Journal of Environmental Management 351 (2024) 119664

Contents lists available at ScienceDirect

Journal of Environmental Management

journal homepage: www.elsevier.com/locate/jenvman

Research article

Model analysis of post-fire management and potential reburn fire behavior

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ARTICLE INFO

Handling Editor: Jason Michael Evans

Keywords:
Post-fire harvest
Severity
Wildfire
Fuels
Fire effects
Fire behavior

ABSTRACT

Recent trends in wildfire area burned have been characterized by large patches with high densities of standing dead trees, well outside of historical range of variability in many areas and presenting forest managers with difficult decisions regarding post-fire management. Post-fire tree harvesting, commonly called salvage logging, is a controversial management tactic that is often undertaken to recoup economic loss and, more recently, also to reduce future fuel hazard, especially when coupled with surface fuel reduction. It is unclear, however, whether the reductions in future fuels translate to meaningful changes to reburn fire behavior, particularly in the context of potentially detrimental effects of harvest on other ecosystem services. We used observed post-fire snag structure in four high severity burn scars located in the Western United States that had variable post-fire snag basal area (13.3–63.9 mg ha^{-2}) to initialize a simulation study of future coarse and fine woody fuel hazard and associated reburn fire behavior and effects. We compared untreated controls to intensive and intermediate intensity harvest treatments, both simulated and actual. All treatments showed some number of years of extreme fire behavior during which flame lengths exceeded thresholds associated with wildfire resistance to control, implying that future fuel reductions achieved by the treatments did not translate to conditions conducive for effective reburn fire management. Harvested stands had less severe soil fire effects (soil heating and smoldering duration) than untreated controls, explained by lower predicted peak coarse woody fuels (CWD) in the harvested stands. At higher pre-treatment snag basal area, harvested stands better maintained CWD within the range desired to maintain ecosystem functions such as nutrient cycling and wildlife habitat. These simulation results indicate that, even with reduced fuel hazard, salvage treatments may still be associated with severe fire behavior for some time after wildfire, but achieved reductions in coarse woody fuels may also reduce some soil fire effects. Tradeoffs in the effects of post-fire harvest must be considered carefully in the context of forest regeneration, local conditions that govern salvage methods, snag fall and decomposition, and associated potential reburn fire effects.

1. Introduction

Wildfire is a disturbance that impacts human and natural systems throughout the globe. Fire regimes are driven by long and short-term feedbacks among climate, vegetation, and human activity (Flannigan et al., 2009; Krawchuk and Moritz, 2011). For example, dry forests across the Western United States had historically experienced frequent low-severity fire regimes that maintained open forest structures with low canopy bulk density (Hessburg and Agee, 2003). Many of these forests have been subject to active fire suppression and land use change, substantially altering them from their historical structure and fire regime (Hagmann et al., 2021; Hessburg et al., 2019; Hessburg and Agee, 2003). This resulted in large areas characterized by high canopy bulk density with both horizontal and vertical fuel continuity, contributing to extreme fire behavior and effects (Agee and Skinner, 2005) associated with large high severity burn areas. In extreme wildfires, the uncharacteristically high bulk density living forest has been replaced with large patches of uncharacteristically severe fire effects (Reilly et al., 2017; Stevens et al., 2017) with high densities of standing dead trees (snags). Over time, these areas may be susceptible to reburn (an area that burns two or more times in a relatively short interval) at high severity (Coppoletta et al., 2016; Prichard et al., 2017). The phenomena of high severity reburn has been observed globally and is not isolated to the ecosystem and management context of the Western US (Barker and

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https://doi.org/10.1016/j.jenvman.2023.119664
Received 24 July 2023; Received in revised form 7 November 2023; Accepted 19 November 2023
Available online 1 December 2023

Price, 2018; Collins et al., 2021; García-Llamas et al., 2020).

There is substantial evidence in various global ecosystems that prior burn severity is a strong predictor of reburn severity (low severity reburns at low, high severity at high), although the effect differs with time between fires, fire weather, and vegetation type (Barker and Price, 2018; Collins et al., 2021; Coppoletta et al., 2016; Holden et al., 2010; Parks et al., 2014; Prichard et al., 2017; Thompson et al., 2007; Thompson and Spies, 2010). Regardless of initial burn severity, wildfire may be self-limiting for reburns within a decade or more, with fuel reduction accomplished by previous fires both limiting fire spread (Collins et al., 2009; Parks et al., 2015) and reburn fire severity (Cansler et al., 2021; Parks et al., 2014; Stevens-Rumann et al., 2016). Reburn severity can increase with time since previous fire (Buma et al., 2020; Harris and Taylor, 2017; Parks et al., 2014; Stevens-Rumann et al., 2016) as both live and dead fuels accumulate. When reburns do occur, an area that previously burned at low to moderate severity is more likely to reburn at low to moderate severity, whereas areas that previously burned at high severity tend to reburn at high severity (Collins et al., 2021; Coppoletta et al., 2016; Holden et al., 2010; Parks et al., 2014; Thompson et al., 2007; Thompson and Spies, 2010).

Over time, snags in high severity burn patches decay and fall to the ground providing woody surface fuels that increase with increasing retained basal area (Peterson et al., 2015; Ritchie et al., 2013). These ground fuels may increase reburn fire intensity and severe fire effects by increasing soil heating and residence time, contributing to high severity reburns (Coppoletta et al., 2016; Lydersen et al., 2019). These sites are also characterized by high density of young, small, vulnerable conifers, or extensive shrub cover in high severity burn scars (Coppoletta et al., 2016; García-Llamas et al., 2020; Nemens et al., 2022; Thompson et al., 2007; Thompson and Spies, 2010). This positive feedback of high severity reburn following high severity wildfire can put a forest on a trajectory for a type conversion from forest to shrub or grassland (Coop et al., 2020; Landesmann et al., 2021; Nemens et al., 2022; Steel et al., 2021) and possibly prevent a return to resilient forest structure at the stand scale. On the other hand, a pattern of reburns over time can produce a mosaic of heterogeneous vegetation at the landscape scale that can reverse contemporary homogenization of landscape forest structure and provide stabilizing feedbacks in fire regimes (Povak et al., 2023).

Given the potential for high severity reburn and its implications for forest resilience, it is important to evaluate different options for post-fire management and whether those activities achieve local and stand-scale management objectives. A controversial action that is utilized across the globe is the harvest of fire-killed trees (i.e., post-fire harvest; USDA Forest Service, 2021; Vallejo and Alloza, 2012), which reduces post-fire snag basal area. Post-fire harvest historically was undertaken to recoup economic loss of merchantable trees killed from wildfire, but more recently has also been part of a post-fire hazardous fuel reduction and forest restoration toolkit (e.g., USDA Forest Service, 2022; 2021). It is not clear what effects fuel reductions achieved by post-fire harvest may have on reburn severity (Leverkus et al., 2021). Depending on method, post-fire harvest may reduce future fine (<7.6 cm; FWD) and coarse (>7.6 cm; CWD) woody fuel loads relative to untreated stands (Johnson et al., 2020), which would be predicted to reduce fuel hazard and potential fire behavior. In the short-term, however, harvest may increase fuel hazard and potential fire behavior (Donato et al., 2006; Johnson et al., 2023) due to the deposition of debris. Furthermore, while the eventual lower surface fuel hazard from some methods of post-fire harvest may be associated with reduced fire behavior, thresholds for extreme behavior, such as those associated with wildfire resistance to control, may still be crossed and result in high severity fire effects (Coppoletta et al., 2016; McIver and Ottmar, 2018). The harvest activity may also compact soils and increase post-fire erosion and sediment (Robichaud et al., 2020; Wagenbrenner et al., 2016).

