should be a priority. Strategic placement of thinning treatments coupled with regular prescribed fire could expand the efficacy of treatments in terms of long-term forest integrity over larger portions of the landscape. Predicting landscape fuel treatment effectiveness is confounded by uncertainty in future fire weather, especially during more “extreme” fire weather conditions that are likely to occur as the climate warms, with increasing frequency and variability throughout this century. We focused our research on three landscapes associated with the federal Collaborative Forest Landscape Restoration Program, namely the Dinkey Creek watershed: within the Sierra National Forest (NF), Malheur NF, and Osceola NF, which all have ongoing fuel treatment programs. The overall objective of this study was to develop prioritization strategies for implementing fuel treatments across these three landscapes, with the goal of maximizing treatment efficacy using optimal placement and prescriptions under extreme fire weather conditions to create more fire resilient landscapes. For all three landscapes, we used the Landscape Disturbance and Succession model, LANDIS-II v.6.0, which is used for understanding ecosystem dynamics, feedbacks associated with wildfire, and fuel treatment effectiveness across space and time. We simulated the regeneration and growth of vegetation, detritus and soil nutrient cycling, heterotrophic respiration, stochastic wildfires, and forest treatments (harvesting, thinning, and prescribed fire). We implemented multiple model scenarios, namely a no-management scenario to determine landscape fire risk, a typical fuel treatment scenario, a prioritized treatments scenario based on simulated fire risk from the no-management scenario. These scenarios were run with contemporary and extreme fire weather conditions. For all three study sites, we found that prioritizing treatments to simulated high fire risk areas yielded comparable treatment efficacy to the other less strategic or typical approaches, but with fewer management inputs. Treatment efficacy is strictly from the landscape perspective, in terms of enhancing carbon sequestration potential, reducing wildfire area burned and reducing fire severity. This provides managers with a model-informed decision framework that can be used for developing spatial placement options for long-term treatment planning. Importantly, the continued application of prescribed fire in perpetuity was required in all instances to maintain landscape scale benefits. Our results suggest that using treated areas to restore surface fire within and between stands in the short-term can yield long-term carbon storage gains (i.e. low overstory mortality through time) across the landscape, particularly later in the century when extreme fire weather is more likely to occur. Long-term prescribed fires maintained a fire-resilient system in terms of increasing forest carbon sequestration potential, reducing long-term emissions from wildfire (when compared to no-management projections), reducing the intensity and severity of wildfires when they do occur in those areas, and is considerably less expensive than mechanical treatments. Only at the more local scale did we find site-specific effects between the treatment placement scenarios. As such, the consideration of localized effects is often site-specific and reliant on local expertise and careful planning. Long-term prioritization approaches to implementing treatment, particularly with the continuation of prescribed fire has been found here to be the most optimal approaches to maintaining carbon stability and increasing fire resilience.

# Objectives

The overall objective of this study was to develop prioritization strategies for implementing fuel treatments across three CFLRP landscapes, with the goal of maximizing treatment efficacy using optimal placement and prescriptions under extreme fire weather conditions to create more fire resilient landscapes. We defined treatment efficacy as the ability to minimize fire severity across the landscape. We simulated multiple scenarios for each landscape to explore site specific strategies for maximizing treatment efficacy. More specifically, our objectives were to:

***Objective 1:*** Determine high priority treatment areas across each landscape by simulating wildfire risk (e.g. rate-of-spread, fires severity) without any treatments. Simulate wildfire risk for each landscape assuming a fully restored landscape (idealized landscape), where fire effects are consistent with the historic, fire-maintained condition. The difference in wildfire risk values between untreated and completely treated will be used to rank areas for treatment in the subsequent objectives.

***Hypothesis 1***: Wildfire risk will be significantly lower in the idealized landscape than in the untreated landscape.

***Objective 2:*** Test the effectiveness of placing treatments (i.e., thinning followed by prescribed fire) in the highest wildfire risk areas (lower proportion of landscape treated) and additionally treating moderate wildfire risk areas (higher proportion of the landscape treated), where treatment placement will be determined as a function of wildfire risk (e.g. rate-of-spread, severity).

***Hypothesis 2***: The effect of additional treated area on landscape wildfire risk will decline after all high wildfire risk areas have been treated.

***Objective 3:*** Test the effectiveness of the two treatment scenarios in objective 2 with the addition of prescribed burning in adjacent untreated areas, on the distribution of wildfire rate-of-spread and severity relative to the idealized landscape.

***Hypothesis 3:*** The addition of prescribed burning across the landscape will restore landscape structure and function to more fire resilient conditions compared to treating high fire risk areas alone (i.e., Objective 2), leading to reduced landscape-scale wildfire risk .

***Objective 4:*** Relate wildfire risk and priority treatment areas to spatial configuration (e.g., treatment area size and distance apart), biotic (e.g., canopy cover), abiotic (e.g., slope, aspect), and socioeconomic determinants (e.g., distance-to-roads, distance-to-infrastructure, population density, etc.). Compare these environmental and socioeconomic relationships among landscapes to derive general principles (commonalities across landscapes) and to identify unique determinants for each landscape.

***Hypothesis 4:*** Wildfire risk is unevenly distributed spatially and is significantly correlated to biotic, abiotic, and socioeconomic patterns on each landscape.

The objectives for this project have been met. They directly responded to the FY14 FON task statement related to treatment configuration effects on future wildfires (objectives 1&2), effects from varying treatment characteristics (objectives 2&3), and proximity to high wildfire risk areas (objective 4) with the overall goal to maximize efficacy in extreme fire weather and across multiple large landscapes (all).

# Background

Active forest management practices (e.g., mechanical thinning, prescribed fire) for reducing fire risk and enhancing forest integrity have become necessary in many U.S. forests (Stephens et al. 2013). The risks of inaction and escalating costs of continued fire suppression far outweigh the risks of implementation (North et al. 2009). Fuel treatments are well known to reduce the intensity and spread of wildfires at the stand level, but their effectiveness is reliant on the timing of future wildfires and the location of fuel treatments across a landscape (Schmidt et al. 2008, Loudermilk et al. 2014). Although thinning treatments are effective at reducing hazardous fuels, their effectiveness has a limited duration (Rhodes and Baker 2008). Beyond this period of effectiveness, typically 10 to 15 years in many western U.S. forests and 1-5 years in southeastern pinelands (Kreye et al. 2014), treatment typically needs to be repeated. If the goal is to maximize the long-term efficacy of treatments, notwithstanding the importance of placement, then creating and maintaining a more fire-resilient forest should be a priority. This requires a more adaptive or dynamic approach to forest management, such as strategic placement of thinning and subsequent increased use of prescribed fire. Prescribed fire not only controls surface fuel loads, but restores ecosystem processes in which, for instance, Sierran mixed-conifer forests (Loudermilk et al. 2013) and southeastern pine forests (Mitchell et al. 2009) have evolved. This cannot be achieved with thinning alone (North et al. 2009). Strategic placement of thinning treatments coupled with regular prescribed fire could expand the efficacy of treatments in terms of long-term forest integrity over larger portions of the landscape (North et al. 2009).

Predicting landscape fuel treatment effectiveness is confounded by uncertainty in future fire weather, especially during more “extreme” fire weather conditions that are likely to occur as the climate warms (Hurteau et al. 2013). Extreme (85th – 100th percentile) fire weather has occurred more often in the last decade as compared to the last century and wildfire activity has increased, even in systems where fire suppression has not altered fuel loads (Littell et al. 2009). These events will likely continue to increase in frequency throughout this century (Westerling et al. 2011) with more variability (Mitchell et al. 2014). In these conditions, fire severity may be higher than usual because of coupled effects from dry fuels and drought stressed trees.

Our research benefits ongoing fuel treatment programs in three landscapes associated with the federal Collaborative Forest Landscape Restoration Program (CFLRP, Title IV of the Omnibus Public Land Management Act of 2009), and will broadly inform future landscape-scale restoration efforts across each region. These three landscapes (Dinkey Creek watershed: within the Sierra National Forest, Malheur National Forest, and Osceola National Forest) are all undergoing extensive fuel treatments and experience regular wildfires. We designed our landscape simulation experiments to inform forest planning by illustrating the complex spatial and long-term interactions that different types of fuels treatments and strategies have on landscape-level wildfire risk and species distributions, particularly when “extreme” fire weather conditions are prevalent. Our research has broad applicability because our analyses were designed to extract general principles about the biotic, abiotic, and management context that can be applied beyond the initial three landscapes.

# Materials and Methods:

## Study Sites

This modeling study utilized three study landscapes (**Figure 1**) namely, the Dinkey Creek watershed (CA), the Malheur National Forest (OR), and the Osceola National Forest (FL), which are all a part of the Collaborative Forest Landscape Restoration Project (CFLRP).

The Dinkey Creek watershed is an 87,500 ha area in the southern Sierra Nevada, CA. The watershed spans roughly 2,700 meters in elevation (300 to 3,000 m), with a precipitation gradient of 50 - 100 cm $yr^{-1}$ and variability in mean daily minimum temperatures from -3 to 10 °C and mean daily maximum temperatures from 12 to 25 °C (DAYMET). Vegetation ranges from mixtures of oak (*Quercus spp.*) and shrubs at the lowest elevations to ponderosa pine (*Pinus ponderosa*) and mixed-conifer forests at mid-elevations, and subalpine forest types at the highest elevations.

The Malheur National Forest is located in the southern Blue Mountains in central Oregon. Its nearly 940,000 hectares are dominated by dry mixed-conifer forests predominantly composed of ponderosa pine, Douglas fir, and grand fir. A smaller component of moist mixed-conifer forest occupies the highest elevations and some north-facing slopes, and there are interspersed sagebrush shrublands and grasslands. Wildfires were historically frequent (10 - 29 year mean fire return interval) and of low and mixed severity (Johnston 2016). Fire suppression and exclusion have led to an increase in fuel density, and recent fires have been uncharacteristically large and severe such as the 2015 Canyon Creek Complex, which burned nearly 45,000 ha (InciWeb 2015, https://inciweb.nwcg.gov). The study landscape is largely publicly managed by the USDA Forest Service with smaller areas managed by other federal and state agencies and some private non-industrial forest. Current management includes a variety of techniques such as pre-commercial thinning, commercial harvest, and prescribed fire to achieve multiple objectives including the reduction of fuels (USDA Forest Service, Malheur National Forest 2015).

The Osceola National Forest is about a 90,000 ha area located in northeastern FL. The Osceola is a relatively flat landscape, with little to no significant topographic relief. However, the low mean elevation of roughly 40 m results in wetlands throughout the forest where any depressions in the landscape persist. This strong dichotomy of dryer 'upland' sites and predominantly saturated wetland sites creates discrete edaphic bins throughout the landscape that dictate the aboveground vegetation structure. The dominant Osceola vegetation is split according to the soil type, with the upland sites being dominated by single or dual age pine (*Pinus palustris*, *Pinus taeda*, *Pinus elliottii*) and a thick understory of *Serenoa repens*. The wetland sites are primarily a dense mixture of *Liquidambar styraciflua*, *Magnolia virginiana*, *Gordonia lasianthus*, *Acer rubrum*, *Nyssa biflora*, *Taxodium distichum* and *Taxodium ascendens*.

**Figure 1.** The three study sites of this project. The Malheur National Forest, OR (yellow cross), the Dinkey Creek watershed, CA (purple diamond), and the Osceola National Forest, FL (green star).

