



fire & fuels management

Simulating the Effectiveness of Improvement Cuts and Commercial Thinning to Enhance Fire Resistance in West Coast Dry Mixed Conifer Forests

Theresa B. Jain,[✉] Jeremy S. Fried,[✉] and Sara M. Loreno

Nine multipurpose silvicultural treatments, formulated as a synthesis of recently implemented prescriptions offered by forest managers, were simulated to evaluate their effectiveness at enhancing fire resistance. The Forest Vegetation Simulator was applied, within the BioSum Framework, on over 3,000 Forest Inventory and Analysis plots representing 5 million hectares of dry mixed conifer forests in eastern Washington and Oregon and California's Sierra Nevada Mountains. We developed a composite fire-resistance score based on four fuel modification principals and metrics: fuel strata gap, canopy bulk density, proportion of basal area in resistant species, and predicted tree survival. The trajectories of stands with and without treatment were compared to evaluate effectiveness immediately post-treatment, and over the three decades that followed. Seventy percent of these forests could be effectively treated in the short term by at least one prescription. Pretreatment forest condition, particularly fire-resistant species abundance, strongly influenced short-term treatment success, and the post-treatment stand dynamics that limit treatment longevity. Treatment effectiveness endured only 10 or 20 years, depending on fire-resistant species abundance, owing to growing space for crown expansion generated by treatment plus regeneration and release and growth of understory tree strata.

Study Implications: This simulation-based study confirmed that some mechanical fuel treatments currently applied in single- and multistory dry mixed conifer forests do immediately enhance resistance to crown fire on over 70 percent of forest area. Treatments that retain less density and eliminate understory trees are more successful as evaluated by a composite resistance score (CRS) that was designed to account for multiple fuels modification objectives, whereas treatments that retain three stories were typically ineffective. Treatment outcomes in both gain and attainment in CRS vary by initial conditions, particularly with respect to fire-resistant species abundance, and should be factored into decisions concerning treatment priority. Stands where resistant species are currently abundant benefit the most from treatment by enhancing or maintaining their resistance, whereas stands that lack resistant species offer few prospects for improved resistance. The fuel strata gap component of CRS offers latitude for managers to select the right gap for each stand based on their experience and knowledge of fuel models in planned treatment areas. Even the best treatments enhance resistance for no more than 20–30 years, so investments in fuel treatment must be followed by investments in treatment maintenance to realize a return on the initial treatment investment.

Keywords: fuel treatment longevity, forest inventory analysis, BioSum FFE-FVS simulation, fire-tolerant species, forest restoration

Forest managers face formidable challenges when seeking to integrate fuels management with other forest-management objectives and land ownership (Stephens et al. 2014). Infrastructure for harvesting, transporting, and processing harvested wood can influence whether management is even possible (Collins

et al. 2010). Social dimensions and considerations add complexity, for example, via pressures to adopt diameter caps that limit the size of trees that may be removed (Hyde et al. 2006). Simultaneously achieving multiple objectives, such as enhancing wildlife habitat, maintaining soil productivity, and conserving riparian areas,

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Affiliations: Theresa B. Jain (tjain@fs.fed.us; terrie.jain@usda.gov), Research Forester, Rocky Mountain Research Station, Moscow, ID 83843. Jeremy S. Fried (jeremy.s.fried@usda.gov), Research Forester, USDA Forest Service Pacific Northwest Research Station, Portland, OR 97205. Sara M. Loreno (sloreno@ecotrust.org), Natural Resources Data Scientist, Ecotrust, Portland, OR 97209.

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requires strategic innovation to craft treatments that achieve consensus on rationale, and, ultimately, broad acceptance (Hyde et al. 2006). Owing to the diversity in topography, forest type, soils, and other aspects of bio-physical settings, one-size-fits-all solutions are rarely viable (Nyland 2016). To be successful, forest managers must evaluate and select among a range of potentially promising, multi-purpose management alternatives that include fuels management as one of many goals.

Fuel-treatment effectiveness has been evaluated via a variety of metrics predictive of crown fire potential, with torching index and crowning index often relied upon. For example, Stephens et al. (2009) evaluated six sites as described by McIver et al. (2009), concluding that mechanical treatment followed by prescribed fire or pile-and-burning was the most effective strategy for reducing both crown fire potential, as indicated by predicted changes in crowning index and torching index, and fire-induced tree mortality. Crowning and torching indices, developed via model simulation and expressed as windspeed at which sustained canopy fire spread or crown fire initiation would occur, provide an ordinal, but not necessarily interval, indication of the likelihood of this occurring (Scott and Reinhardt 2001). However, clear and actionable interpretations of these metrics are elusive, given their numerous embedded assumptions, including surface fuel model, topographic setting (i.e., slope) and fuel moisture parameters that are subjectively or imprecisely assigned (Scott and Reinhardt 2001, Cruz et al. 2014). Although offering some insights, these metrics offer little guidance in addressing managers' "real world" challenges (e.g., developing marking rules) in the context of integrated, multiobjective fuel management. A quantitative framework for representing treatment effectiveness is essential, for example, to understand the relative cost-effectiveness of alternative fuel-management strategies (Fried et al. 2017a).