Fuel hazard is not the sole post-fire management concern that may be impacted by post-fire harvest. For example, managers may want to preserve some biomass in the form of snags and fallen CWD as they serve many ecological functions including wildlife habitat and nutrient cycling (Brown et al., 2003; Bull et al., 1997; Hagan and Grove, 1999). CWD management is concerned with maintaining sufficient biomass to provide ecological benefits while avoiding CWD loadings associated with high fuel hazard. This implies that, depending on site characteristics and management objectives, there is a desired or optimal range of CWD loading (Brown et al., 2003) that post-fire harvest may be able to target. Our analysis will investigate different post-fire harvest scenarios for their effects on both predicted reburn fire behavior and effects as well as CWD management for an example desired target range (Brown et al., 2003).

Retrospective burn severity analysis is opportunistic by necessity, precluding a true experimental design (McIver and Ottmar, 2018; Thompson and Spies, 2010). Rather, analysis often relies on modeling studies of the post-treatment landscape (McGinnis et al., 2010). Models allow for investigation of scientific questions where empirical analysis is difficult and data are sparse. Our main objective is to use simulation to investigate potential reburn fire behavior and effects under alternative post-fire management scenarios.

We use measured (first year post-treatment) and simulated post-fire surface fuel loadings from high severity burn patches within four fires located in Washington and California, USA. We use FFE-FVS (the Fire and Fuels Extension to the Forest Vegetation Simulator (FFE-FVS; (Rebain et al., 2015) to predict woody fuel accumulations and FOFEM/BURNUP (First Order Fire Effects Model) for our simulations, which are commonly used to develop forest management plans and associated environmental documentation in the US. The BURNUP model (Albini et al., 1995; Albini and Reinhardt, 1995) used by FOFEM (Lutes, 2017) includes interactions among fuels of different sizes to calculate fuel consumption, which can be used to calculate fireline intensity and fire effects such as soil heating. Such calculations may better predict potential reburn fire behavior and effects than fire behavior models that rely on semi-empirical formulations such as Rothermel (1972), which use fine surface fuels (usually represented by stylized fuel models such as Scott and Burgan, 2005) and do not incorporate the contributions of CWD. Although these models are primarily used in the US, results of this analysis will inform use of similar models used globally.

The scope of this project has been motivated by our co-production approach to management-relevant research (Lemos and Morehouse, 2005), in which experimental design and treatment prescriptions are produced in close collaboration with local managers. This co-production model is essential if science is to be successfully applied to management decisions and actions, even if it complicates the details of experimental design. In this case, we and managers are interested in the stand-level consequences of post-fire harvest on post-fire fuel hazard in the context of potential reburn fire behavior and effects. There are three main components pertinent to modeling potential wildfire reburn that we will evaluate:

1. What is the predicted rate of fuel accumulation and how does it differ among post-fire harvest treatments?
2. What is the pattern of potential reburn fire behavior over time, how does it differ among post-fire harvest treatments, and do simulated flame lengths cross important fire behavior thresholds associated with resistance to control?
3. What are the relative importance of snag basal area (and post-fire management reductions thereof), woody fuel loadings, and other fuel layers (herb, litter, shrub) on simulated reburn flame length, soil heating, and smoldering duration?

2. Methods

2.1. Methods overview

The wildfires included in this study are part of a larger effort to establish co-production relationships with forest managers throughout the Western US (Johnson et al., 2022), wherein researchers and managers collaborate at the early stages of study development to ensure that research objectives align with management questions and issues (Lemos and Morehouse, 2005). Our research questions, site selection, treatment prescriptions, and experimental design were all completed in collaboration with local managers and to provide empirical information regarding potential consequences of planned management actions. We used field measurements of post-fire stand structure in high severity burn patches in four wildfires in the Western US to initialize our 30-year simulation study of fuel accumulation and potential reburn fire behavior and effects (Fig. 1, Table 1).

2.2. Site descriptions

In 2015, the Stickpin fire burned 21,901 ha in Colville National Forest, northeastern Washington, USA (Fig. 1), resulting in large patches of 98–100% basal area mortality. Large high severity burn patch size ranged from approximately 100 to 10,000 ha. The pre-treatment mean total basal area in the measured units was 27.6 m^2 ha^{-1} (Table 1) and the area was dominated by *Pinus ponderosa* and *Pseudotsuga menziesii*. In that same year (2015), the North Star wildfire burned 88,442 ha in the Colville Reservation (northeastern Washington), managed by the Confederated Tribes of the Colville Reservation. The wildfire was of overall mixed severity, but resulted in large patches of >90% basal area mortality dominated by *Pinus ponderosa* and *Pseudotsuga menziesii*. Large high severity burn patch size ranged from approximately 100 to 6000 ha. The pre-treatment mean basal area in measured units was 13.3 m^2ha^{-1} (Table 1).

Table 1
Basic site description including number of treatment blocks, mean snag basal area (BA), and treatment scenarios. DBH indicates diameter at breast height. BA measures are m^2ha^{-1}; standard deviation given in parentheses.

Fire	King	Mendocino	North Star	Stickpin
Location	Eldorado National Forest (CA)	Mendocino National Forest (CA)	Confederated Tribes of the Colville Reservation (WA)	Colville National Forest (WA)
Year	2014	2018	2015	2015
Number of blocks	5	6	5	3
Pre-treatment mean snag BA (m^2ha^{-1})	63.9 (11.7)	44.1 (10.9)	13.3 (2.1)	27.6 (3.7)
Harvest method	Simulated	Simulated	Actual whole-tree	Actual whole-tree
Intensive	all stems DBH ≥35.56 cm	all stems DBH ≥35.56 cm	All merchantable trees	Thin to 3.4 m^2ha^{-1}residual BA
Intermediate	All stems DBH (35.56, 53.09 cm)	All stems DBH (35.56, 53.09 cm)	Thin to 3.4 residual BA	Thin to 10.3 residual BA