## Landscape modeling approach: LANDIS-II

For all three landscapes, we used the Landscape Disturbance and Succession model, LANDIS-II v.6.0, which is used for understanding ecosystem dynamics, feedbacks associated with wildfire, and fuel treatment effectiveness across space and time. LANDIS-II's Century Succession extension was used to simulate the regeneration and growth of vegetation, detritus and soil nutrient cycling, and heterotrophic respiration (Scheller et al. 2011, Loudermilk et al. 2013). Vegetation growth and response to disturbance and climate is determined by the life history attributes of woody vegetation, available soil water, and available nutrients. Wildfires were simulated using the Dynamic Fire and Fuels extension (Sturtevant et al. 2009), which simulates stochastic mixed severity wildfires. Fire behavior (rate of spread, direction, intensity) is dependent upon fuels, daily weather conditions, ignition rates, and topography. To determine mortality, crown fraction burned is estimated using a combination of rate of spread, fine foliar moisture content, and fuel-type specific parameters, all indicators of fire intensity. Fire severity depends on the tree species present and their relative susceptibility to fire. The extension was parameterized to reflect each landscape's wildfire regime (e.g., fire rotation period, ignition rates). The wildfire regime under more extreme fire weather conditions was simulated such that fire effects are an emergent property of changing weather patterns. Forest thinning and prescribed fire used for fuel treatments were simulated using the Biomass Harvest extension (v. 2.0.1). This extension simulates the removal of aboveground live leaf and woody biomass of designated species and ages within selected areas and simulates post-treatment effects on wildfire behavior.

## Model Implementation

The following paragraphs describe model parameterization, calibration, and scenario design for each of the three modeled landscapes.

## Dinkey Creek watershed

As all of the methods for the Dinkey Creek watershed have been published (Krofcheck et al. 2017, 2018), details here are brief. For input projected climate, we forced the model using projections from the Coupled Model Intercomparison Project Phase 5, using the Localized Constructed Analogs statistically downscaled climate projections (Pierce et al., 2014), a daily, 1/16th degree resolution downscaled product that has been shown to track local variability in precipitation better than the coarser resolution parent models. We developed fire weather distributions using temperature and precipitation from the climate model projections and empirical windspeed data. Similar ‘extreme’ fire weather data were used as inputs to the Dinkey Creek simulations (as the other two sites), with published results (Krofcheck et al. 2017). The inclusion of climate projections was an added value to this project, also with published results (Krofcheck et al. 2018).

**Scenario development:** We developed three scenarios: no-management, naive placement, and optimized placement. Both management scenarios employed combinations of mechanical thinning and prescribed burning. The naive placement scenario simulated mechanical thinning from below and prescribed fire to all forest types that have experienced a departure in fuel load and stem density from their historic condition due to fire exclusion. Within each forest type that received mechanical thinning, thinning was constrained based on operational limits (slope > 30%, which totaled 22,436 ha available for mechanical thinning). The optimized placement scenario further constrained the area that received mechanical thinning by limiting thinning to areas that also had a high probability of mixed- and high-severity wildfire. The optimization process was based on 50 replicate simulations resulting from previous work (Krofcheck et al. 2017), wherein we simulated wildfire across the watershed using a distribution of fire weather from the extreme tail of the distribution over a 100 year period. To achieve the optimization, we calculated average total number of fires per grid cell and then we calculated the number fires per grid cell that resulted in some crown mortality (fires $\geq$ severity class 3 in the model). Finally, we divided the number of crown killing fires by the total number of fires in each grid cell. The resulting probability surface described the likelihood of crown fire across the watershed, in aggregate under the most extreme fire weather events captured in the contemporary record. We used this surface to prioritize areas for treatment and excluded areas available to treat that had a low probability of severe fire, resulting in a total of 7,266 ha identified for mechanical thinning. This approach accounted for the influences of fuel type, canopy base height, slope, and fire weather on the probability of severe wildfire (Krofcheck et al. 2018).

## Malheur National Forest

Although the methods for the Malheur National Forest are included in a recent dissertation, they are not otherwise published and more detailed methods are provided here. The soil and weather data were used to classify the landscape into 25 ecoregions that are assumed to have homogeneous climate and soil moisture conditions. Soil data were obtained from SSURGO soil data Soil Resource Inventory data. Maximum temperature and average precipitation for growing season months (June, July, and August) were obtained as 30-year normals (1980 – 2010; PRISM Climate Group) and reclassified into five climate regions using Iso Cluster Unsupervised. All methods, results, and discussion for the Malheur are found in Cassell (2018).

Initial community vegetation data was obtained from the Gradient Nearest Neighbor (GNN) maps from the Landscape Ecology, Modeling, Mapping and Analysis (LEMMA) group (https://lemma.forestry.oregonstate.edu/data/home) and the GAP Analysis Program's Ecological Systems map ( https://gapanalysis.usgs.gov/gaplandcover/data/download/). There were 4,631 unique communities on the landscape, each with up to 11 tree species, four shrub functional groups, and native and non-native grasses. Life history traits were obtained from the literature and available public datasets including the USDA Fire Effects Information System, USGS Vegetation Atlas of North America, the Northeastern Ecosystem Research Cooperative's Foliar Chemistry Database, the National Atmospheric Deposition Program, the Oak Ridge National Laboratory database, and from previous studies (Loudermilk et al. 2014, Lucash et al. 2014, Creutzburg et al. 2016).

Historical fire data were retrieved from the Monitoring Trends in Burn Severity database (2016) and the USFS (Blue Mountains Fire History Polygons, released 2016). Two versions of the Dynamic Fire and Fuels System (DFFS) extensions (Sturtevant et al. 2009) simulated wildfire disturbance and interactions with climate and fuels. Extreme weather fire simulations were completed using DFFS v2.1, which allows a separate input file for fire weather than that for the NECN Succession extension. DFFS v3.0 (unpublished), which links weather between NECN and DFFS, was used for contemporary-weather scenarios to simulate fire events with the same daily weather conditions that control vegetation growth. Both versions of DFFS utilize vegetation succession data from NECN, dynamically changing fuel beds based on current vegetation. Fuel types were developed to represent 15 unique combinations of tree species and ages, as well as shrublands and grasslands, with individual fire behavior and consumption parameters. Slope and aspect maps were also inputs.

For contemporary weather, daily weather data were retrieved from the USGS Data Portal (maximum and minimum temperatures (˚C), average precipitation (mm/day), daily average wind speed (m/s; Maurer et al. 2002), and wind direction (degrees clockwise from north; Abatzoglou, 2013) for the period 1979 – 2010, using area-weighted grid statistics for each of the five climate regions. To ensure that treatments and fire events would be applied to consistent forest composition and structure across scenarios, historical climate controlled tree growth and forest succession for all scenarios. Therefore, for both contemporary weather and extreme weather scenarios, trees were grown with identical daily weather conditions. For simulations under extreme weather, climate inputs were decoupled between forest succession and wildfire. Extreme weather inputs were derived from years with greater-than-normal fire activity on the study landscape: 1990, 2007, 2014, 2015, and the entire year's daily precipitation, temperature and wind speed and direction data were included.

Growth and biomass validation was accomplished by comparing aboveground tree biomass with Forest Inventory Analysis (FIA) data. Simulated total biomass ranged from 0 to 105 Mg/ha with a mean value of 45 Mg/ha, while biomass estimates from FIA data ranged from 0 – 236 Mg/ha with a mean of 45 Mg/ha. Out of the 11 tree species simulated, nine achieved average biomass within 30% of GNN data for that species. Fire was calibrated to approximate annual area burned and fire size for the period 2000 – 2014 within the study area. The DFFS extension uses log-normal duration data to generate the distribution of fire durations, which was then used to calibrate annual area burned, which also follows a log-normal distribution. Three replicates of 50 years were run and averaged during the calibration process.

Fuel treatment scenarios were designed to compare among: 1. weather scenarios (contemporary weather vs. extreme fire weather); 2. management extent scenarios (i.e., treating more and less area with prescribed fire per year and adding treatments in riparian areas); and 3. spatial scenarios, i.e., distributing treatments across the landscape vs. targeting areas with high fire risk (hereafter "distributed" and "optimized"). They were developed from workshops and meetings with USFS personnel. Fuel treatment prescriptions included mechanical thinning for ponderosa pine, dry mixed-conifer and moist mixed-conifer forest, pre-commercial thinning, and prescribed burning. Management scenarios included, 1. untreated landscape (Untreated), 2. "business as usual" (BAU) management, 3. additional treatments in Riparian Habitat Conservation Zones (Riparian), 4. application of additional prescribed fire (2x the area of BAU; RxFire), and 5. tripled application of additional prescribed fire (3x the area of BAU; RxFire3x).

**Scenario development:** All scenarios were run under both contemporary and extreme weather conditions, and each of the three management scenarios that include treatments (i.e., all except the untreated scenario) were run with fuel treatments placed through two different spatial strategies: 1. distributed across the entire forested portion of the landscape and 2. with optimized placement of treatments in areas of the landscape that have the highest likelihood of high severity fire (**Figure 2**). Ten replicates of each simulation were run for 100 years.

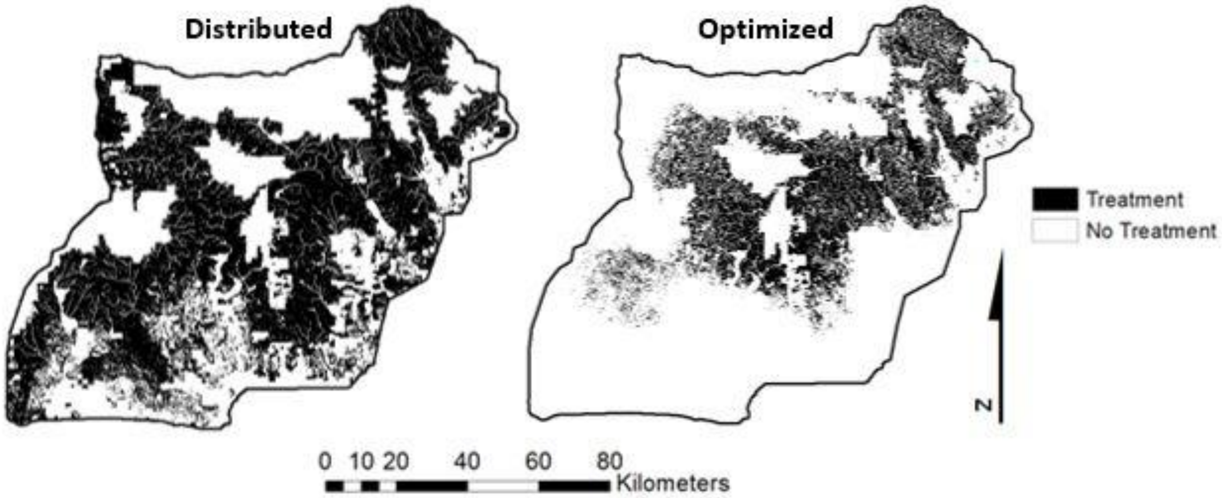

**Figure 2.** Distributed and spatially optimized management areas. About half of the land is under USDA Forest Service management with the remainder divided among private landowners and other federal and state agencies. The Distributed map represents all publically-managed land available for fuel treatments. The Optimized map targets treatment placement in areas that frequently burned and where wildfire severity was highest over 1,000 simulation-years concentrates treatments in 43% of the area available when treatments are distributed.