Agee and Skinner (2005) identified four basic principles for increasing a forest's resistance to crown fire: (1) reduce surface fuel loadings to attenuate flame length, (2) increase vertical separation between canopy and surface fuels to inhibit crown fire initiation, (3) reduce canopy density to inhibit crown fire propagation, and (4) shift stand composition, favoring larger (>15 cm, 6 in.) size classes of fire-resistant species (see also Peterson et al. 2005). Researchers have evaluated treatments that address these four principles and concluded that some types of mechanical treatment designed to thin the overstory and remove understory trees, followed by either prescribed fire or pile-and-burn to reduce surface fuel loading, have the most impact on fire outcomes after treatment (e.g., Stephens and Moghaddas 2005, Stephens et al. 2009, Roccaforte et al. 2015). However, treatment longevity varies depending on the productivity of the site and regeneration potential (e.g., Stephens and Moghaddas 2005, Vaillant et al. 2015, Tinkham et al. 2016). Regeneration can reduce treatment longevity, particularly under circumstances where the desired treatment outcome of reduced canopy density has the effect of increasing growing space for the regeneration and establishment of trees and other vegetation (Agee and Skinner 2005, Keyes and Varner 2006). Using the Fire and Fuels Extension of the Forest Vegetation Simulator (FFE-FVS) (Rebain 2010), Tinkham et al. (2016) simulated the effect of regeneration and fuel treatment longevity for 100 years on four ponderosa pine (*Pinus ponderosa* Lawson & C. Lawson) stands over a range of productivity. On highly productive sites, faster height growth elevated canopy base height more quickly, increasing the size of the gap separating surface and crown

fuels. However, treatment longevity was reduced by 10 years when regeneration after treatment exceeded 150 trees ha⁻¹ in a single cohort. Roccaforte et al. (2015) found that within 5 years of treatment in ponderosa pine forests in Arizona, such regeneration so reduced canopy base height as to make it statistically indistinguishable from pretreatment, whereas canopy bulk density (CBD) remained unchanged from reduced, immediate post-treatment levels. Working in dry and moist mixed conifer forests in California and assessing effectiveness 8 years post-treatment, Vaillant et al. (2015) confirmed the comparatively short-term elevation of canopy base height and the more durable reduction in CBD. The consistent finding, across multiple studies, of a short duration for canopy base height elevation underscores the importance of accounting for longevity when evaluating treatment effectiveness to guide investment in both initial and maintenance-oriented fuel treatments.

To better inform forest managers about the effectiveness of their forest-management activities from a fuel-treatment perspective, we sought to (1) develop and implement a modeling framework that supports comparison among multiple treatment scenarios across the full range of extant forest conditions using fire-resistance metrics to evaluate how treatments alter forest structure and species composition—the core, controllable factors driving crown fire potential, and (2) apply this framework to a landscape representative sample of dry mixed conifer forests, drawn from the USDA Forest Service Forest Inventory and Analysis program (FIA) databases, to evaluate short- and long-term treatment effectiveness.

A unique aspect of this study is reliance on the Bioregional Inventory-Originated Simulation Under Management (BioSum) analysis framework (Fried et al. 2017a, b), which uses FFE-FVS (Rebain 2010) to simulate management of a fully representative sample based on the consistent, quality-controlled field measurements collected by the FIA Program (McRoberts et al. 2005). The BioSum analysis framework (<http://biosum.info/biosum/downloads/>) and a project file (<http://biosum.info/biosum/FTCE/>) provide anyone interested an opportunity to explore in detail the effects of the treatments modeled in this paper, and any others they wish to simulate and consider, for this multiowner, multistate forest landscape. We also evaluate, and use as context, pretreatment conditions as an integral part of the analysis. This allows us to understand how pretreatment conditions affect the success in sustaining or increasing fire resistance under different kinds of fuel treatments over the entire forested landscape. The silvicultural prescriptions underlying these treatments were informed by extensive engagement with forest managers across the northwestern United States; thus, conclusions and inferences that flow from this study relate closely to the kinds of treatments that are already occurring. The study provides insights into how common prescription parameters influence post-treatment conditions, both immediately and in the ensuing decades. It also offers an assessment, spanning 4 million forested hectares (10 million acres), of fuel-related treatment needs and the potential benefits that could be delivered from such treatments.

Methods

To address the study objectives, we used and refined BioSum (Fried et al. 2017a, b), an inventory analysis and projection framework and workflow management software package for generating and comparing among alternative management trajectories over very large (>1 million acres) forested landscapes. There were five major tasks in

the workflow (Figure 1): Task 1—obtain a representative forested landscape sample from the FIA database; Task 2—devise treatments; Task 3—devise a composite fire-resistance score and classify stands based on pretreatment conditions; Task 4—simulate treatments in FFE-FVS (Rebain 2010), then project for 1, 10, 20, and 30 years, saving outputs describing forest structure, species composition, and predicted mortality to calculate fire resistance metrics; Task 5—evaluate treatment effectiveness, longevity, and impact over the forest landscape.