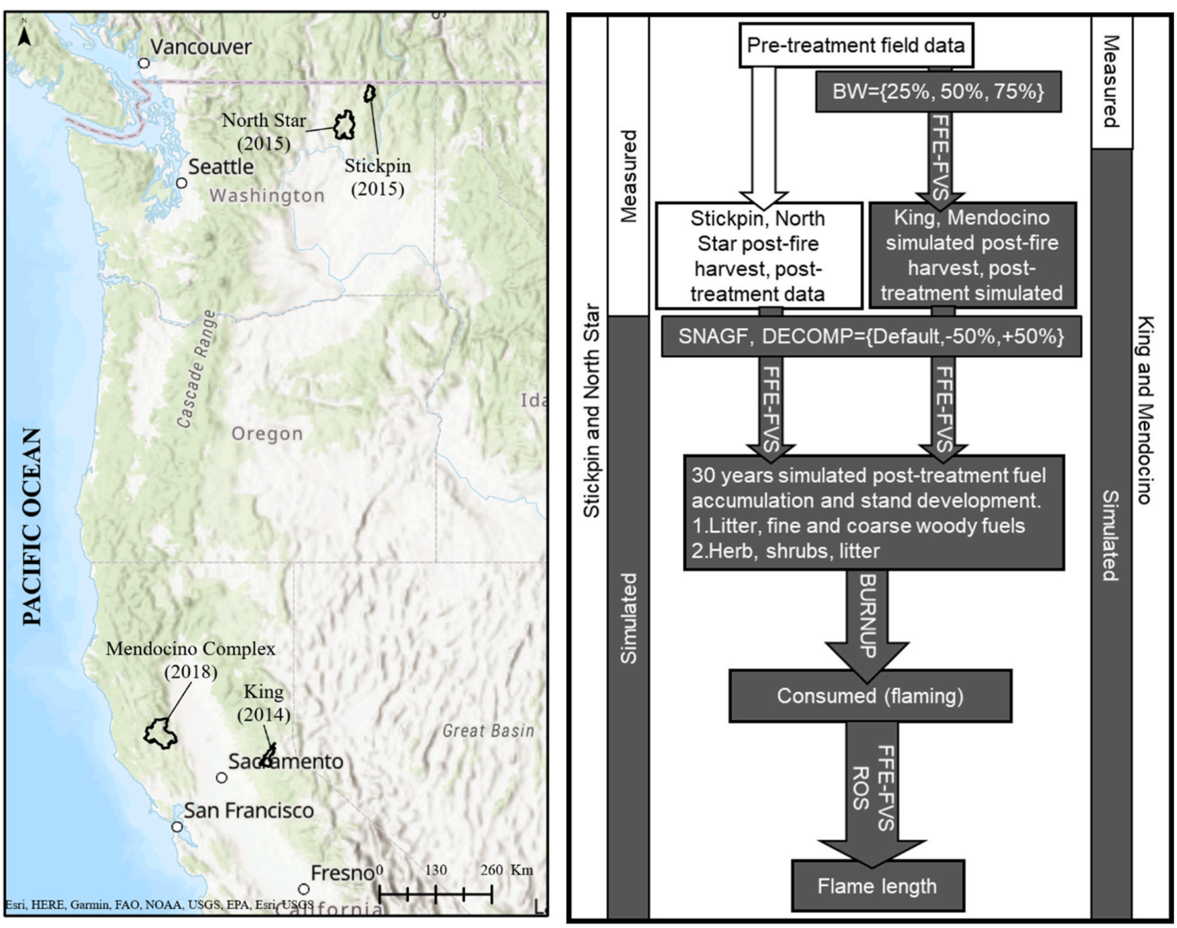

Fig. 1. The study sites are wildfires in California and Washington States, USA. Burn severity maps can be found in Fig. S1. Simulation study flow diagram shows the model inputs, settings, and calculations performed. All simulations were replicated with different combinations of percent branchwood (BW), snag fall rate (SNAGF), and decomposition rate (DECOMP).

In 2014, the King Fire burned 39,544 ha in Eldorado National Forest (central Sierra Nevada, California, USA), with 50% of the burn area with >90% basal area mortality. Large high severity burn patch size ranged from approximately 100 to 12,000 ha. The pre-treatment mean basal area in the measured units was the highest among the study areas at 63.9 m^2ha^{-1} (Table 1) and was dominated by *Pinus ponderosa, Pseudotsuga menziesii*, and *Quercus kelloggii*. The Ranch Fire was part of the 2018 Mendocino Complex Fire that burned 185,800 ha in Mendocino National Forest, northwestern California, USA. 47% of the Ranch Fire burned with >90% basal area mortality. Large high severity burn patch size ranged from approximately 100 to 50,000 ha. The area was dominated by *Pinus ponderosa* and *Pseudotsuga menziesii* with a pre-treatment mean basal area in the measured units of 44.1 m^2ha^{-1} (Table 1). More detailed site descriptions can be found in Johnson et al. (2020) for the Stickpin, Johnson et al. (2023) for the North Star, and Johnson et al. (2022) for the King and Mendocino Fires. Some additional site descriptions and initial burn severity maps and study locations are found in Fig. S1.

2.3. Sampling design

We implemented a generalized randomized block design (GRBD) at all sites to take post-fire, pre-treatment field measurements (hereafter, initial). These were taken assuming that post-fire harvest would be implemented. At the Stickpin and North Star study areas, we repeated the measurement protocol after post-fire harvest treatments. Prioritization of areas for post-fire harvest varied according to local site conditions and guidelines, but is commonly based on several factors, including: burn severity, basal area, management and policy restrictions, and feasibility of timber sale success. We identified multiple blocks (Table 1) with similar stand conditions and burn severity within each fire and within the area prioritized by local managers for post-fire harvest. Areas chosen for post-fire harvest represent a small proportion of the total burn area.

Within each block we randomly assigned treatments to three 2.2 ha (125 × 175 m) experimental units, each with a 30 m buffer to avoid edge effects from roads or other treatment types. The experimental units included two harvest treatments (Intensive, Intermediate) and an untreated (Control) for each block. These intended treatments were completed at the Stickpin and North Star fire areas (described below) but not in the King and Mendocino Complex fire areas (due primarily to lack of bids on the timber sale). We then took pre-treatment and post-treatment measurements at each site. The general GRBD study and measurement design, as implemented in the Stickpin fire area, is described in detail in Johnson et al. (2020). A similar protocol was used in each wildfire area and is described briefly below.

Species, diameter at breast height (DBH, cm), total height (m), and tree crown base height (CBH, m) were recorded for each snag >11.4 cm DBH within a regular grid of 24, 202 m^2 circular, fixed-area plots in each treatment unit (Table 1). Data for snags< 11.4 cm DBH were recorded on an 81 m^2 plot. Woody fuel loadings were estimated using the planar-intercept method as described by Brown (1974) on four 12-m planar transects originating from random azimuths. Angles were not corrected for slope. Woody fuel loadings were recorded by size (or fuel time-lag) class (Fosberg and Deeming, 1971): 1-h, 0–0.64 cm diameter; 10-h, 0.64–2.54 cm; 100-h, 2.54–7.62 cm; 1000-h, >7.62 cm. Sampling distances varied by surface fuel timelag class: 1-hr fuels were sampled 10.8–12 m, 10-hr fuels 9–12 m, and 100- and 1000-hr fuels 0–12 m along the transect. Woody material loading and woody material density were calculated from relationships that use number of pieces intersected and transect length (and wood specific gravity for loading) developed by Brown (1974) and Safranyik and Linton (1987).

2.4. Model descriptions

Fig. 1 gives a flow chart of the simulation study. We used the field data described above to initialize FFE-FVS simulations of stand development and fuel accumulation. In some cases, FFE-FVS also simulated the salvage treatment (King, Mendocino). There are three FFE-FVS submodels relevant to this study (see Rebain et al., 2015 for detailed description). The snag submodel simulates snag decay, breakage, and snag fall, which contributes to woody fuel loadings. The fuel submodel simulates the accumulation and decomposition of dead woody fuels and litter. Fuels accumulate through litterfall, snagfall, and mortality. Herbs and shrubs are not simulated directly in FFE-FVS and we did not include measured values for model initialization. Rather, the model assigns values dynamically using a combination of percent cover and dominant species. As those change over time, so do shrubs and herbs. FFE-FVS generally predicts fire behavior by dynamically classifying stands into one (or two with dynamic weighting) of the 40 Scott and Burgan (2005) stylized fuel models (FM40). The fire submodel estimates surface fire behavior using the semi-empirical FIREMOD, based on existing models (Albini, 1976; Andrews, 1986; Rothermel, 1972). We used FFE-FVS to estimate wildfire rate of spread. The annual FFE-FVS predicted fine woody fuels, coarse woody fuels, herb, litter, and shrub loading were used as input to FOFEM for prediction of fuel consumption and soil fire effects.

FOFEM 6.8.2 (Lutes, 2017) uses a combination of empirical equations and the process-based BURNUP module to predict fuel consumption (Albini et al., 1995; Albini and Reinhardt, 1995). BURNUP predicts heat transfer and burning rates of litter and woody fuels by size class. Litter is usually 100% consumed. The consumption of larger fuels in BURNUP depends on interactions with smaller fuels. This model therefore predicts variable consumption and associated fire behavior depending directly on fuel loadings (Kennedy et al., 2020), in contrast to fire behavior models that rely on stylized fuel models which coarsen variability in fuel loading and associated fire behavior (Kennedy et al., 2021). Smoldering and flaming consumption in BURNUP is differentiated by estimated intensity of burning. Herbaceous consumption ranges from 90 to 100% and shrub consumption from 50 to 90%. We included the fuel layers litter, herbaceous, fine woody, coarse woody, and shrubs in BURNUP calculations.

2.5. Post-fire management

In this area, post-fire management is considered in the landscape context and features of the burned area. Environmental assessment is required for any action (see, e.g., USDA Forest Service, 2021) and, overall, most of the high severity burned area is not treated. Post-fire harvest had either been implemented (Stickpin, North Star) or was planned but not yet implemented (King, Mendocino) in the study sites. We used measured post-treatment stand structure and fuel loadings in the Stickpin and North Star fire areas and simulated treatments in the King and Mendocino fire areas (Fig. 1).