### Osceola National Forest

We modeled carbon dynamics using the NECN extension (a version up and re-naming of the Century extension), the Dynamic Fuels and Fire extension to simulate fire and fuels interactions, and the Biomass Harvest extension to simulate management and harvest within our modeling environment. We modeled the landscape on a 150 m grid, resulting in 2.25 ha pixels. Given the lack of topographic variability across the Osceola, we let the edaphic variability across the region govern ecoregion creation. We used a geospatial layer of swampland areas (USFS, personal communication) to delineate the 'lowland' stands, and took the remainder of the vegetated area for the 'upland' stands to create the simulation ecoregions (**Figure 3**). We then used a method similar to Krofcheck et al., 2017 to assign the soil characteristics to each ecoregion using GSSURGO data (https://gdg.sc.egov.usda.gov/).

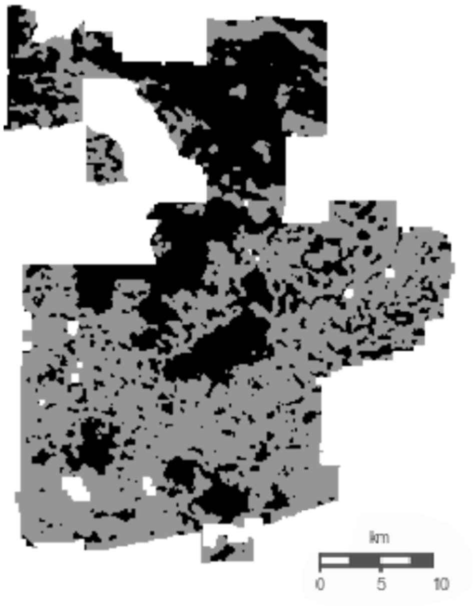

**Figure 3.** Ecoregions used to simulate the uplands (gray) and lowlands (black) across the Osceola National Forest. White regions within the simulation represent open, unvegetated water or land ownership zones not part of the national forest

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To parameterize and calibrate the Dynamic Fuels and Fire extension we used 17 years of fire history data recorded by the Osceola National Forest to parameterize the mean fire size and number of fires per year for the landscape, following a methodology described in Krofcheck et al. 2017.

For the Biomass Harvest extension, we split the study site into areas that receive specific fuels management or harvest prescriptions throughout the landscape. We chose to simulate management across the entire upland, pine dominated ecoregion, and created a second management unit that included a 300m buffer around the lowland ecoregion. In this manner, we were able to prioritize the application of fuels management to upland, pine dominated stands that bordered un-managed, swampland stands.

To initialize the landscape, we used FIA plots stratified by upland and lowland ecoregions to create species and age distributions for the area. We then used maps of stand age and recent harvests provided by the Osceola National Forest to inform the mean stand age for a given grid cell. The species assignment for each upland grid cell was then a probabilistic function of stand age, and the species abundance described by the FIA plots. The resulting upland stand structure was constrained to meet the desired age demographics, consisting of primarily single or double age stands. The lowland ecoregion cells were populated entirely using FIA data and time since disturbance, such the resulting landscape scale values for region coincided well with published data.

We drove vegetation dynamics with Daymet daily surface weather over a 1-km grid for the period 1980–2015, acquired via the USGS Geo Data Portal (http://cida.usgs.gov/gdp/, Thornton et al. 2012). We computed weighted area grid statistics for the Osceola using the export service in the data portal and converted these data to monthly means for simulating vegetation growth and reproduction in the NECN extension. We chose to use the same climate inputs for both ecoregions, given their similar elevations relatively small spatial extent.

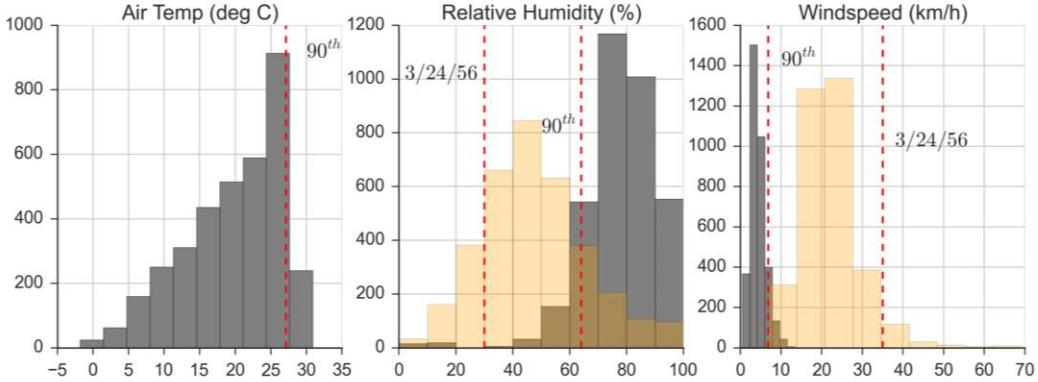

**Figure 4.** Contemporary (gray) and extreme (orange) fire weather distributions used to drive wildfire in the model simulations. The 90th percentile of the contemporary distribution data is shown along with the measured conditions during a notable high severity wildfire that took place on March 24, 1956 (the Impassible Bay fire).

For the Dynamic Fire and Fuels extension we used local RAWS stations to generate distributions of temperature, relative humidity, and precipitation from which we generated the required fire weather inputs for the simulation (see Krofcheck et al. 2017 for details). We generated two bins of fire weather: contemporary and extreme. We generated the contemporary fire weather in the manner described previously using the entire 15 years of RAWS data. We used the 90th percentile subset of that data to generate the extreme fire weather, a conservative distribution according to historical documents that were associated with large and notable fires in the Osceola, for example the Impassible Bay fire which took place on 3/24/1956 (**Figure 4**).

We developed three management prescriptions: 1) no-management, 2) thin and burn, and 3) thin, burn and harvest, and were all developed from meetings and input from ongoing management at the Osceola. We ran simulations of each of these management prescriptions with wildfire events driven by either contemporary or extreme fire weather (described above), resulting in 6 model scenarios. In both management prescriptions, the rates of thinning and burning were identical (**Table 1**), with mechanical thinning from below removing fractions of the biomass in a given stand based on the species and age combinations present in that grid cell. Harvest was simulated by removing 50% of the cohorts in a stand above 30 years in age, and was applied at a rate of 2% per year. Prescribed burning in the model functions in a similar way, but targets the majority of smaller, younger cohorts and tends to leave the majority of older, larger cohorts undamaged. We assigned treatment rates for mechanical thinning such that only the pixels surrounding the lowland regions ("Lowland Buffer") received mechanical thinning treatments, and the entire area was treated once in the first five years of each simulation. Mechanical thinning of the uplands region, which comprises the remainder of the pine dominated stands across the Osceola, received no mechanical thinning. In contrast, the harvest prescriptions were only applied to the upland region, and not to the lowland buffer. Prescribed fire was applied to all the pine dominated management zones (both uplands and the lowland buffer) on a mean return interval of 5 years. No management prescriptions were applied to the lowland ecoregions.

| | Prescribed fire (%/year) | Prescribed fire (ha/year) | Thinning* (%/year) | Thinning* (ha/year) | Harvest (%/year) | Harvest (ha/year) |
|---|---|---|---|---|---|---|
| **Upland** | 20 | 4,831.6 | - | - | 2 | 483.16 |
| **Lowland Buffer** | 20 | 6,094.6 | 20 | 6,094.6 | - | - |
| **Lowland** | - | - | - | - | - | - |
| **Total** | | **10,926.2** | | **6,094.6** | | **483.16** |

**Table 1.** Management prescriptions used in the scenarios where fuels reduction and biomass harvest were applied. *All thinning treatments were conducted over a 5 year period, and not repeated for the duration of the simulations. Prescribed fire rates resulted in a 5 year return interval across the treated areas. No lowland areas were treated with any management prescriptions.

We ran 30 replicate 100-year simulations for each of the six model scenarios. We used analysis of variance and Tukey's honestly significant difference for mean separation following Bartlett's test for homoscedasticity. For comparisons where data were heteroscedastic, we employed Kruskal–Wallis tests with post hoc Dunn's comparisons. We conducted all model parameterization and output analyses, as well as figure generation using Python (Python Software Foundation, version 2.7. http://www.python.org).

# Results and Discussion

In all three landscapes, we achieved our project goals of determining site specific strategies of implementing fuel treatments in order to maximize their long-term efficacy. We worked with managers and multi-stakeholder groups to develop treatment prescriptions and applied those in a landscape context to explore ideal spatial and temporal configurations. As per our objectives and hypotheses, we successfully parameterized simulation models for all 3 CFLRP landscapes determining that 1) wildfire risk is drastically lower in a continuously treated landscape compared to an untreated landscape, ***H1***), 2) that treatment effectiveness is greatest in the beginning of the simulations, with more intensive initial thinning treatments are used at high carbon cost, but continuous less-intense treatments (light thinning and/or prescribe burning) thereafter maintain effectiveness over time at a low carbon cost, ***H2***), 3) that the addition of prescribed fire is necessary to maintain landscape resiliency to overall wildfire risk and maintain fire resiliency compared to treating high fire risk areas alone (placement and continued prescribed fire are important, ***H3***), and 4) that wildfire risk is spatially complex, requiring a landscape-level understanding (hence landscape simulations) of linked components of geographic structure, forest composition, and connectivity/fragmentation (***H4***). This work is supportive and supplemental to what we know about fuel treatment effectiveness, particularly pertaining to the importance of treatment initialization and continuation (Reinhardt et al. 2008), treatment placement (Schmidt et al. 2008), and short-term carbon loss and long-term net carbon gain from the ecosystem due to landscape fuel treatments and resulting efficacy (Loudermilk et al. 2014, Loudermilk et al. 2017, North et al. 2011). There has been however, a stronger focus on understanding fuel treatment efficacy in western forest systems, where this is one of the few landscape-scale modeling studies (e.g., Martin et al. 2015) that examines these long-term dynamics in a southeastern forest.

Overall advancements provided by this study are the use of a site-parameterized model in three very different landscapes to inform on high fire risk areas due to interactions between extreme fire weather, topography, fuel and forest conditions, and ignition patterns, which all interact in complex ways over space and time. The model was utilized successfully to determine optimal treatment placement due to extreme fire weather, but each site required unique management strategies to maintain resilience.

Similarities between treatment strategies included applying an initial round of intensive thinning treatments to kickstart the long-term management process of efficacy, and then supplementing with prescribed burning based on specific site needs, such as required frequency and location based on when and where wildfires would likely occur on the landscape. We found that although spatial complexity, including connectivity or fragmentation, have an effect on wildfire risk, these landscapes are relatively cohesive in structure and are not bordered by a significant amount of urban infrastructure. Fragmentation is primarily geographic and legacy from past management as opposed to development.

Below are more specific results and discussion for each simulated landscape.

## Model Results by Research Site

### Dinkey Creek watershed

In all three scenarios, the greatest burn severity (**Figure 5a-c**) occurred in areas dominated by ponderosa pine and pine-dominated mixed-conifer forests. The impact of treatment in both management scenarios was lower mean fire severity relative to the no-management scenario. In both management scenarios mean severity was significantly reduced, with a mean reduction of 16.1% for the naive placement, and 18.4% for the optimized placement scenario ($p < 0.001$; **Figure 5d-e**).