Task 1: Representative Landscape Sample from the FIA Database

This paper describes findings on treatment effectiveness in dry mixed conifer forests for the east side and interior portions of Washington and Oregon and California's Sierra Nevada (Figure 2), relying on a full cycle (10 panels) of FIA field plot data collected between 2004 and 2013 to represent the “current” forest. FIA samples forest attributes using clusters of four fixed-radius (7.31 m; 24 ft) subplots, called plots, on a systematic randomized sample “grid” with a sampling intensity of approximately one plot per 6,000 ac (and a mean 5-km [3.1-mile] distance separating plots in north-south and east-west directions). When discontinuities occur within a plot footprint (e.g., in ownership class, reserve status, forest type, size class, density class, disturbance history, or treatment legacy), or where an otherwise-forested plot contains sufficiently sized nonforest portions such as roads, a plot may be split into two or more “conditions,” each less than a full plot in size. Because FIA data do not include a

“dry mixed conifer” type designation, we developed decision rules, separately for the different biophysical settings where this type is found (Jain et al. 2012), to identify dry mixed conifer forest based on the assemblage of tree species present (Supplement 1). Conditions, which the BioSum Framework transforms into FVS stands, were dropped from the analysis as untreatable if they contained too little stocking to be eligible for any treatment alternative (e.g., when current basal area or trees per acre are below the target residual stand density of any treatment) or occurred within wilderness, parks, or other areas legally designated as reserved from management. We ultimately modeled 2,106 single-story stands, representing 3.13 million hectares (7.7 million acres) and 1,051 multistory stands, representing 1.2 million hectares (2.9 million acres).

Task 2: Devise Treatments

Collect Multiobjective Prescriptions

To evaluate contemporary multiobjective treatments that contained a fuel-treatment component, we sought and received guidance from 25 National Forest System managers and silviculturists in regions where these forests are managed (Northern Rocky Mountain, Pacific Northwest, and Pacific Southwest), yielding a library of 86 treatment prescriptions formulated to, for example, restore resilient ecosystems, enhance winter forage for wildlife, and increase forest structure diversity. We summarized these prescriptions by silvicultural treatment categories such as commercial thin (CT),

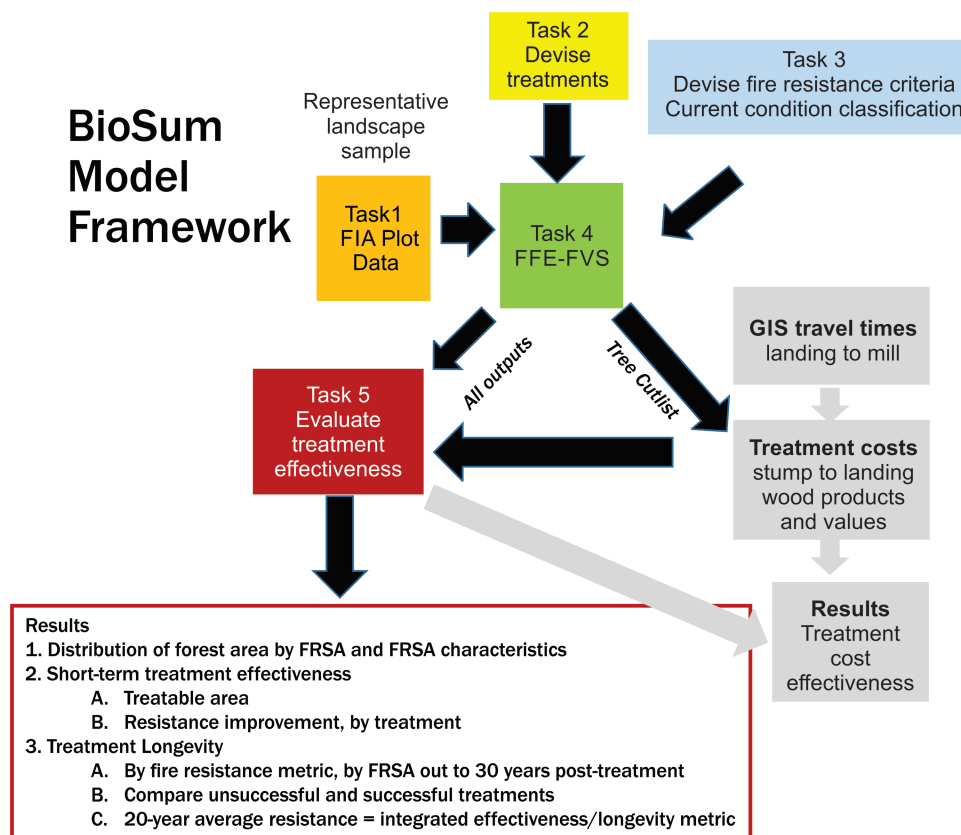


Figure 1. BioSum Framework (Fried et al. 2017a, 2017b), an inventory analysis and projection framework and workflow-management software package for generating and comparing among alternative management trajectories. In this study, we conducted five major tasks outlined in the workflow of the BioSum Framework: Task 1—identify a representative landscape sample, Task 2—devise treatments, Task 3—devise fire-resistance criteria and current condition, Task 4—conduct treatment simulation in FFE-FVS, and Task 5—evaluate treatment effectiveness to produce the kinds of results listed in the red-outlined box.