The treatments generally included a higher intensity (Intensive) harvest, a lower intensity (Intermediate) harvest, and no harvest (None; Fig. 1). Actual targets differed by location and were informed by management preferences. In the Stickpin fire area this translated to target residual basal areas of 3.4 m^2 ha^{-1} for the Intensive salvage treatment and 10.3 m^2 ha^{-1} for the Intermediate treatment (locally named Standard Salvage Retention and Green Tree Retention, respectively). In the North Star Intensive treatments all merchantable timber was harvested, whereas in the Intermediate treatment the target residual basal area was 3.4 m^2 ha^{-1} (locally named Intensive Salvage and Seed Tree Harvest, respectively). There was no post-harvest treatment of the surface fuels as the managers on the ground were satisfied by the results of the whole-tree harvest (C. Desautel, J. Pass, personal communication). Implementation of the treatments was highly variable in both locations (Johnson et al., 2020), often missing residual targets. They did, however, achieve lower residual snag basal area than control units (Fig. 2). The treatment levels should be interpreted as a relative change in snag BA within each fire area rather than a precise description of the

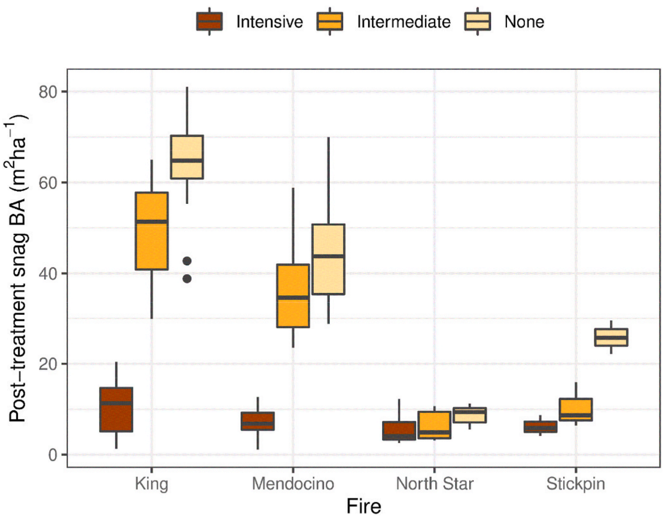

Fig. 2. Post-treatment residual snag basal area for each fire and salvage treatment. The None treatment can be considered the distribution of pre-treatment snag BA for each fire. The Intensive and Intermediate treatments are then reductions in snag BA relative to None.

silvicultural prescription.

We used FFE-FVS to simulate the post-fire harvest in all measured units in the King and Mendocino fire area, such that each measured unit was simulated with Intensive, Intermediate, and None post-fire harvest treatment. For the intensive treatment, the prescription was to harvest all stems ≥35.56 cm in diameter, whereas for the intermediate treatment the prescription was to harvest all stems with diameters between 35.56 and 53.09 cm, leaving the largest stems intact (Fig. 2; Fig. S2). FFE-FVS allows the user to specify the percent of branchwood retained (BW) after the simulated harvest. We replicated our simulations with 25% 50%, and 75% BW, representing harvest methods with variable deposition of slash.

We also simulated 1482 stems ha^{-1}plantings at every site, in consultation with local managers, to approximate forest regeneration. This is a standard reforestation practice in the area to give managers flexibility and options for actions such as pre-commercial thinning and to hedge against low seedling survival. This resulted in planting 100% *Pinus ponderosa* in the King, Mendocino, and North Star sites, and planting 33% each of *Pseudotsuga menziesii*, *Pinus ponderosa*, and *Larix occidentalis* at the Stickpin site.

2.6. Simulated surface fuel accumulation

We used FFE-FVS to predict woody fuel accumulation and herb, shrub, and litter loading for 30-years after post-fire management. We used the Western Sierra variant (Keyser and Dixon, 2019) for the King fire, the Inland California/Southern Cascades (Dixon et al., 2021) for Mendocino, the Inland Empire Variant for Stickpin, and the East Cascade variant of FFE-FVS (Keyser, 2018; Rebain et al., 2015) for the North Star fire. Fine woody fuel loadings (<7.62 cm) predicted by FFE-FVS are sensitive to decomposition rate (DECOMP) and predicted coarse woody fuel loadings (>7.62 cm) are sensitive to snag fall rate (SNAGF; Kennedy et al., 2021), so we simulated woody fuel accumulation with default rates and rates ± 50% of default for each parameter. We use the desired range of CWD loading defined by Brown et al. (2003) for similar forest types (11.1–44.8 Mg ha^{-1}) as an example management target for our sites, where values below the range may be considered insufficient for ecological functioning (e.g., nutrient cycling) and values above the range may be considered high fuel hazard. Predictions for coarse and fine woody fuels in Stickpin were first reported in Johnson et al. (2020) and in Johnson et al. (2023).

2.7. Potential reburn behavior and effects

We focused on flame length, soil heating, and smoldering duration to represent important measures of fire behavior and effects. To determine predicted flame length, we first calculated (Byram, 1959) fireline intensity (I):

$$I = Hwr, \tag{1}$$

where I is fire intensity (kW m^{-1}), H is heat yield of fuel (kJ kg^{-1}; 18,608 kJ kg^{-1} as used in the stylized fuel models of Scott and Burgan, 2005), w is weight of available fuel (fuel that is consumed; kg m^{-2}, flaming consumption calculated in BURNUP), and r is the fire rate of spread (m s^{-1}; rate of spread calculated by FFE-FVS). Flame length (FL; m) is calculated from intensity as (Byram, 1959):

$$FL = 0.775I^{0.46}. \tag{2}$$

We considered potential reburn flame length in two ways: the magnitude of flame length and whether predicted flame length exceeded thresholds associated with resistance to control and extreme fire behavior (Andrews and Rothermel, 1982). At a flame length >1.2 m (4 ft), the fire is considered "too intense for direct attack", at >2.4 m (8 ft) "fires may present serious control problems", and at >3.4 m (11 ft) "control efforts at head of fire are ineffective." We determined the timing and duration these thresholds were exceeded for each stand and for mean flame lengths across all stands for a given fire x treatment combination.

Soil heating is simulated in FOFEM using the Campbell soil heating model (Lutes, 2017) with one-dimensional downward flow of heat into the soil. We used the non-duff model, which assumes BURNUP-simulated radiant heating from flaming combustion heats the soil surface. We make the implicit assumption that the duff layer is not well-developed in these dry forests, particularly after a high severity wildfire (Dunn and Bailey, 2015; Eskelson and Monleon, 2018). We then recorded predicted soil heating and smoldering duration to represent potential severity of surface and soil fire effects.

2.8. Analysis

Variability for each site in fuel accumulation and predicted fire behavior is introduced through the replicated randomized block design (Johnson et al., 2020). We summarized fuel loading over time for each treatment and fire combination by the median, 25th, and 75th percentiles across all blocks within each year since fire.

We assessed how pre-treatment snag BA and treatment intensity affected the 95th percentile predicted flame length, fine and coarse woody fuels, and soil heating and smoldering duration. The 95th percentile, in this case, represents peak values for a given simulation across the 30-year simulation timeframe. We also quantified the number of years within the 30-year simulation that the predicted flame length in a given stand exceeded the thresholds associated with resistance to control (1.2, 2.4, 3.4 m) and the number of years the predicted CWD loading in the stand was within the target range defined by Brown et al. (2003; 11.1–44.8 Mg ha^{-1}). We assessed trends in these metrics with pre-treatment snag BA, generalized across wildfires, using a loess smoother (using geom_smooth in the ggplot 2 R package, separately for each treatment).

We calculated partial rank correlation coefficients (pcc; R sensitivity package; Pujol et al., 2017) to compare the relative effects of different fuel layers (fine and coarse woody fuel loading, herbs, litter, shrubs) on predicted flame length, soil heating, and smoldering duration. The pcc characterizes the relationship between two variables after accounting for the effects of other variables, with values near one indicating strong relationships and values near 0 indicating no relationship. We used rank correlation coefficients because data likely violate standard correlation assumptions including linearity and constant variance.