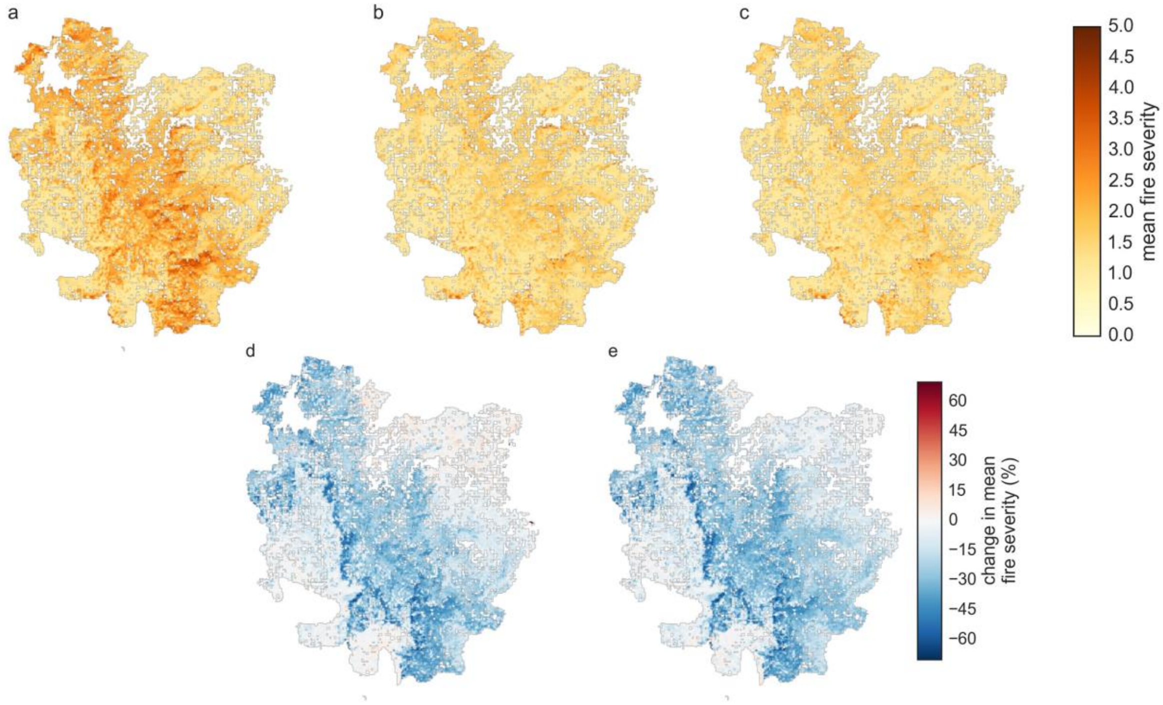

**Figure 5.** Mean fire severity for the no management (a), naive placement (b), and optimized placement (c) scenarios, and the resulting percent change in fire severity relative to the no management scenario caused by the naive (d) and optimized (e) treatments.

The similarity between these two treatment outcomes and the reduction in fire severity from the no-management scenario was captured in the abovegound carbon results. We hypothesized that patterns of landscape aboveground carbon (AGC) accumulation would be similar in both treatment scenarios over both the short- (<20 years) and long-term (20-100 years). From simulations using climate projections (Krofcheck et al. 2018), the range of AGC across replicates and climate projections for each scenario are shown in **Figure 6**.

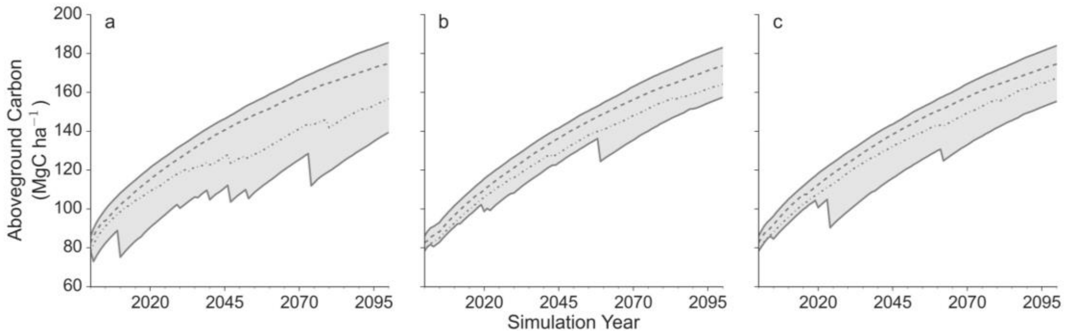

**Figure 6.** Above ground carbon (AGC) for the no-management scenario (a), the naive placement scenario (b), and the optimized scenario (c). Each subplot shows the absolute minimum, maximum, mean (dashed) and lowest 95th percentile (dotted) of AGC for each year across 200 total simulations

The no-management scenario showed a wide range of potential outcomes, from 90.5 to 121.2 Mg C ha$^{-1}$ in the short term and 139.4 to 185.6 Mg C ha$^{-1}$ in the long term. Both management scenarios showed significantly smaller variances in AGC relative to no management, with the naive scenario ranging from 98.7 to 115.4 Mg C ha$^{-1}$ and the optimized scenario ranging from 100.6 to 118.3 Mg C ha$^{-1}$.

The maximum AGC is the maximum value for a given year from the 200 replicate simulations for a given scenario. The initial treatment costs associated with mechanical thinning are most apparent in the comparison of maximum AGC, where treatment scenarios have lower maximum AGC than the no-management scenario during the first decade when thinning treatments are implemented. However, this difference diminishes over the full 100 years of simulation (**Figure 7a**). Short-term reductions in maximum AGC relative to no management were 5.7 Mg C ha$^{-1}$ for naive placement and 2.9 Mg C ha$^{-1}$ for optimized, with long-term reductions of 2.6 Mg C ha$^{-1}$ for naive and 1.6 Mg C ha$^{-1}$ for optimized placement.

The minimum AGC is the minimum value for a given year from the 200 replicate simulations for a given scenario. Therefore, the difference in minimum landscape AGC between treatments and the no-management scenario (**Figure 7b**) represents the gains in worst-case AGC that result from treatment. The naive scenario had minimum AGC values that were greater than the no-management minimum throughout the simulation period. The 67% reduction in thinned area in the optimized scenario yielded lower minimum AGC values than the naive scenario over the majority of the simulation period and had lower minimum values than the no-management scenario in the short-term (**Figure 7b**). The lower minimum values in the short-term are a function of the occurrence of a large wildfire in one replicate simulation early in the simulation, before the initial prescribed fire treatments had all been implemented.

The lower 95th percentile of AGC represents the collection of highest disturbance affected simulation years from the 200 replicate simulations for each scenario. When we compared the difference in the lower 95th percentile AGC between the treatment scenarios and the no-management scenario, both treatment scenarios were lower than the no-management scenario in the short-term (**Figure 7c**). However, the lower 95th percentile of AGC for the optimized scenario surpassed the no-management scenario in year 31 and in year 36 for the naive scenario. While both the naive and optimized treatment placement scenarios underwent mechanical thinning and prescribed fire over the same time intervals, substantially less biomass was removed annually via mechanical thinning across the landscape in the optimized scenario (**Figure 7d**).

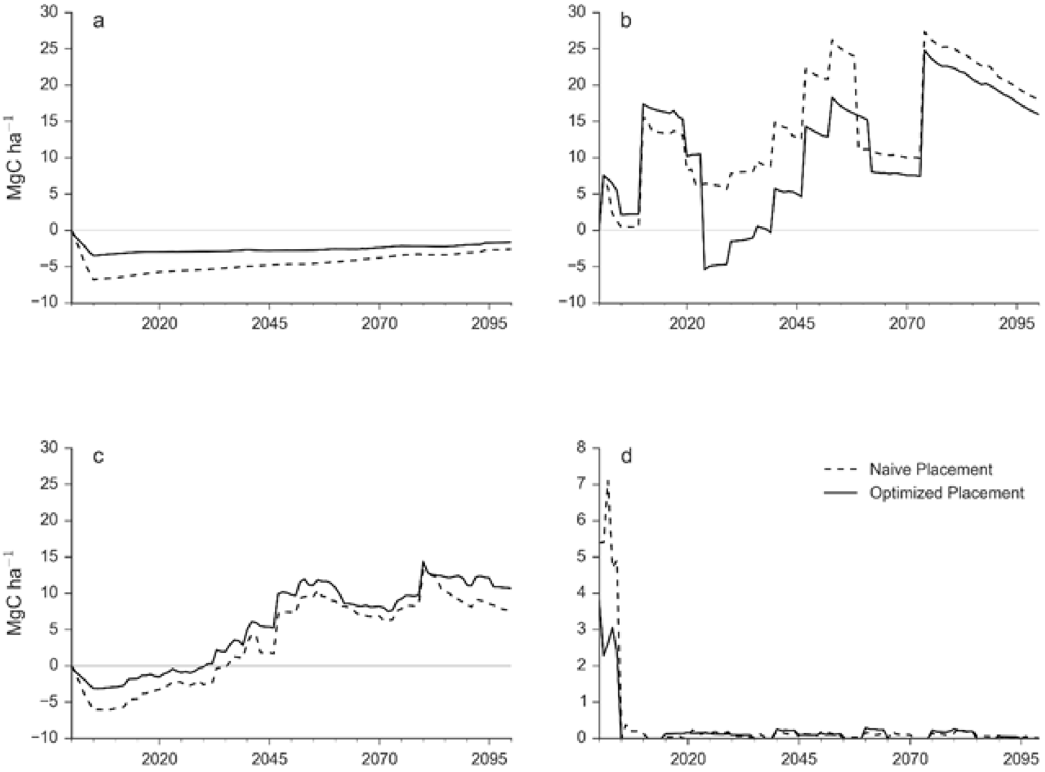

**Figure 7.** Relative differences in above ground carbon (AGC) between the naive placement (dashed), optimized placement (solid), and the no management scenarios (zero line). Differences between the maximum (a), minimum (b), lowest 95th percentile (c), and the AGC removed during management (d) are shown for each year of the simulation across 200 replicates.

## Malheur National Forest

The addition of fuel treatments in riparian areas did not result in any differences in wildfire activity at the landscape scale from the BAU scenario. Therefore, there will not be any further discussion of riparian treatment results in this section.

Overall, treatment reduced area burned under both historical and extreme weather ($0.000 < p < 0.02$). Doubling the area treated with prescribed fire resulted in small additional reductions in average annual area burned, and tripling the area of prescribed fire resulted in a significant reduction from the BAU scenario ($p < 0.006$). Increasing treatment area also increased the number of years without any fire at all under both contemporary weather (from 139 years out of a possible 1,000 simulation years under BAU to 166/208 years with BAU+RxFire/BAU+RxFire3x respectively) and extreme weather (from 117 years to 132/172 years). Spatial optimization of treatments into high-risk areas of the landscape was equally effective in reducing annual area burned, regardless of weather, for 5 out of the 6 scenario combinations ($p = 1.0$). The exception was RxFire3x under extreme weather, where spatially optimized treatments resulted in greater area burned than distributed treatments ($p = 0.000$; **Figure 8**).