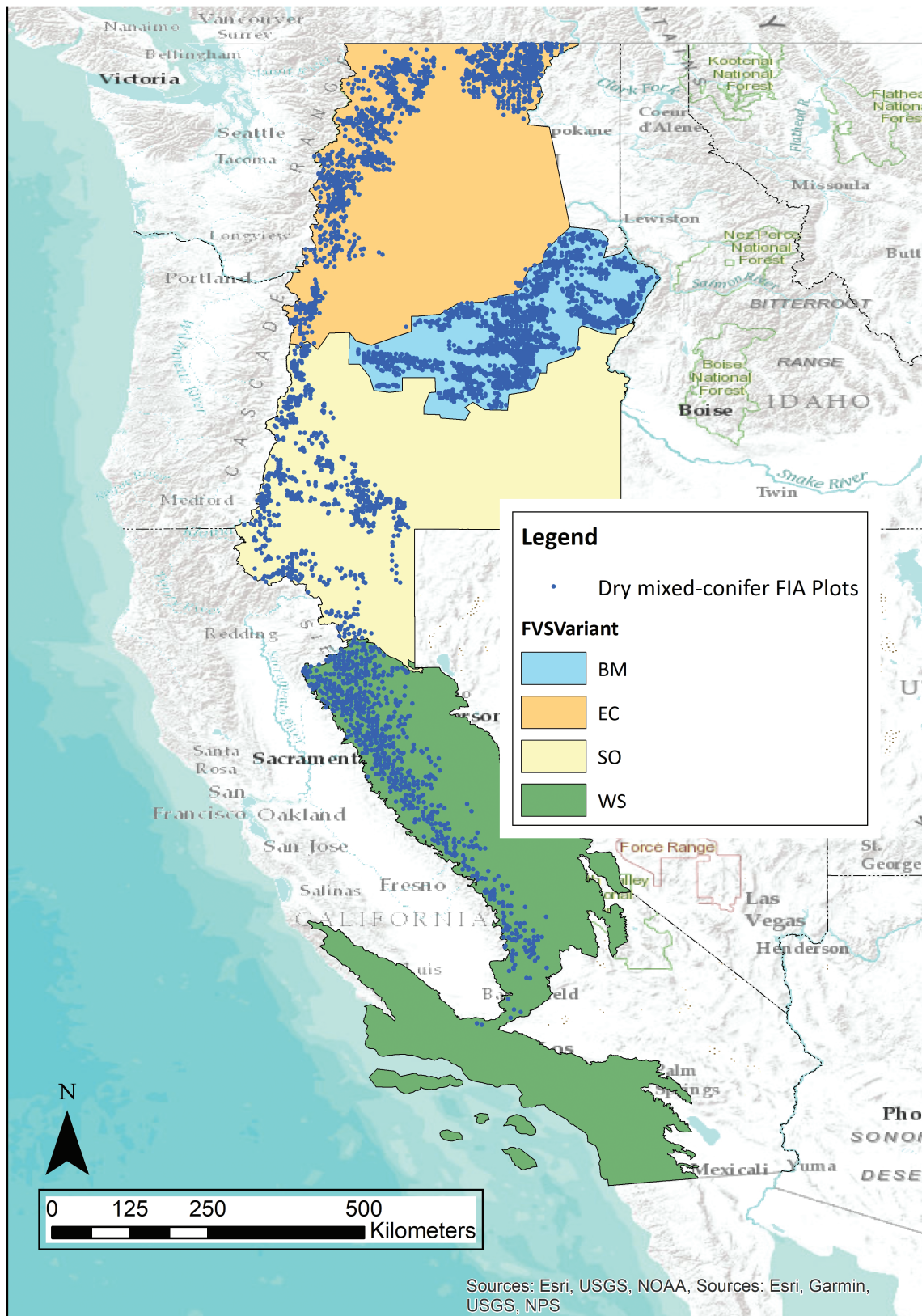


Figure 2. Study area, composed of dry, mixed conifer forests in eastern Washington, eastern Oregon, and California's Sierra Nevada, as indicated by FIA plots with dry mixed conifer present, and spanning four variants of the Forest Vegetation Simulator: Blue Mountains (BM), Eastern Cascades (EC), Southern Oregon (SO), and Western Sierra (WS).

shelterwood, release, or improvement cut (IC) (Deal 2018). We focused on CT and IC, which, unlike shelterwoods (intended as a regeneration harvest) and precommercial thins (intended as a release

treatment), always contained a fuel-management objective; these were also the most commonly applied treatments in our study area (e.g., CTs or ICs constituted 62 percent of treated area in the Pacific

Southwest and 86 percent in the Pacific Northwest Region based on Forest Service Activity Tracking System data, <https://data.fs.usda.gov/geodata/>).

Craft Treatments and Prescription Parameters

For this analysis, we synthesized the submitted prescriptions to craft three CT and six IC prescriptions (Box 1) that spanned a range of diameter caps (thresholds above which no trees would be harvested), residual basal area within a diameter range of commercial-sized trees, and residual density (trees ha⁻¹) for submerchantable-sized trees (Table 1). IC treatments were applied to stands containing at least two stories, as determined from strata count attribute calculated by FFE-FVS and reported in its structure class output (Crookston and Stage 1999) (Table 1). Treatments IC 8 and IC 9 are identical to IC 1 and IC 2, except that treatments IC 8 and IC 9 omit the diameter cap requirement. CT prescriptions CT 5, CT 6, and CT 7, which were applied to stands dominated by a single story, were specified as a thin-from-below with a target residual tree density defined in terms of basal area or trees per hectare.