We assessed sensitivity of model predictions to the percent branchwood (BW) from simulated post-fire harvest (King, Mendocino), decomposition rate of downed wood (DECOMP), and the snag fall rate (SNAGF). We calculated the percent change in model output for + -50% change in model parameter from the model output at baseline model parameters. A value near zero indicates that the model output is not sensitive to changes in the model parameter. A negative value indicates that increasing the model parameter decreases the model output and a positive value indicates that increasing the model parameter increases the model output.

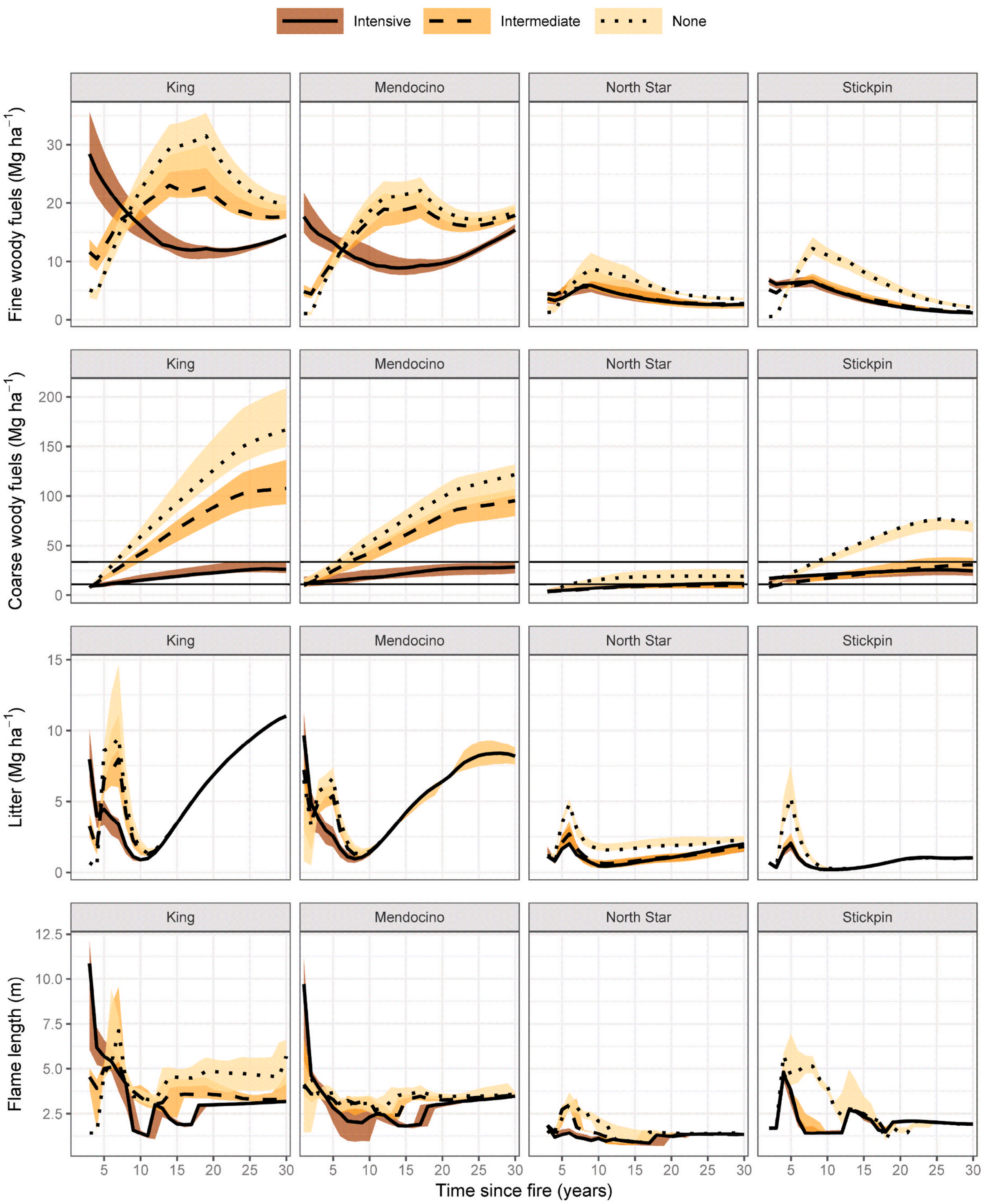

Fig. 3. Predicted fine woody fuels (<7.62 cm; first row), coarse woody fuels (>7.62 cm; second row), litter (third row), and flame length (fourth row) over time since fire across wildfire and treatment. Lines represent median values at each time since fire. Ribbons envelop the 25th and 75th percentiles for each time since fire. Horizontal lines in the second row bound example target range for CWD loadings (11.2–44.8 Mg ha^{-1}; Brown et al., 2003). Note that predicted litter accumulation converges among treatments ~10 years since fire. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

3. Results

3.1. Surface fuel accumulation

Initially, FFE-FVS-predicted fine woody fuels were higher in Intensive and Intermediate salvage treatments relative to None (no harvest control), but over time None surpassed both Intensive and Intermediate (Fig. 3). The initial pulse in fine woody fuels was higher for Intensive than Intermediate treatments. Coarse woody fuels were initially low in all treatments, then increased with time since fire. The None treatment accumulated the most fine and coarse woody fuels, followed by Intermediate, then Intensive. In King and Mendocino, with the highest pre-treatment snag BA (Table 1), CWD loading exceeded the upper thresholds of the target range (Brown et al., 2003) in the None and Intermediate treatments, but maintained CWD below the threshold in the Intensive treatment. In North Star, with the lowest pre-treatment snag BA, both Intermediate and Intensive treatments kept CWD below the target range, whereas the None treatment maintained CWD within the target range. In Stickpin, with intermediate pre-treatment snag BA, the target range was maintained for Intensive and Intermediate treatments and exceeded for the None treatment. Predicted litter loading was initially highest in the Intensive treatments. Over time, the litter accumulation increased in None and Intermediate treatments, peaking between 5 and 10 years after the fire, declining due to decomposition, then increasing again as the vegetation recovered.

Both fine and coarse woody fuel accumulation increased with pre-treatment snag basal area (Fig. 4). The 95th percentile fine woody fuel loadings attained over the 30-year simulation window were similar among treatments regardless of pre-treatment snag BA, whereas the 95th percentile coarse woody fuel loadings were similar only at low pre-treatment snag basal area. At higher pre-treatment snag BA, 95th percentile coarse woody fuels decreased with treatment relative to control. Intensive harvest maintained target CWD levels longer than Intermediate and None, except at the lowest pre-treatment snag BA.

3.2. Predicted fire behavior and effects (flame length, smoldering duration, soil heating)

Predicted 95th percentile flame length was similar among the treatments, but the timing of when the value was reached differed. Predicted flame length was initially higher for harvested stands, associated with increase in fine woody fuels and litter following harvest. Over time since fire the predicted flame length decreased in Intensive stands and increased in control stands with trajectories similar to that for the litter and fine woody fuels (Fig. 3).

Whether predicted flame length exceeded resistance to control thresholds differed by pre-treatment snag BA and treatment. 95th percentile predicted flame length generally increased with pre-treatment snag basal area and was similar among the treatments (percent branchwood = 50%; Fig. 5). The number of years during which predicted flame length surpassed resistance to control thresholds also increased with pre-treatment snag BA and differed among the thresholds (Fig. 5). The treatments were similar at the 1.2 m flame length threshold. At higher pre-treatment snag BA, the Intensive treatment had fewer years above the 2.4 and 3.4 m flame length thresholds, with the treatment effect strongest at the 3.4 m threshold.

There was a strong positive relationship between pre-treatment snag BA and both 95th percentile soil heating and smoldering duration (Fig. 5). Salvage treatments decreased both smoldering duration and soil heating relative to None, with the Intensive treatment having the largest reduction in both at high pre-treatment snag BA.