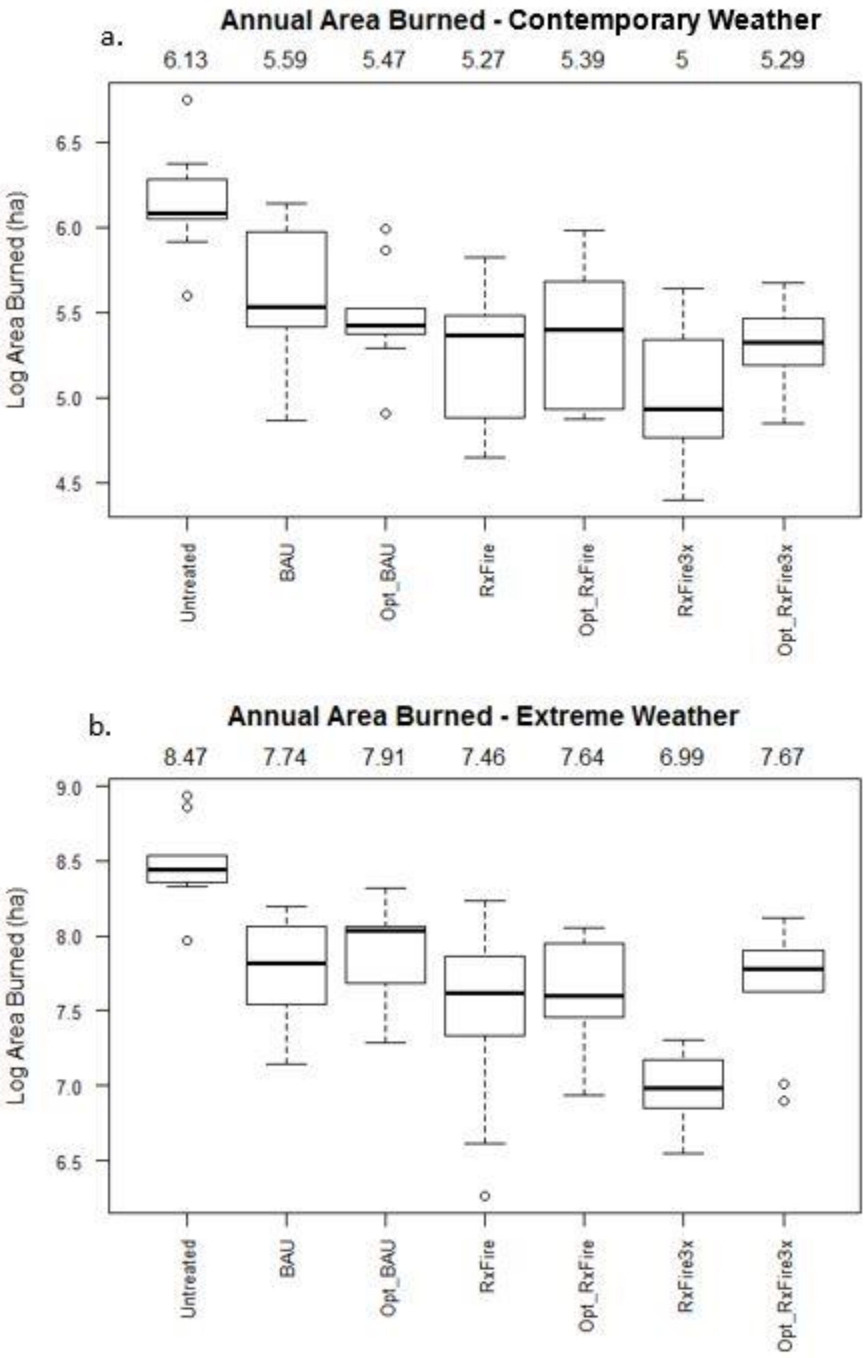

**Figure 8.** Boxplots of wildfire annual area burned under contemporary (a.) and extreme (b.) weather for each management scenario. Under both weather scenarios, fuel treatments reduced annual area burned as compared with the untreated landscape (*p* = 0.0). Doubling the area treated with prescribed fire was not sufficient to significantly reduce area burned (Contemporary: p = 0.22, Extreme: p = 1.0), but tripling the area treated with prescribed fire resulted in significant decreases under both contemporary (*p* = 0.0008) and extreme weather (*p* = 0.0005). Spatially optimizing treatments resulted in similar annual area burned for each treatment type under contemporary weather (i.e., no significant differences), indicating that under

moderate conditions, concentrating treatments in areas with high likelihood of burning at high severity is effective. However, under extreme weather, RxFire3x was more effective when distributed across the landscape (*p*=0.019). Area burned is expressed as the natural log, and log-mean values for annual area burned are listed above each corresponding box.

Wildfire was most frequent on the untreated landscape, and all treatment scenarios led to less frequent fire in all areas of the landscape with the greatest reductions in the central and southwestern portions. Fire rotation period (FRP) under contemporary weather was 90.53 while BAU management was 157 years, reflecting the significant reduction in annual area burned. Tripling the amount of area treated with prescribed fire had the greatest impact with an FRP of 170 years. Under extreme weather simulations, fire frequency is based on forcing a much higher number of simulated fires than would be expected under normal conditions, and therefore FRP should be considered as an index to compare among treatments and not as a realistic number of years. FRP for the untreated landscape was 12.1 years, and treatment increased it to a range of 16.5 years (BAU) to 19.0 years (RxFire3x). Spatially optimizing treatments reduced fire frequency in the areas treated (central and northeastern areas) but resulted in greater area burned in the untreated portion of the landscape (southwestern areas; **Figure 9**). This effect was most pronounced in the RxFire3x scenario where FRP decreased from 19.01 to 18.28 years when treatment placement was optimized.

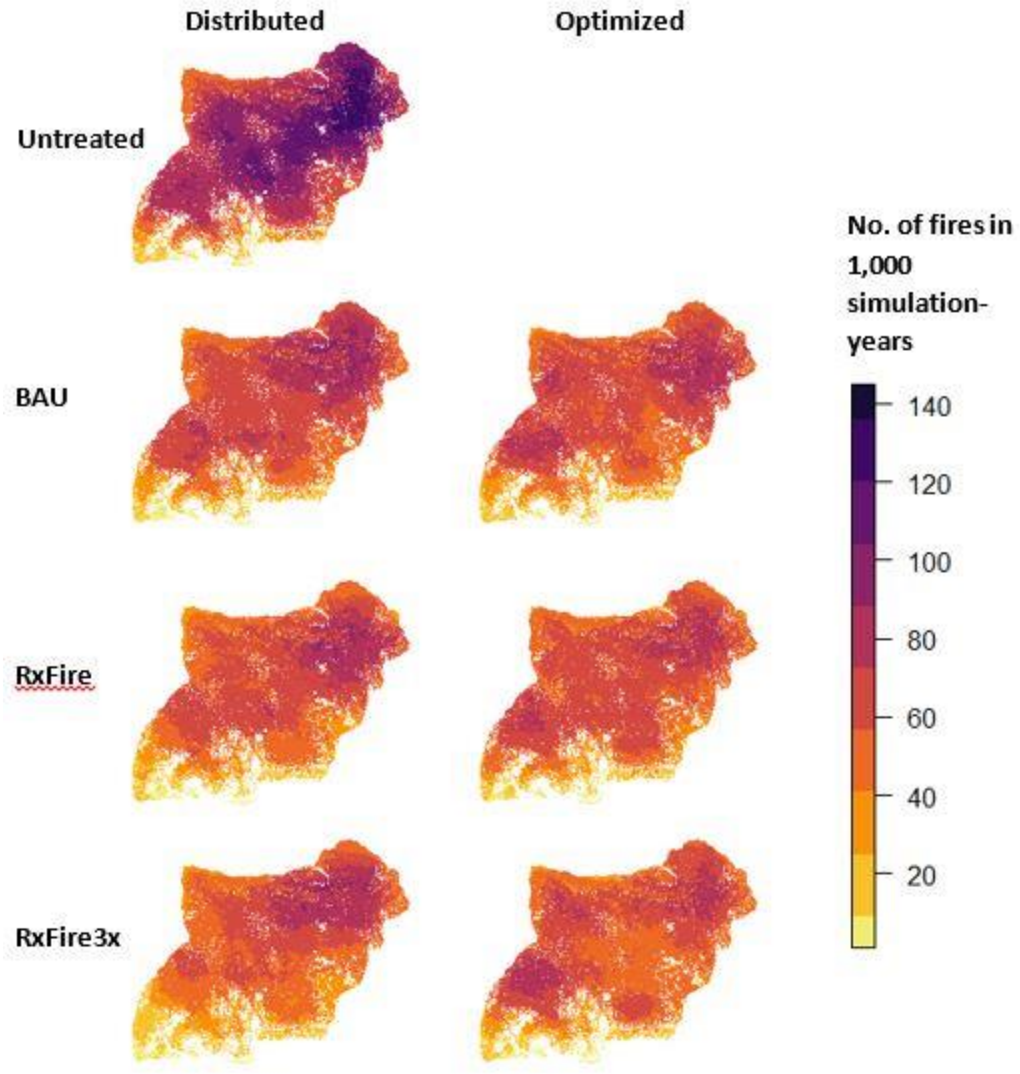

**Figure 9.** Maps of total wildfire occurrence at each site over all replicates and years under extreme weather. Scale represents the number of fires that occurred in each individual cell over 100 years and 10 replicates. With management, fire was less likely over a greater proportion of the landscape, and the RxFire3x scenario led to the greatest reductions in fire occurrence. Spatially optimizing treatments reduced fire in the areas treated (central and northeastern areas) but resulted in greater area burned in the untreated portion of the landscape (southwestern areas).

Under contemporary weather, reductions in severity at the landscape scale were not statistically significant ($p = 0.165$), and increased area treated with prescribed fire did not provide a significant further reduction in landscape-level fire severity. However, under extreme weather, all treatment scenarios had significantly lower severity than Untreated ($0.0000 < p < 0.001$), and resulted in a 9-11% decrease in severity (**Figure 10**). The most effective treatment scenarios were spatially optimized BAU and distributed RxFire3x, both which resulted in 11% decreases in severity. The effects found from our multi-scenario design are in **Table 2.**