Task 3: Devise Fire-Resistance Metrics and Classify Current Fire Resistance

In lieu of relying entirely on FFE-generated fire hazard metrics, nearly all of which depend on assumed or assigned surface fuel model, we adapted the logic underlying the recommendation by Agee and Skinner (2005) that four forest attributes be modified to reduce crown fire likelihood and improve fire resistance: (1) reduce live and dead surface fuels, ideally to a level that reduces fireline intensity; (2) increase the vertical separation of surface and canopy fuels; (3) decrease canopy bulk density (CBD) to increase space between crowns; and (4) retain the largest trees of fire-resistant species. We developed metrics supporting each of these four strategies and developed scoring thresholds for each metric that subdivide their range into four fire-resistance categories, from 0 (none) to 3 (high).

Integrating Fireline Intensity and Vertical Separation of Fuel Strata

Given that fuel treatments are intended to diminish the likelihood of surface fire transitioning into crown fire, they are often designed to remove ladder fuels (e.g., understory trees, shrubs, needle drape; Scott and Reinhardt 2001) to increase the vertical separation between surface and canopy fuels, and surface fuels are treated via removal or rearrangement to decrease fireline intensity (Agee and Skinner 2005). The effectiveness of this approach depends on surface fireline intensity, which is a function of surface fuel model, slope, fuel moisture, and weather (which itself depends on forest structure characteristics such as tree height, canopy density and canopy base height, all of which can impact, for example, windspeed driving the surface fire) (Scott and Reinhardt 2001). Torching index has been relied on to evaluate treatment effectiveness, in part because it is a single value that integrates parameters such as weather and surface fuel model; however, this metric can take on values that do not make sense. For example, Stephens et al. (2009) reported torching index (km h⁻¹) up to 1,500 km h⁻¹ (932 mph). We also observed calculated values in this study's dataset that are not credible: FFE-FVS calculated torching indices over 80 km h⁻¹ (50 mph) for 48 percent of our stands and over 160 km h⁻¹ (100 mph) for 20 percent of our stands. Rather than reporting values that rarely occur or that so indirectly represent practical effects of,

Box 1. Description of manager treatment parameters

Thinning is a harvest that reduces the density of trees, pole-sized or larger, reallocating a stand's growth potential to the unharvested trees (Helms 1998). Typically, a CT treatment is applied to single-story, even-aged stand; however, many of the prescriptions provided to us implied the possible presence of an understory given that some had spacing requirements for trees of submerchantable size (e.g., <12.7 cm diameter breast height, dbh). Because the overarching goal of thinning is to enhance growth of residual trees, spacing among the unharvested or "residual" trees tends to be homogeneous. When fuel reduction is an objective of CT, the intent is to reduce canopy bulk density (CBD) in the residual stand by increasing space between tree crowns.

Most prescriptions specified thin-from-below to remove ladder fuels; these remove the smallest trees first, then successively larger trees until a residual density target is achieved (Graham et al. 1999). These prescriptions typically retained early-seral and comparatively fire-resistant species, including ponderosa pine, sugar pine, and Douglas-fir, where feasible and prioritized fire-vulnerable species (e.g., white and grand fir) for removal, although even these were sometimes retained when larger than a specified dbh. CT achieves immediate increase in crown spacing and decrease in CBD; however, it also enhances regrowth of the residual trees (as intended), often leading to crown closure within 10–20 years, greatly diminishing any reduction in potential for sustained crown fire. The manager-provided prescriptions typically specified an average spacing but allowed for a range. For example, a CT prescribed 5 m (17 ft) spacing but accepted a range of 4–6 m (15–20 ft). Another prescription, which we used in our analysis (CT 7), retained all ponderosa pine >30 cm (>12 in.) dbh, whereas ponderosa pine <30 cm (<12 in.) were retained when they occurred at least 3 m (10 ft) away from larger pines.

Improvement cut prescriptions, which some forest managers consider to be good prospects for multistoried stands that contain trees with different ages and or sizes, were quite complex. These are designed to manipulate a multistoried stand (typically with three stories) and maintain a multistoried structure, and are often burdened with multiple, not entirely compatible objectives. Examples include resistance to disturbance (e.g., leading to lower likelihood of tree damage or mortality when disturbance occurs) and resilience (e.g., ensuring a high probability that a stand will return to its predisturbance conditions within a reasonable time following a disturbance), resilience to impacts of climate change, and enhancement of wildlife habitat, alongside reduction in hazardous fuels. In these prescriptions, each story or canopy layer, defined by a range of tree diameters, was assigned its own spacing or density target and species-composition goals. They also specified parameters targeting spatial heterogeneity in tree size (e.g., retain trees with dbh <5 in. [13 cm] only in openings located beyond some distance from larger trees, to forestall the development of fuel ladders). In these prescriptions, there was always a range of basal areas, such as 11–23 m² ha⁻¹ (50–100 ft² ac⁻¹) with an average of 16–18 m² ha⁻¹ (70–80 ft² ac⁻¹). Some specified a maximum retention of 27 m² ha⁻¹ (120 ft² ac⁻¹). Diameter caps were common and were as low as 43 cm (17 in.) and as high as 81 cm (32 in.). Similar to the CTs, the fire-resistant species were always favored, and nonfire-resistant species were retained only when they exceeded a specified diameter.

for example, treatments designed to elevate canopy base height, we sought another approach. The concept of a "target canopy base height" has been reported as useful in accounting for the indirect relation between surface fuel models and potential for a surface fire to transition into a crown fire (Scott 1998, Keyes and O'Hara

Table 1. Silviculture prescription parameters for treatments modeled in Fire and Fuels Extension of the Forest Vegetation Simulator.