3.3. Sensitivity of model predictions to fuel layers and parameter values

Flame length was strongly correlated with litter loading across all wildfires (Table 2), In the King and Mendocino fires, where woody fuel loadings were highest, predicted flame length was also sensitive to fine woody fuel loading. Remaining correlations with flame length were relatively low, with the next highest associated with herb or shrub loading, depending on fire. In contrast, predicted soil heating and smoldering duration were both strongly correlated with coarse and fine woody fuel loading. Only in North Star was there a strong correlation between litter and soil heating.

Model sensitivity to parameter uncertainty, reflecting potential variability in local conditions, varied by parameter and model prediction (Table 3; Figs. S3–S8). Predicted 95th percentile FWD and flame length decreased with increasing decomposition rate and were not sensitive to snag fall rate (Figs. S3 and S4). They both increased with higher percent branchwood left after simulated salvage (BW) for the Intensive salvage treatment. In contrast, predicted 95th percentile CWD, soil heating, and smoldering duration increased with a higher snag fall rate and decreased slightly with higher decomposition rate (Fig. S8). They were not sensitive to BW. Variability in parameter values also modified treatment comparisons in some cases. At lower snag fall rate, Intermediate and None treatments exceeded Intensive in the number of years CWD was within the example target range, whereas at higher snag fall rates Intensive had the highest number of years (Fig. S8). Higher BW resulted in Intensive 95th percentile flame length exceeding Intermediate and None, rather than having similar values (Fig. S4).

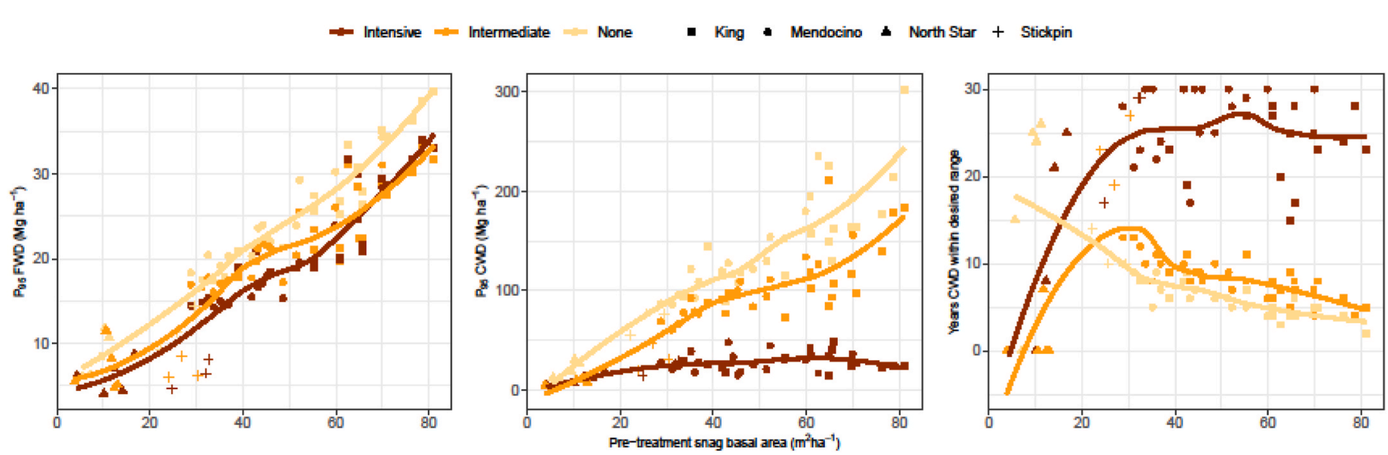

Fig. 4. Predicted 95th percentile fine and coarse woody fuels and number of years CWD falls within the example target range plotted against increasing pre-treatment snag basal area. Color indicates treatment type. Lines are loess smooth through the points for each treatment type. BW = 50%. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

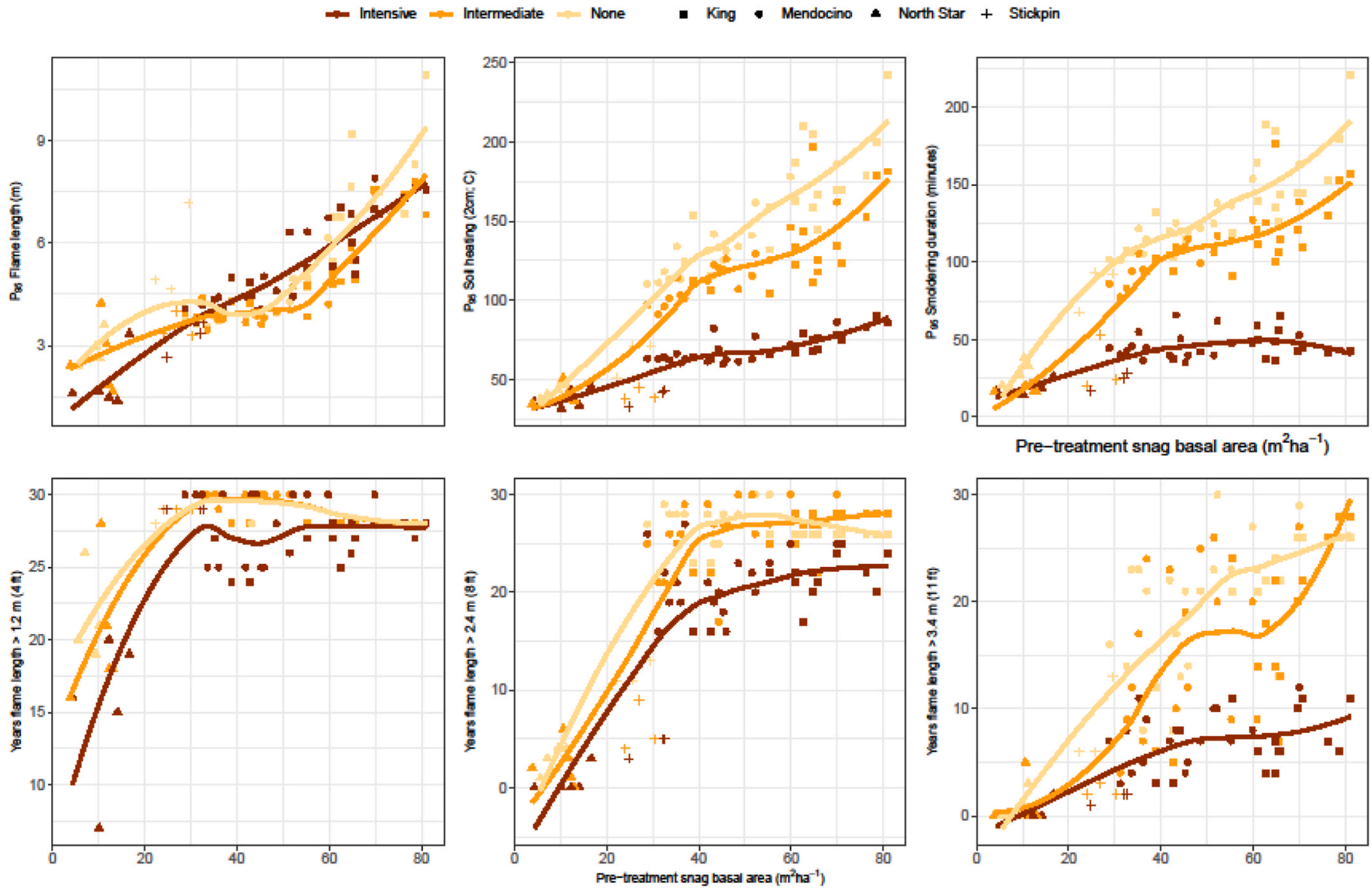

Fig. 5. Top row: 95th percentile flame length, soil heating and smoldering duration. Bottom row: number of years flame length thresholds are exceeded, all plotted against pre-treatment snag basal area. Color indicates treatment type. Lines are loess smooth through the points for each treatment type. Note that the simulation ran for 30 years, forcing an artificial asymptote if the years above threshold approached 30 years. BW = 50%. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

Table 2
Partial rank correlations coefficients between model predicted fire behavior and effects (Y) and fuel layers (X), considering all model runs.