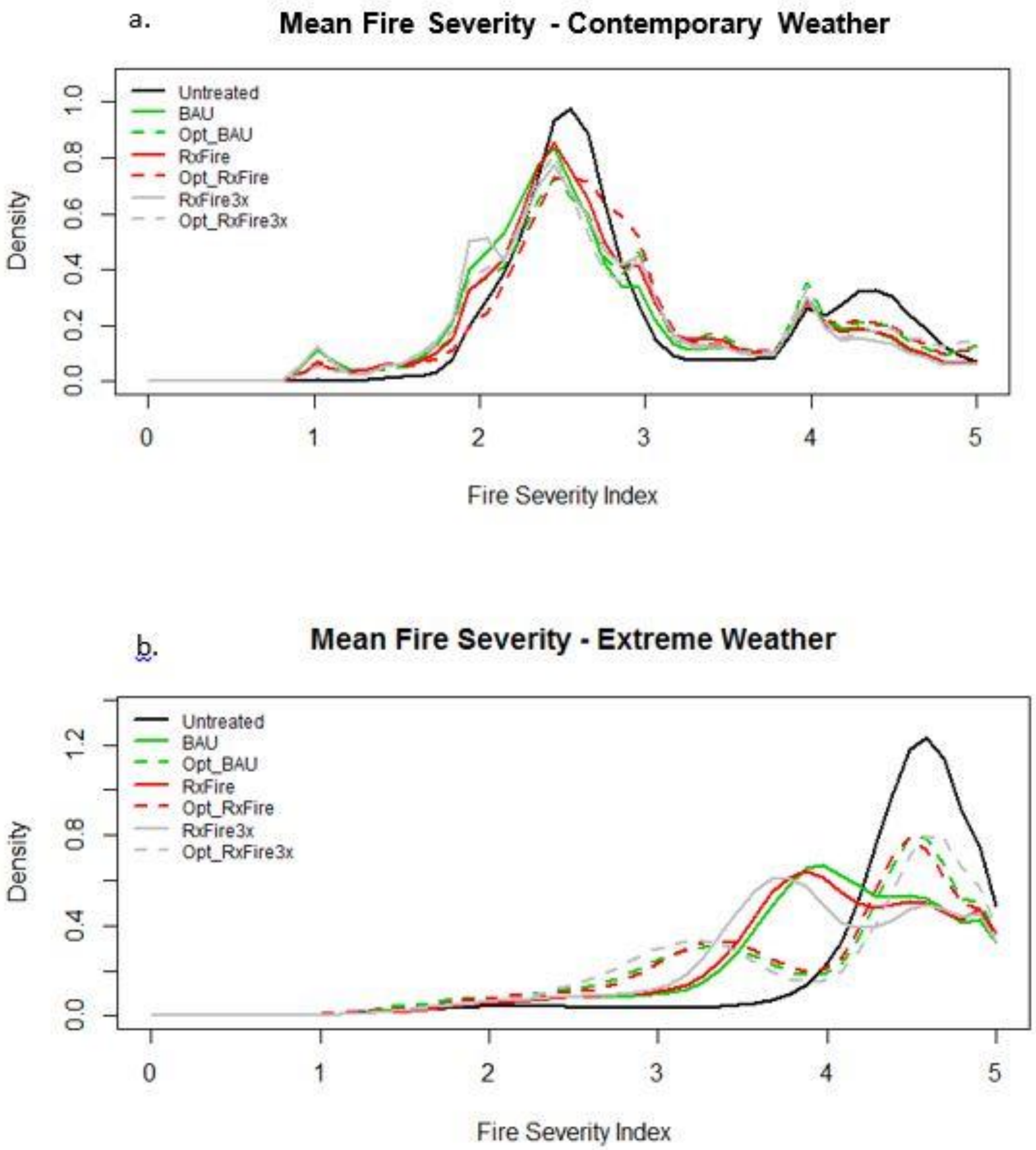

**Figure 10.** Density plots of mean fire severity under historical and extreme weather. Active management reduced mean fire severity under both historical (a) and extreme (b) weather scenarios, and tripling the amount of area treated with prescribed fire produced the greatest reductions. Under extreme weather, spatial optimization of fuel treatments further reduced mean fire severity, with the greatest reduction in fires in the 3.3 – 4.2 range of severities.

**Table 2.** Comparison of management scenarios' effects on wildfire annual area burned and severity for 1) contemporary and extreme weather and 2) distributed and optimized treatment placement for the Malheur National Forest simulations.

| | Contemporary Weather | Extreme Weather |
|---|---|---|
| Distributed Placement | · Active management reduced annual area burned, but reductions to severity were not statistically significant.<br>· Doubling the area treated with prescribed fire was not sufficient to reduce annual area burned or severity at the landscape level.<br>· Tripling the area treated significantly reduced area burned. | · Active management reduced annual area burned and wildfire severity.<br>· Doubling the area treated with prescribed fire reduced annual area burned, but had no effect on severity.<br>· Tripling the area treated significantly reduced area burned and led to lower landscape-level fire severity. |
| Optimized Placement | · Performed similarly in reducing area burned as distributed placement.<br>· The RxFire3x scenario reduced area burned from BAU, but was not as effective as distributing treatments.<br>· Reduced fire severity in the portion of the landscape that was treated, but resulted in an increase in overall mean severity. | · Performed similarly in reducing area burned as distributed placement (except RxFire3x).<br>· RxFire3x significantly increased area burned as compared with the RxFire3x distributed treatment placement.<br>· Severity was reduced in all but the optimized RxFire3x scenario. |

### Osceola National Forest

Under contemporary fire weather conditions, the mean wildfire severity of both treatment scenarios differed very little when compared to the No Management scenario (**Figure 11**). The variance of fire severity however was significantly reduced under both treatment scenarios, with the principal regions of high variance in fire severity surrounding patches of dense or extensive swampland. There were no significant differences in either wildfire severity or variance in wildfire severity between the Treatment Placement and Treatment Placement with Harvest scenarios, however there was a moderate decrease in mean fire size (from 9170 to 7690 ha) when harvest was combined with Treatment Placement.

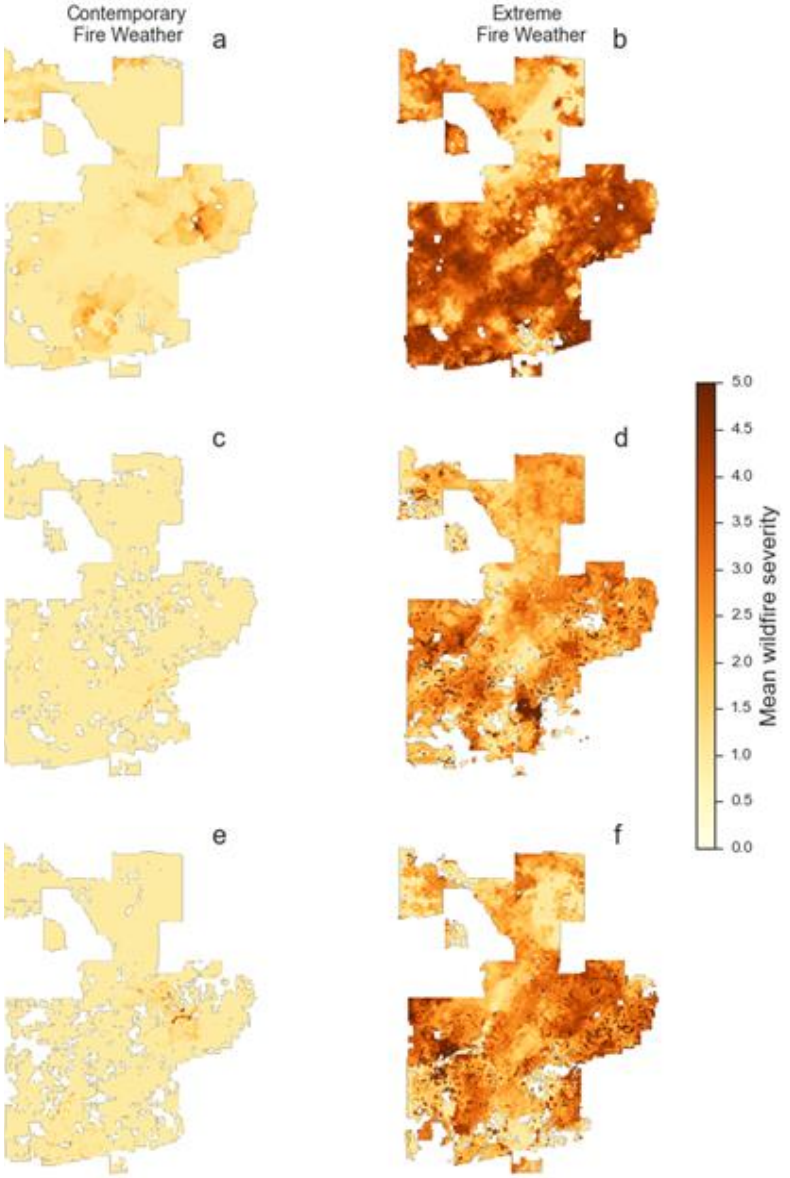

**Figure 11.** Mean wildfire severity for both contemporary fire weather (left column) and extreme fire weather (right column) simulations. No management (a,b), treatment placement (c,d), and treatment placement with harvest (e,f) are shown from top to bottom.

Extreme fire weather conditions significantly increased mean wildfire severity in all scenarios, with the No Management showing the largest increase of roughly 260% relative to contemporary, followed by the Treatment Placement with 235% increase, and Treatment Placement with Harvest increasing mean wildfire severity by 240% (**Figure 12**). The percent reduction in mean wildfire severity due to treatment was greatest in the Treatment Placement scenario, reducing mean wildfire severity by 21.7% relative to No management, and Treatment Placement with Harvest showing a similar reduction of 18.4% relative to No Management. The variance of mean wildfire severity also showed significant reductions with treatment, with the Treatment Placement scenario reducing the variance in mean wildfire severity by 38% relative to No Management, and the addition of harvest reducing the variance slightly less at 34%

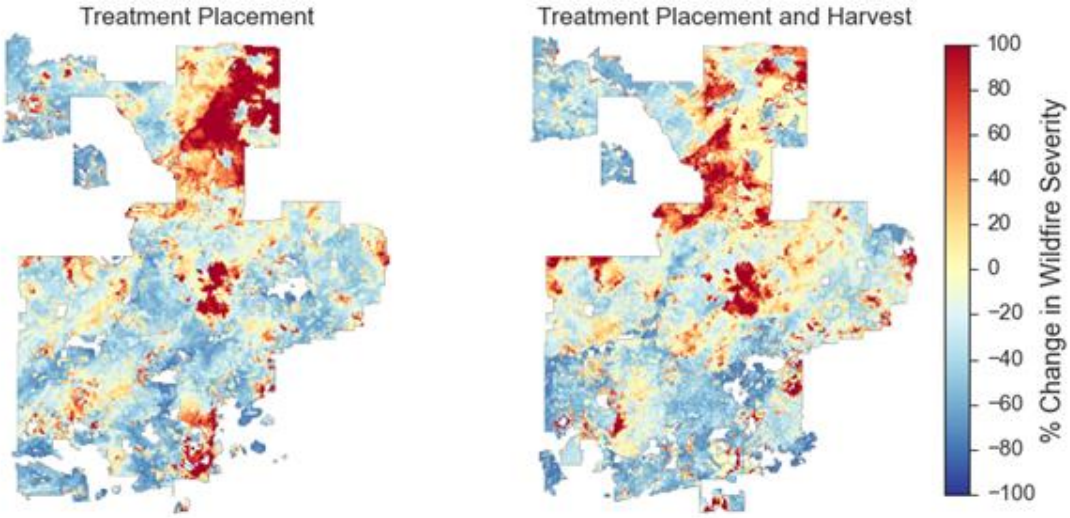

**Figure 12.** Percent change in mean wildfire severity between no management and treatment scenarios under extreme fire weather conditions.

Spatially, the reduction in mean fire severity under extreme fire weather was largest in the pine dominated areas where wildfires intersected with mechanical thinning and prescribed fire treated areas (**Figure 12**). A reduction in mean fire size in the pine dominated ecosystems due to treatment resulted in fewer fires that originated in pine dominated areas spreading into swamp stands. Consequently, the swamp stands showed an increase in mean fire severity relative to no management, due to a relative increase in fuels accumulation in those systems.

Aboveground carbon dynamics showed little difference across all scenarios under contemporary fire weather (**Figure 13**). Carbon accumulation after the first 50 years under No Management showed a range of 54.2 to 57.8 Mg C ha, with a mean AGC of 68.7 Mg C ha by the end of 100 years of simulation. Both treatment scenarios showed a moderate increase in mean AGC of 3 Mg C ha by end of simulation when compared to the No Management scenario. Under extreme fire weather, treatment showed a much larger impact on the mean and range of AGC accumulation. While maximum AGC did not vary between scenarios, large and severe wildfires early in both treatment scenarios significantly reduced the range of AGC by the end of each simulation. No Management ranged from 59.2 to 69.2 with a mean of 66.3 Mg C ha, Treatment

Placement ranged from 70.9 to 72.7 with a mean of 71.9 Mg C ha, and Treatment Placement with Harvest scenarios ranged from 70.7 to 72.9 with a mean of 71.9 Mg C ha.