Treatment no.	Diameter cap, cm (in.)	Commercial-sized trees		Noncommercial-sized trees	
		Diameter range, cm (in.)	Residual basal area, m ² ha ⁻¹ (ft ² ac ⁻¹)	Upper diameter, cm (in.)	Residual density trees, ha ⁻¹ (trees ac ⁻¹)
IC					
IC 1	53 (21)	12.7–53 (5–21)	23 (100)	12.7 (5)	370 (150)
IC 2	53 (21)	15.2–53 (6–21)	15 (80)	15.2 (6)	0
IC 3	48 (19)	15.2–48 (6–19)	15 (80)	15.2 (6)	564 (222)
IC 4	81 (32)	17.8–81 (7–32)	19 (85)	17.8 (7)	564 (222)
IC 8	NA	>12.7 (5)	23 (100)	12.7 (5)	370 (150)
IC 9	NA	>15.2 (6)	15 (80)	15.2 (6)	0
CT					
CT 5	NA	>17.8 (7)	34 (150)	17.8 (7)	127 (50)
CT 6	NA	>12.7 (5)	21 (90)	12.7 (5)	51 (20)
CT 7 ^a	30 (12)	12.7–53 (5–12)	479 trees ha ⁻¹ (194 trees ac ⁻¹)	12.7 (5)	0
Grow-only					
Grow-only	NA	NA	NA	NA	N

Note: CT, commercial thin; IC, improvement cut; NA, not applicable. There were six improvement cut treatments and three commercial thin treatments. Stands treated with ICs 1, 2, 3, 4, 8, and 9 had two or three stories, and those treated with CTs 5, 6, and 7 had one story, not counting regeneration layers consisting of trees smaller than 1 in. in diameter at breast height. The ICs include the diameter cap, diameter range of commercially viable trees, residual tree density (basal area), and noncommercial tree size threshold and residual density. The commercial thins did not have a diameter cap, and some parameters were NA, depending on the treatment. We also evaluated a “grow-only” scenario under which no treatment occurred.

^aCT 7 required a total of 479 trees ha⁻¹ with 172 trees ha⁻¹ (70 trees ac⁻¹) of them larger than 53 cm (21 in) in diameter.

2002, Tinkham et al. 2016). The concept applies Van Wagner’s (1977) canopy ignition equation that integrates canopy foliar moisture content and fireline intensity, the latter a function of surface fuel moisture, windspeed, slope percent, and fuel model:

$$\text{Target canopy base height} = \frac{\text{fireline intensity}^{\frac{1}{1.3}}}{[(0.01)(460 + 26 \times \text{canopy fuel moisture})]} \quad (1)$$

We used First BehavePlus version 5 (Heinsch and Andrews 2010) to calculate fireline intensity for dozens of combinations of Scott and Burgan (2005) fuel models (grass fuel models GR1, GR2, GR3, GR4, GR7, timber litter fuel models TL1, TL3–TL9, timber understory fuel models TU1, TU5, and shrub models SB1 and SB 2), canopy foliar moisture content (70 percent and 90 percent), surface fuel moisture content (1-h fuels were 3 percent, 10-h fuels were 4 percent, 100-h fuels were 5 percent, herbaceous fuels were 30 percent, and shrub fuels were 60 percent), windspeed (0–64 km h⁻¹ by 8 km h⁻¹ intervals, 0–40 mph by 5 mph intervals) and slope (0–60 percent by 10 percent intervals). This allowed us to compute a minimum target canopy base height for each combination (that we operationalize as a fuel strata gap as explained below) (Figure 3). For example, a stand with a timber-litter (TL1) fuel model would require a target canopy base height of at least 2.1 m (7 ft) to prevent crown fire initiation at very low windspeeds (8 km h⁻¹, 5 mph). Where a treatment elevates fuel strata gap above 9.1 m (30 ft), a stand would have high resistance to crown fire under a much larger number of combinations of fuel model, windspeed, and slope. We relied on the work of Andrews and Rothermel (1982), which related flame length and fireline intensity to fire-suppression opportunities, as a basis for setting the scoring thresholds shown in Table 2. There are several advantages of using target canopy base height: (1) it is a function of surface fuel model, windspeed, slope, fuel moisture, and fireline intensity; (2) it can be applied across a range of fuel models, biophysical settings and weather, making the identified thresholds more applicable across our study area; and (3) it allows

fuel managers some latitude in determining whether canopy base height is sufficient, contingent on surface fuel model (Figure 3).