Response variable	Fuel layer	King	Mendocino	Stickpin	North Star
Flame length	CWD	0.141	−0.024	0.02	−0.174
	FWD	0.51	0.533	0.254	0.336
	litter	0.636	0.712	0.591	0.612
	herb	0.052	0.473	0.318	0.278
	shrub	0.304	0.184	−0.383	−0.044
Soil heating (2 cm)	CWD	0.812	0.84	0.754	0.442
	FWD	0.828	0.868	0.757	0.949
	litter	0.426	0.523	0.29	0.804
	herb	0.078	−0.037	0.237	0.254
	shrub	−0.069	−0.048	0.262	0.533
Smoldering duration	CWD	0.951	0.956	0.912	0.863
	FWD	0.741	0.790	0.723	0.904
	litter	0.217	0.102	0.012	0.245
	herb	0.089	−0.069	−0.036	0.036
	shrub	−0.084	−0.049	0.109	−0.047

4. Discussion

High severity burn scars have the self-reinforcing potential to reburn at high severity (Collins et al., 2021; Coppoletta et al., 2016; Holden et al., 2010; Parks et al., 2014; Thompson et al., 2007; Thompson and Spies, 2010), with associated potential vegetation type conversions (Coop et al., 2020; Landesmann et al., 2021). It is an open question how to, and even whether to, manage these high severity burn areas (North et al., 2021). It is imperative to understand how post-fire management modifies trajectories of net fuel accumulation, wildfire resistance to control, and extreme fire behavior and effects. The analysis presented here demonstrates that not only magnitudes of effects, but also important thresholds and their timing, should be evaluated when considering post-fire management.

4.1. Predicted FWD, litter, and flame length

Time since wildfire is an important predictor of reburn severity (Buma et al., 2020; Cansler et al., 2021; Harris and Taylor, 2017) because of dynamic fuel accumulation following wildfire. A typical post-fire trajectory of fuel hazard in a high severity burn patch would be characterized by low hazard immediately following the wildfire due to the reduction of surface fuels through combustion. In a high severity burn patch, surface fuels accumulate with increasing time since wildfire. Snags are the primary contributor of surface fuels in these high severity burn patches, depositing woody fuels to the ground as the snag experiences breakage and eventually falls (Dunn and Bailey, 2015; Peterson et al., 2015, 2022; Ritchie et al., 2013). Post-fire harvest modifies this expected trajectory of post-fire surface fuel accumulation (Figs. 3 and 4), in some cases steering the stand towards more desirable future conditions.

In contrast to the expected self-limitation in the first decade or so following a wildfire, predicted fuel hazard can be much higher immediately following post-fire harvest (Figs. 3 and 4). The elevated surface fuel loadings in treated stands can produce predicted flame lengths above resistance to control thresholds in years very close to the previous

Table 3
Median percent change in model prediction for a 50% change in parameter value. Positive values indicate increasing the parameter value increases the model prediction. Negative values indicate increasing the parameter value decreases the model prediction. A value near 0 indicates low sensitivity to changes in parameter value. Percent branchwood refers to the percentage of original branchwood that is left on the ground after simulated post-fire harvest.

	Percent Branchwood			Decomposition			Snag fall		
	Intensive	Intermediate	None	Intensive	Intermediate	None	Intensive	Intermediate	None
P_{95} FWD	33	2	0	−14	−28	−25	0	0	0
P_{95} CWD	1	0	0	−13	−11	−11	1	15	30
P_{95} FL	23	3	0	−19	−28	−25	0	0	0
FL > 1.2	0	0	0	−8	0	0	0	0	0
FL > 2.4	4	0	0	−48	−36	−20	0	0	0
FL > 3.4	17	4	0	−100	−75	−67	0	0	0
P_{95} Smoldering duration	2	0	0	−18	−11	−10	0	3	12
P_{95} Soil heating	3	0	0	−16	−17	−15	0	1	2

wildfire (Fig. 3). This early increase in fuel hazard is driven in part by the deposition of fuels resulting from actual (Donato et al., 2006; Johnson et al., 2020) and simulated harvest activities. For simulated post-fire harvest, the modeled 95th percentile amounts were particularly sensitive to the percent branchwood left on the ground (Table 3; Figs. S3–S4). High percent branchwood represents methods where the logs are processed on site, leaving large amounts of residual materials. Low percent branchwood represents methods, such as whole-tree harvest, where the processing occurs at a common landing site. Such whole-tree salvage methods may reduce immediate deposition of surface fuels (Johnson et al., 2023). Additional fuel treatments, such as prescribed fire and pile and burn, may mitigate this initial fuel hazard. The implications of this deposition also vary by system. In some cases, it may hinder conifer tree regeneration (Donato et al., 2006), and in others it may be desirable to leave a legacy of surface fuels to provide organic inputs and to enhance regeneration (Taboada et al., 2018), potentially providing a facilitative effect in dry forests (Marzano et al., 2013). Slash that is deposited during harvest activities may also mediate erosion and runoff (Robichaud et al., 2020).

Harvested stands also defy the typical trajectory of fuel hazard as time since fire increases (Peterson et al., 2015). Over time, the surface fuels deposited by the harvest activity decompose and, since there are fewer residual snags left to fall, additional surface fuel accumulations remain low in model simulations (Figs. 3 and 4). In an untreated high severity burn scar fuel hazard peaks around the first decade following fire (depending on the snag fall rate, which is predicted by species and decreases with snag diameter; Everett et al., 1999), exceeding resistance to control thresholds. In contrast, predicted fuel hazard and associated flame length in harvested sites can fall below resistance to control thresholds around the first decade following fire.

The timing of simulated fuel accumulation is sensitive to both the decomposition rate and the snag fall rate (Table 3, Figs. S5–S7). The model sensitivity of surface fuel loading and predicted flame length to decomposition rate in particular may be problematic for future projections of fuels, as decomposition rate itself is unlikely to be constant in a changing climate, differs by ecosystem and disturbance agents, and represents a source of uncertainty in fire regime models (Hanan et al., 2022). The effect of post-fire harvest may also be sensitive to harvest timing (e.g., regeneration success; Splawinski et al., 2014), which is not investigated here as the actual and simulated harvest occurred in the first year after the wildfire at all study locations.

Pre-treatment snag BA had a strong relationship with predicted surface fuels and fire behavior. Stands with pre-treatment snag BA > 20 m^2ha^{-1} exceeded the lowest flame length threshold (>1.2 m) very quickly following wildfire and for most of the 30-year simulation, regardless of treatment (Fig. 5). For a forest with young, small trees, this flame length may also represent a threshold above which crown fire and tree mortality is likely. For example, 15 years after a wildfire in Oregon McIver and Ottmar (2018) found mean height to crown base of 0.1–0.5 m and severe fire effects in a reburn event regardless of treatment. Such low canopy base heights would likely suffer mortality and high severity even below the lowest resistance to control threshold (1.2 m). In contrast, Lyons-Tinsley and Peterson (2012) found that in an extreme wildfire in Washington State (Tripod Fire), young areas planted after clear cut harvest experienced low severity fire effects if sites had been broadcast burned before planting. This study strongly suggests that reducing surface fuels (not simulated here) may mitigate subsequent fire severity in young plantations.

4.2. Predicted CWD, soil heating, and smoldering duration

Depending on local site ecology and composition, there may be a desired range of CWD loading of interest to forest and fire managers (Brown et al., 2003). A minimum level is desirable for its ecologically beneficial effects on wildlife and biogeochemical cycling, while it is also prudent to prevent excessive fuel hazard as CWD accumulates. Post-fire harvest substantially modified simulated CWD accumulation. At the highest pre-treatment snag BA, the harvested stands maintained CWD loadings within the desired range for more years than untreated (Figs. 4 and 5), mainly by keeping the CWD below the upper threshold. At the lowest pre-treatment snag BA, the harvested stands had fewer years within the desired range because the treatment prevented sufficient CWD accumulation to cross the lower threshold for the desired range. In such cases, depending on fine surface fuel accumulation and treatment, harvest operators may intentionally leave CWD on the ground to achieve desired loadings and associated ecological effects (Larson et al., 2022).