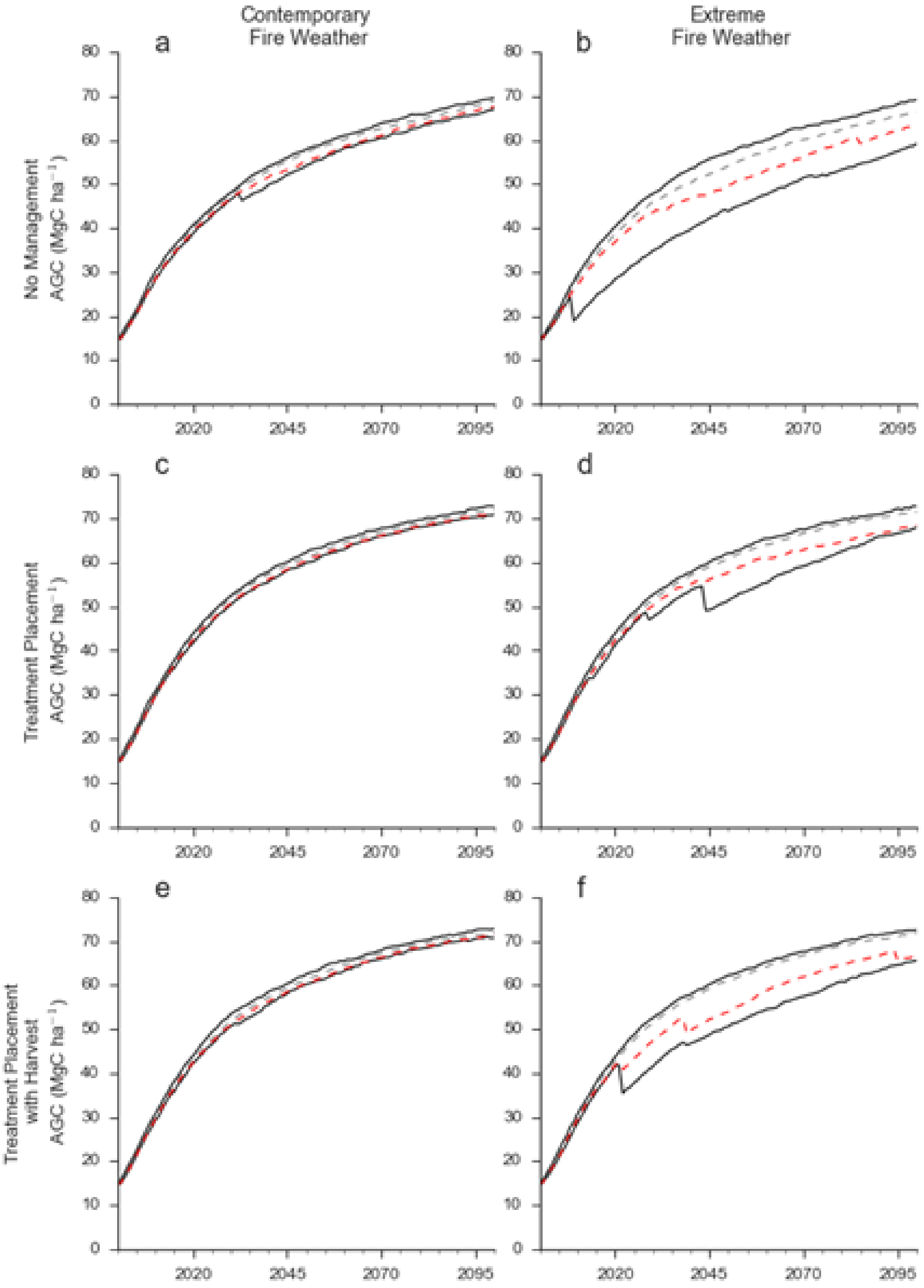

**Figure 13**. Above ground carbon for both contemporary (left) and extreme (right) fire weather scenarios. Treatments are shown by row: no management (a,b), treatment placement (c,d) and treatment placement with harvest (e,f). Each subplot shows the absolute minimum, maximum, mean (dashed) and lowest 95th percentile (red) of AGC for each year across 30 replicate simulations .

These landscape differences in AGC were largely driven by changes in biomass accumulation in the pine dominated ecosystems, with both treatment scenarios showing landscape scale significant increases in biomass accumulation relative to No Management (6.0% for the Treatment Placement scenario and 7.3% for the Treatment Placement with Harvest). Despite the moderate increases in swampland area mean fire severity with treatment, those regions showed little change in biomass accumulation, often a moderate decrease (**Figure 14**).

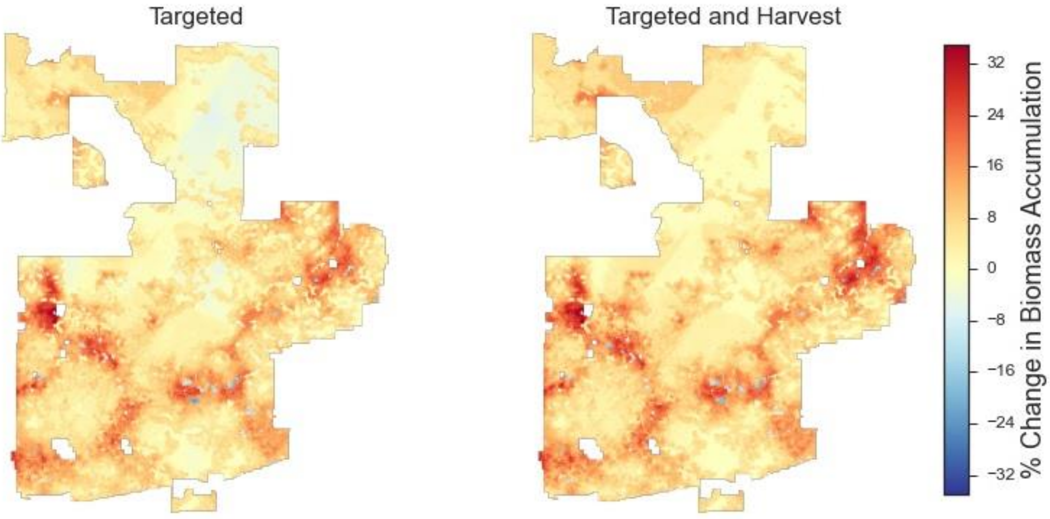

**Figure 14.** Percent change in accumulated above ground carbon between no management and treatment scenarios under extreme fire weather conditions.

## Science Delivery Activities

As per our proposed deliverables, we have worked with the three Fire Exchange Networks associated with each of the three regions (PNW, SW, SE) to disseminate three webinars and three research briefs. We have completed one webinar (May 2017) and one research brief (March 2017) for the California Fire Science Consortium, one webinar (March 2018) and one research brief (June 2018) for the Northwestern Fire Science Consortium, and one upcoming webinar and one upcoming research brief (both Fall 2018) for the Southern Fire Exchange. These are all produced after the model simulations have been finalized, publications are in preparation/review, and ready for "first looks" as a public release in the form of a webinar or research brief. We have presented four conference (oral/poster) presentations, with one planned for the *Ecological Society of America* (for the Osceola modeling) in August 2018, and others to come. We will exceed the number of (3) promised journal articles, where we will have *at least* two publications for each study site, resulting in 6 total. We already have two publications for the Dinkey landscape, three in preparation for the Malheur NF (currently written in a completed dissertation, see **Appendix B**), and two in preparation for the Osceola NF. We also plan to write a cohesive manuscript that incorporates results from all three CFLRP landscapes examining commonalities among sites with distinct restoration goals. We will continue to work with managers, stakeholders, and interested parties to utilize the results of our work in adaptive management planning.

# Conclusions, Implications, & Future Research

## Conclusions & Key Findings

For all landscapes, our approach to determine the optimum placement of fuels treatments required simulations with multiple replicates to capture effects from stochastic wildfire ignitions and spread. The probability of high-severity fire across each landscape served as a means of determining optimum placement, in a post-hoc "treat the highest probabilities first" framework. This approach yielded a comparable treatment efficacy to other less strategic approaches, but with fewer management inputs. We also found that efficiently allocating resources for thinning, prescribed fire, or a combination thereof depended on site. Our results suggest that using treated areas to restore surface fire in the short-term can yield long-term carbon storage gains because this approach restores adaptive capacity for more extreme fire weather that is projected to occur more often.

The model optimization approach, based on targeting treatment areas from projections of wildfire risk, was successful for all three study sites. Prioritizing thinning treatments across the landscape using the probability of high severity wildfire illustrated a significant reduction in the area required for either mechanical thinning or thinning in general to achieve landscape scale reductions similar to a fully treated landscape. Importantly, the continued application of prescribed fire in perpetuity was required in all instances to maintain landscape scale benefits, i.e. promoting fire-adapted tree species, reducing fire severity, and sequestering carbon. Specifically for the Malheur National Forest, our largest study site, we found that increasing the present-day annual area treated with prescribed fire by a factor of *three* was required to realize a detectable reduction in annual area burned by wildfire across the landscape regardless of fire weather scenario. These effects were evident in aboveground carbon values causing improved landscape carbon stability. Overall, carbon costs, including losses from prescribed fire, wildfire, and/or thinning treatments, were minimized (resulted in significant decreases compared to no-management scenarios) under prioritized thinning and burning scenarios when compared to less-strategic or naïve treatment placement scenarios. These carbon stabilization effects were particularly robust during extreme fire weather events, and also when implementing climate projections, which is highlighted in this report for the Dinkey Creek watershed. Notably, the reduction in the range of AGC - indicating more stable landscape carbon - often came with no change in the maximum sequestration potential found across replicates when treatments were implemented. On the other hand, without treatments ('no-management' scenarios), maximum sequestration potential was reached much later in the century.

At the landscape scale, fuel treatments were the most effective under extreme fire weather conditions, where the intersection of fire and treatments are most likely to occur compared to less extreme weather conditions, and significant reductions in wildfire severity were found. At the local scale, however, treatments were useful regardless of fire weather conditions because treatments increased forest resilience by promoting fire-dependent species, reducing drought-stress, and maintaining low fire risk conditions within those areas. And although treatment prescriptions were unique by site, their continued application through time and strategic placement were the most important aspects for reducing wildfire severity, area burned, and increasing landscape carbon sequestration potential and stability. Differences in prescription type at each site were less important. For example, adding harvesting of merchantable trees to the current prescription regime (prescribed fire and thinning treatments) at the Osceola National Forest did not significantly alter the mean or variability of fire severity nor the total ecosystem carbon stored in the system. Similarly, adding mechanical and prescribed fire treatments in riparian habitat conservation areas of the Malheur National Forest was insufficient to alter landscape-scale fire severity or area burned.

In some instances however, the effects of prioritizing treatments did have an impact on areas not treated, illustrating more localized effects on fire severity. For example, at the Osceola National Forest, concentrating treatments in the uplands, which are spatially intertwined with the swamplands (or lowlands) reduced the amount of fires that originated in the pine-dominated uplands from spreading into the swamplands. But, this came at a future cost: The swamplands that did experience fire resulted in a higher mean fire severity relative to the no-management scenario due to increased fuel accumulation and less frequent fire. In conclusion for all three landscapes, we found that prioritizing treatment placement based on fire risk and implementing a long-term prescribed fire regime were the most optimal approaches to maintaining carbon stability and reducing wildfire severity and area burned.