Because the term canopy base height can be confusing when applied to multistory stands, where the objective may be to separate an overstory of larger trees from the top of an understory tree canopy layer composed, for example, of advanced regeneration, we use the term fuel strata gap (Cruz et al. 2004, Tinkham et al. 2016) to denote the distance from the top of the surface fuelbed (which may be a tree canopy layer in multistory stands) to the lower limit of the aerial fuel stratum composed of mid- or overstory trees. We derived fuel strata gap from the outputs in FFE-FVS’s STRCLASS table (Crookston and Stage 1999), generated using the default FVS parameters guiding the preparation of that table, as the greatest distance from the top of the understory (strata 2 or 3) to the base of the crown in the midstory or overstory (strata 2 or 1). We scored fuel strata gap based on natural breakpoints in the number of combinations of Scott and Burgan (2005) fuel models, slopes, and windspeeds (Table 2, Figure 3) for which fuel strata gap would be sufficient to prevent canopy fire initiation. For example, with no wind and a 60 percent slope, a fuel strata gap of 2.1–6.0 m (7.0–20 ft) was sufficient to prevent canopy fire initiation for five fuel models (TL1, TL3, TL4, TL5, TL7), meriting a score of 1. Note that even a fuel strata gap of >9.1 m (>30 ft), the threshold for a score of 3, is insufficient to prevent canopy fire initiation for timber understory fuel models at 60 percent slope and no wind, but for stands on flat ground, a gap of this size would be sufficient (Figure 3).

CBD

To track increased separation among tree crowns, we used FFE-FVS default CBD values and scored the following thresholds from 0 to 3 following a few assumptions. CBD values above 0.15 kg m⁻³ (0.009 lb ft⁻³), which indicate near-maximum canopy bulk density potential (Keane et al. 2005) and no fire resistance, were scored as 0. One point (low resistance) was assigned for a CBD of 0.11–0.15 kg m⁻³ (0.007–0.009 lb ft⁻³), a range that exceeds Agee’s threshold but may sometimes be needed to achieve nonfuel

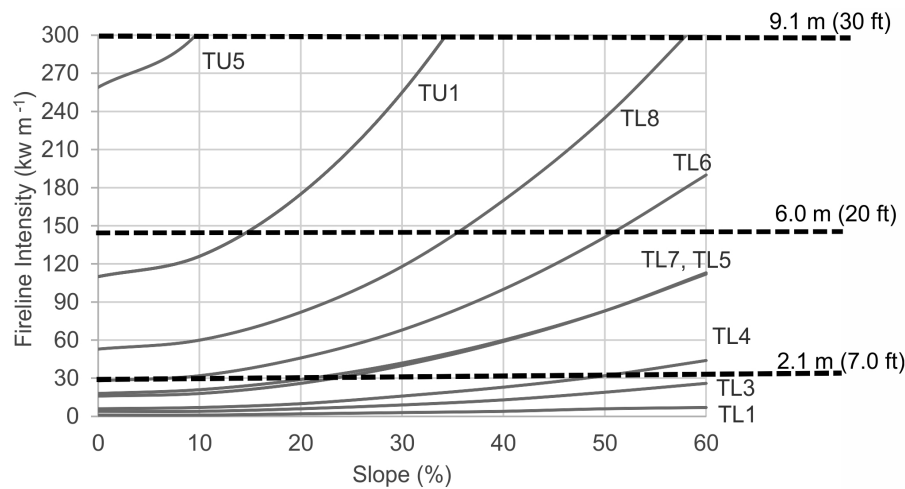


Figure 3. Relation among fuel model, slope, fuel strata gap threshold, and fireline intensity, when wind is held constant at zero. Dotted lines indicate the fuel strata gap thresholds of 9.4 m, 5.7 m, and 2.0 m. Fireline intensity reflects 1.2 m (4 ft) flame length (30 kw m^{-1}), 2.4 m (8 ft) flame length (145 kw m^{-1}), and 3.6 m (12 ft) flame length (300 kw m^{-1}). Points on a fuel model curve that lie below a fuel strata gap threshold indicate the range of slope for which achieving and maintaining that fuel strata gap can be expected to prevent crown fire initiation.

Table 2. Fire-resistance components and subscore assignments. Every stand is assigned a value between 0 and 3 for each of the four components, so the composite resistance score obtained by summing these subscores has a maximum value of 12.

Component subscore	Canopy bulk density kg m^{-3} (lb ft^{-3})	Fuel strata gap, m (ft)	Resistant species (percent)	Survival (percent)
0	>0.15 (0.009)	≤ 2.1 (7)	≤ 25	≤ 2
1	0.11–0.15 (0.007–0.009)	2.1–6.1 (7–20)	25–50	2–30
2	0.051–0.10 (0.003–0.006)	6.1–9.1 (20–30)	50–75	30–75
3	≤ 0.05 (0.003)	>9.1 (30)	75–100	>75

objectives (e.g., maintain cover for the northern spotted owl [*Strix occidentalis caurina*]). A CBD in the range 0.051–0.10 kg m^{-3} (0.003–0.006 lb ft^{-3}) earned a CBD score of “2” based on Agee’s (1996) empirical finding of a 0.10 kg m^{-3} (1.6 lb ft^{-3}) threshold. Based on Van Wagner’s (1977) proposal of a theoretically based CBD threshold of 0.05 kg m^{-3} (0.003 lb ft^{-3}), we assigned a “3” to any stands with a CBD lower than 0.05 kg m^{-3} (0.003 lb ft^{-3}), following logic that this would preclude crown fire spread for a longer period before expansion of the canopy would require re-treatment.