CWD is strongly associated with the smoldering phase of combustion (Ottmar, 2014), so it is unsurprising that the lower CWD accumulation in the Intensive treatment reduced both simulated soil heating and smoldering duration, particularly at the highest pre-treatment snag BA (Fig. 5). Soil fire effects are more severe as fire duration increases (Certini, 2005; Neary et al., 1999), indicating potential consequences beyond fuel hazard for the predicted CWD accumulation in control stands. Increased duration and increased soil heating can affect the biomass and composition of soil microbes, with microbe mortality happening at temperatures as low as 50 C and as high as 210 C, depending on the organism (Neary et al., 1999). The Intensive treatment is expected to have 95th percentile soil heating less than 100 C at even the highest initial snag BA (Fig. 5). Soil heating can also cause nitrogen volatilization beginning at temperatures greater than 200 C and can affect biogeochemical cycles. Soil water repellency may develop at temperatures between 176 and 288 C, temperatures that are predicted to be met or exceeded in the None and Intermediate treatments.

4.3. Limitations

While it is clear that post-fire harvest would reduce woody fuel accumulations relative to controls (we need only the principle of conservation of mass for this conclusion), its effects on other dead and live components of the fuelbed (e.g., litter, herbs, shrubs) are highly variable (Leverkus et al., 2020), difficult to predict, and may not be different between treated and control stands (Campbell et al., 2016; McGinnis et al., 2010). Here, predicted flame length was most sensitive to litter loading (Table 2), consistent with the results of Kennedy et al. (2020). Treatment effects on dead surface fuels, especially litter accumulation, are important to consider when evaluating treatment efficacy. This represents an area of high uncertainty particularly when we consider potential climate change effects on litter accumulation and decomposition (Hanan et al., 2022) and post-fire understory responses such as potential vegetation type conversion (Coop et al., 2020; Landesmann et al., 2021; Nemens et al., 2022; Steel et al., 2021).

Time since fire is an important variable when considering potential reburn fire behavior and effects (Buma et al., 2020; Harris and Taylor, 2017; Parks et al., 2014; Stevens-Rumann et al., 2016), and understanding when extreme behavior peaks and when thresholds are crossed is valuable for post-fire management. This analysis relies heavily on model projections of post-fire fuel accumulation (Fig. 1), which dictate the timing of extreme fire behavior and effects. It is imperative to understand the reliability of predicted fuel accumulations, yet it is difficult to compare modeled values to observed given the scarcity of long-term data. Studies of post-fire fuel accumulation tend to rely on chronosequences that substitute space for time and there is a paucity of long-term fuels monitoring data (Johnson et al., 2022) that can be used to assess model predictions of fuel accumulation and decay. For example, Johnson et al. (2022) show that at default parameter values, coarse and fine woody fuel accumulation predicted by FFE-FVS do not match the empirical models estimated by Peterson et al. (2015). We require substantial long-term data to assess the adequacy of simulated fuel accumulation and associated time to extreme fire behavior and effects.

4.4. Management implications and future needs

There are several conclusions to be drawn from this analysis:

1. Post-fire harvest modifies the timing of peak fuel loadings; harvested stands have higher predicted fuel loading and associated fire behavior in the first few years following fire. Fuel reductions and associated reductions in predicted flame length are achieved with increasing time since fire.
2. Treatment effects on CWD management depend on pre-treatment snag BA. At lower initial snag BA and depending on management objectives, post-fire harvest may prevent sufficient woody fuel accumulation to provide desired ecological benefits (such as for biogeochemical cycling or wildlife). At high initial snag BA, post-fire harvest did maintain coarse woody fuels within desired ranges and reduce hazardous fuel accumulation relative to untreated controls.
3. At high initial snag BA, harvested sites had long time periods where they were predicted to have flame lengths that exceed wildfire resistance to control thresholds. This indicates that quantifying other fire-relevant metrics (such as predicted flame length associated with wildfire resistance to control) informs whether woody fuel reductions translate to desired outcomes for wildfire. Furthermore, other fuel layers (such as shrub regeneration and litter) also contribute to extreme fire behavior and should be considered when evaluating treatment efficacy.
4. Harvested stands potentially ameliorated severe soil fire effects in predicted reburns by reducing CWD accumulation over time.

These results demonstrate that there is no simple “yes or no” answer to the question of whether post-fire harvest will achieve lower reburn severity than untreated sites. The interpretation of treatment effects depends on potentially conflicting management objectives. Empirical studies have documented small to no differences in reburn severity when comparing treated to untreated stands (McIver and Ottmar, 2018). The timing of reburns may be important to predict subsequent fire effects, as are the pre-treatment snag BA and intensity of the harvest treatment. Post-fire harvest modifies the timing of peak fuel loads, with higher initial input of fuels compared to controls. Over time, as fuels accumulate in control stands, treated areas have lower fuel loads.

Other components of the fuelbed, such as shrubs, litter, and herbaceous materials, may overwhelm any post-fire harvest effect on woody fuel loadings and reburn fire behavior (Coppoletta et al., 2016; McGinnis et al., 2010; McIver and Ottmar, 2018; Thompson and Spies, 2010), particularly in a young and regenerating site. Post-fire harvest effects on these other fuel components are not well understood (Leverkus et al., 2020) and require additional study.

Minimizing fuel hazard may require additional surface fuel treatments, but some surface fuels may be desirable to control erosion, improve regeneration, and provide organic material and wildlife habitat. CWD management requires characterizing site-specific target ranges for desired ecosystem services, then designing post-fire treatments to achieve those targets. Furthermore, given potentially conflicting post-fire management objectives, including landscape-scale benefits of variable burn severities, and the relatively limited area that is affected by salvage logging, operations may be targeted for fuel reduction in high value areas.

Long-term monitoring of fuel accumulation in a variety of ecosystems, including woody fuels, litter, herbs, and shrubs, with treated areas compared to controls, would be ideal to understand trajectories of woody fuel accumulation and to assess model predictions. Model analysis should consider not only the deposition of fuels (phenology, mortality, snag fall) but also the decomposition of fuels and potential climate change effects on these processes (Hanan et al., 2022).

CRediT author statement

MK: Conceptualization, Formal analysis, Investigation, Methodology, Project administration, Software, Supervision, Visualization, Writing-original draft; MJ: Conceptualization, Data curation, Funding acquisition, Investigation, Methodology, Project administration, Resources, Supervision, Writing-review and editing, SH: Data curation, Investigation, Methodology, Visualization, Writing-review and editing.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

Acknowledgements

This project was funded by the US Forest Service Pacific Northwest Research Station, US Forest Service Mendocino National Forest, US Forest Service Colville National Forest, US Forest Service Eldorado National Forest, Colville Confederated Tribes. We thank the members of our many field crews over the years: Joe Restaino, Claire Accettullo, Sara Hwong, Lesly Franco, Samantha De Abreu, Jenny Yang, Haley Wiggins, Anthony Martinez, Ashley Hillis and Keelee Wilder Boozer. We sincerely thank the following individuals for their support, assistance and logistics: Hinda Darner, Frank Aebly, Gary Urdahl, Ann Carlson, April Hargis, Angela Chongpinitchai, Bryan Yost, Amy Galetka, Cody Desautel, Joseph Holford, Shay Logue, James Pass Karen Honeycutt, Dana Walsh, Eric Knapp, and Bob Carlson. We thank Mei Lin Lantz. Four anonymous reviewers helped in clarifying the scope and strengthening the inference of the study. Chris Karnes and James Northup assisted in script development and BURNUP simulations in the early stages of the project. Duncan Lutes provided batch executables for FOFEM 6.8.2.

The data and code used in this study will be made available upon request.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.jenvman.2023.119664.

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