## Implications for Management/Policy

Treatments are only effective for reducing high-severity fire risk if they intersect with subsequent wildfires, and the probability that wildfire will occur in any particular location on a landscape is low. From this study, we used a landscape modeling technique to simulate interacting biophysical factors to identify high fire risk areas. We found that prioritizing treatments to these high fire risk areas yielded comparable treatment efficacy to the other less strategic approaches, but with fewer management inputs. Treatment efficacy is strictly from the landscape perspective, in terms of enhancing carbon sequestration potential, reducing wildfire area burned and reducing fire severity. This provides managers with a model-informed decision framework that can be used for developing spatial placement options for long-term treatment planning. Prioritizing treatment strategies is particularly helpful as resources for implementing treatments can take significant effort and resources, and can be constrained by regulatory restrictions. Fortunately, increasing the amount of prescribed fire on the landscape is an effective way to achieve multiple objectives, even if an initial more “heavy” treatment of thinning is needed to kick start the restoration process. Our results suggest that using treated areas to restore surface fire in the short-term can yield long-term carbon storage gains, particularly later in the century when extreme fire weather is more likely to occur. Long-term prescribed fires maintain a fire-resilient system in terms of increasing forest carbon sequestration potential, reducing long-term emissions from wildfire (when compared to no-management projections), reducing the intensity and severity of wildfires when they do occur in those areas, and is considerably less expensive than mechanical treatments. And, as wildland fires are an integral part of North American terrestrial ecosystems and imminent increases in extreme fire weather are likely, a ‘no-management’ strategy is not economically or socially viable. Site implementation however, also takes into consideration local concerns, such as protection of small biodiversity hotspots, adjacency to urban infrastructure, native lands, archeological sites, etc. For these three particularly large study sites, we found that they are relatively cohesive in construct and not bordered by a significant amount of urban interface. In fact, any fragmentation was primarily geographic and a legacy from past management, as opposed to development. This could allow for more flexibility when attempting to increase prescribed fire across these large landscapes, particularly for the Malheur National Forest and Dinkey Creek watershed. The Osceola National Forest is perhaps unique in that it already has a strong prescribed fire program in place and is effective at maintaining fire resilience in the pine uplands. However, the effects of treatment prioritization on adjacent inter-mixed swamplands was confounded. Although optimizing treatments around the swamplands may protect them even more from wildfire (reducing area burned), it may cause higher fire severity when a wildfire does occur due to more fuel accumulation. These fire events and fire spread potential are also dependent on seasonal and decadal water levels within these swamplands. As such, the consideration of localized effects is often site-specific and reliant on local expertise and careful planning. Long-term prioritization approaches to implementing treatment, particularly with the continuation of prescribed fire, have been found here to be the most optimal approaches to maintaining carbon stability and increasing fire resilience.

## Future Research

A future research direction could include examining human adaptation to extreme fire weather, reducing accidental fires through educational efforts, and reducing the flammability of structures. Another avenue would be to design better support mechanisms for management as they implement their long-term treatment plans. This would provide a more positive accounting approach to monitor treatment efficacy. As managers are often forced to adhere to restrictions, they could be rewarded by reaching certain treatment efficacy goals through time. In addition to this, supporting the use of managed wildfire, rather than strictly “suppressing all wildfires” could be a useful avenue of research. As public opinion can be a barrier to carrying out prescribed fire operations, a focus on public outreach and education about the safety and efficacy of prescribed fire may be beneficial.

In association with modeling efforts, a new LANDIS-II fire extension has been developed and is currently being tested in the eastern Sierra Nevada. We could expand our current treatment scenarios and compare these with the two different approaches to simulating wildfires. In addition, there could be improvement to model carbon allocation, specifically to the relatively unknown production rates and storage potential of recalcitrant or black carbon, which can be stored for long periods of time (decades to centuries). If these values are substantial, frequently burned forests may have higher sequestration potential than currently understood.

More fire-related studies could be focused in the eastern, specifically southeastern U.S. where extensive prescribed burning is performed and opportunities for fire science and ecology research are abundant. Literature is limited in the southeast, focused at landscape-level simulations as they pertain to management feedbacks associated with net ecosystem carbon dynamics, disturbance, and ecosystem resilience (e.g., Martin et al. 2015, Swanteson-Franz et al. 2018). There is extensive and intensive management using prescribed fire (as well as thinning, herbicide, mulching, etc.) that is applied in the southeast. For example, more than two million acres of prescribed fire are applied per year in Florida alone. Understanding efficacy in all North American systems is important in future climate conditions and in the increasing wildland-urban interface.

For lands that have fire-sensitive wetlands (but do experience periodic fires) and border more fire-prone areas, it would be interesting to study the spatial dynamism of wetland progression - expansion and retraction - across the landscape, as well change in ecosystem state - from wetland to pineland to wetland again. This was not included in the simulations for Osceola, but the transitions could be rather quick (a few decades) given projected drought and fire conditions.

In the Malheur, future study could include fire dynamics in the moist mixed-conifer forests, which are more prevalent in the northern portion of the National Forest as well as the Wallowa-Whitman National Forest. Although historical fire frequency was similar in these forests as the drier, more southerly forests, future interactions between extreme fire weather and wildfire may lead to unique shifts in forest composition and an altered fire regime.

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# Appendix A

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# Appendix B

## Articles

### Published

Krofcheck D.J., Hurteau M.D., Scheller R.M. & Loudermilk E.L. (2017). Restoring surface fire stabilizes forest carbon under extreme fire weather in the Sierra Nevada. Ecosphere, 8.

Krofcheck D.J., Hurteau M.D., Scheller R.M. & Loudermilk E.L. (2017). Prioritizing forest fuels treatments based on the probability of high-severity fire restores adaptive capacity in Sierran forests. Global Change Biology, 24, 729-737.

### In preparation

Cassell, B.A., Hurteau, M., Loudermilk, E.L, Lucash, M., Scheller, R.M. More and widespread severe wildfires under climate change lead to dramatic declines in high-elevation species in the dry mixed-conifer forests of the inland western U.S. (In preparation)

Cassell, B.A., Hurteau, M., Loudermilk, E.L, Lucash, M., Scheller, R.M. Optimizing placement of fuel treatments and accelerating prescribed fire ameliorates weather-driven wildfires in western mixed-conifer forests. (In preparation)

Cassell, B.A., Nielsen-Pincus, M., Scheller, R.M., Loudermilk, E.L. Local resident perspectives on forest management and implications for fuel treatments in a rural community in eastern Oregon, U.S. (In preparation)

Krofcheck, D., Hurteau, M. Hiers, J.K., Scheller, R. Loudermilk, E.L. Fuels management at the wetland-pine interface affects landscape scale wildfire severity under extreme fire weather conditions in the Osceola National Forest, FL. (In preparation)

Krofcheck, D., Hurteau, M. Hiers, J.K., Scheller, R. Loudermilk, E.L. Future interactions between projected climate, wildfire, and management in a highly heterogeneous southeastern pine forest. (In preparation)

## Technical Reports

None.

## Textbooks or book chapters

None.

## Graduate Thesis

Cassell, B.A. (2018). Assessing the Effects of Climate Change and Fuel Treatments on Forest Dynamics and Wildfire in Dry Mixed-Conifer Forests of the Inland West: Linking Landscape and Social Perspectives. Portland State University, Portland, OR. (Doctoral Dissertation)

## Conference Proceedings

None.

## Conference Abstracts

Krofcheck, D.J., Loudermilk, E.L., Scheller, R.M., Hurteau, M.D. Forest management and wildfire under alternate climate futures in eastern Oregon. Ecological Society of America Conference, Portland, OR. August 2017. (oral presentation, published abstract)

Cassell, B.A., Scheller, R.M., Loudermilk, E.L., Hurteau, M.D. Under extreme weather conditions, dry mixed-conifer forests in the western U.S. benefit from spatial optimization of fuel treatments. US-IALE 2018 Annual Meeting, Chicago, IL. April 2018 (oral presentation, published abstract)

## Posters

Cassell, B.A., Scheller, R.M., Nielsen-Pincus, M. Would you like fires with that? Using stakeholder-derived forest management preference maps to model landscape-level fuel reduction treatment effects on wildfire spread. International Association for Landscape Ecology – US-IALE 2017 Annual Meeting, Baltimore, MD. April 2017. (poster presentation, published abstract)

Cassell, B.A., Scheller, R.M., Loudermilk, E.L., Hurteau, M.D. Assessing the Effectiveness of Fuel Treatments in a Mixed-Conifer Landscape: Linking Landscape and Social Perspectives. Association for Fire Ecology – 6th International Fire Ecology and Management Congress, San Antonio, TX November 2015. (poster presentation, published abstract)

## Workshop Materials

None.

## Field Tour Summaries

We toured all three field sites. We met with federal cooperators at the Malheur National Forest in April 2015.We toured the area and discussed project objectives and directions in relation to management goals. Several 'on the ground' personnel were present at various meetings. They expressed the need for this type of research at the Malheur and offered considerable insight into fuel treatment operations, includes Rxfire. In June 2016, we toured the Dinkey Creek CFLRP with the District FMO, a District Burn Boss, the District Silviculturist, the CFLRP Coordinator, and the Province Ecologist. On the tour, we described the objectives of the project and discussed some of the challenges and operation limitations that this CFLRP faces. In November 2016, we met with the Osceola National Forest management, AFMO, and personnel, toured the site and discussed project objectives and needs of management.

## Website Development

None.

## Presentations, Webinars, Science Delivery

Cassell, B.A. Fuel treatment effectiveness in the southern Blue Mountains of Oregon. Northwest Fire Science Consortium, March 21, 2018. (webinar)

Cassell, B.A. Climate impacts on forest succession and wildfire in the Blue Mountains of Oregon. Portland State University, Environmental Science and Management Friday Science Seminar, March 21, 2018. (oral presentation)

Cassell, B., Scheller, R. 2018. Spatially optimized fuel treatment and increased prescribed fire reduce wildfire activity under extreme weather. Research Brief provided to the USDA Forest Service and Northwest Fire Consortium. 1pp. (research brief)

Cassell, B.A., Scheller, R.M., Loudermilk, E.L., Hurteau, M.D. Under extreme weather conditions, dry mixed-conifer forests in the western U.S. benefit from spatial optimization of fuel treatments. US-IALE 2018 Annual Meeting, Chicago, IL. April 2018. (oral presentation)

Hurteau, M. Climate, wildfire, and management influences on forest carbon carrying capacity. California Fire Science Consortium. May 2, 2017. (webinar)

Hurteau, M., Krofcheck, D. 2017. Restoring Surface Fire Stabilizes Forest Carbon. Research Brief provided to the USDA Forest Service Pacific Southwest Research Station and Southwest Fire Consortium. 1pp. (research brief)

Krofcheck, D.J., Loudermilk, E.L., Scheller, R.M., Hurteau, M.D. Forest management and wildfire under alternate climate futures in eastern Oregon. Ecological Society of America Conference, Portland, OR. August 2017. (oral presentation)

# Appendix C

Metadata for this project include all input text and GIS raster files used to run LANDIS-II simulations for all three study sites. These files will be archived with the USDA Forest Service Research Data Archive (https://www.fs.usda.gov/rds/archive/) as publications associated with the project are released and can be linked to the data source on this website. GIS input files include, e.g. ecoregions, fire regions, management areas, and stand units. Text files are used for parameter inputs for LANDIS-II, which include information such as species life history traits and physiological attributes, fire weather, climate, and management strategies, as well as calibrated parameters, such as forest productivity and wildfire regimes. Data sources used to develop these parameters will be provided in all associated publications and this final report. All simulation outputs can be replicated by running LANDIS-II with the input files provided. We did not use the repository with Pennsylvania State University as stated in the management plan because Co-PI Hurteau (originally with Penn State) has transferred to the University of New Mexico.