Basal Area of Fire-Resistant Species

Agee and Skinner (2005) suggested that stands that contain an abundance of fire-resistant species are more resistant to mortality from crown fire. Jain et al. (2012 chapter 3) summarized fire resistance of tree species across the study area and reported that western larch (*Larix occidentalis* Nutt.), ponderosa and Jeffrey pine (*Pinus jeffreyi* Balf.), sugar pine (*P. lambertiana* Douglas), red fir (*Abies magnifica* A. Murray bis), and Douglas-fir (*Pseudotsuga menziesii* [Mirb.] Franco) are highly resistant to fire when mature. Resistance increases with both diameter at breast height (dbh), as bark thickens, and height (as branch recession leads to elevated crown base height). To account for the relative abundance of fire-resistant species, we calculated the proportion, as a percentage, of stand basal area composed of species on the highly resistant species list (above), for trees ≥ 12.7 cm (5 in) dbh. We divided the range of fire-resistance species abundance (referred to hereafter as resistant species) into four subranges, assigning a resistance score to each subrange (Table 2).

Expected Postfire Survival

Agee and Skinner (2005) emphasized the importance of tree size (“large fire-resistant species”) for elevating resistance; however, because resistance varied among the 50 species in our dataset, even for similarly sized trees, diameter thresholds alone cannot adequately capture mortality reduction accomplishment. We relied on FOFEM (Lutes 2013) to predict a fire mortality rate for each tree as a function of its species, diameter class, height, bark thickness, species group, and crown ratio, for flame lengths of 1.82 m and 2.44 m (6 ft and 8 ft). Our analysis of FOFEM parameters suggested that many trees survive flame lengths below 1.82 m (6 ft), and many die when flame length exceeds 2.44 m (8 ft). Mean mortality rates were calculated for each species group and diameter class as the mean of the FOFEM parameters for these two flame lengths, and survival rates as the complement (1—mean mortality). Stand-level survival volume at any point in the simulation is the sum, over all live trees in the stand, of the product of three calculated attributes of each tree: (1) survival rate, (2) the trees per acre it represents, and (3) FVS-calculated volume. Percentage survival is calculated from the ratio of expected survival volume to total stand volume. “Survival” scores were then assigned, as outlined in Table 2.

Each resistance subscore offers insight into what may happen when a stand is encountered by fire (Table 2), with higher scores predicting greater resistance to crown fire and mortality. To better understand how the forest is currently arrayed with respect to fire resistance, and to estimate the potential for increasing fire resistance through management, we calculate a composite resistance score (CRS) as the sum of all four component subscores: Fuel Strata Gap,

CBD, Resistant Species, and Survival. With each subscore computed as 0, 1, 2, or 3, CRS ranges from 0 to 12. In general, treatments that elevate CRS will increase fire resistance of the residual stand; however, evaluating the success of management, whether a priori or post hoc, is only valid in the context of objectives, current conditions, and desired future conditions.

Current Condition

To determine the suitability of treatments for moving stands from their current condition toward greater resistance as measured by both subscores and CRS, we grouped stands by abundance of fire-resistant species (Table 3) and CRS before any treatment was applied, labeling them fire-resistant species abundance (FRSA) 1–4. Definitions of FRSA 1 (low abundance) and FRSA 2 (moderate abundance) differ only by fire-resistant species abundance, with FRSA 1 assigned when fire-resistant species comprise <25 percent of stand basal area and FRSA 2 assigned when they comprise 25–75 percent. For stands with more than 75 percent of basal area in resistant species (high abundance), we defined two classes. FRSA 3 was assigned if CRS < 9 to identify stands that, while rich in fire-resistant species, may be deficient with respect to other resistance elements (e.g., fuel strata gaps, the bark thickness that comes with large tree size and CBD), suggesting potential for improved resistance if appropriate treatments

are applied. FRSA 4 was assigned when CRS ≥ 9 to identify stands that had larger trees to account for the forest structure components that are embedded in this resistance score, as they are also important predictors of fire resistance.

Task 4: FFE-FVS Simulation

In the FFE-FVS simulation, we (1) specified preferences for retaining trees of fire-resistant species (ponderosa pine, Jeffrey pine, sugar pine, western larch, California red fir and Douglas-fir) and cutting trees of less resistant species (e.g., white and grand fir [*Abies concolor* [Gord. & Glend.] Lindl. ex Hildebr. and *A. grandis* [Douglas ex D. Don] Lindl.), and (2) prioritized removal of trees with a live crown ratio <40 percent. We simulated harvest at the end of year 1 (the pretreatment year) using whole tree harvest systems with 10 percent of nonbole material left in the stand as incidental harvest residue. We invoked a surface fuel treatment, a pile-and-burn (using the FFE-FVS default fuel load calculation of 80 percent of the fuels from 70 percent of the stand being concentrated into piles that cover 10 percent of the stand's area), when total fuel loads (1-h, 10-h, and 100-h, combined) exceeded 36 Mg ha⁻¹ (15 tons ac⁻¹) (Graham et al. 1994). Graham et al. (1994) noted that the amount of coarse down wood in dry mixed conifer

Table 3. Pretreatment forest structure characteristics within and among FRSA classes.

Forest structure characteristics		FRSA 1		FRSA 2		FRSA 3		FRSA 4	
<i>Criteria for FRSA classes</i>		0		1 or 2		3		3	
Resistant species score		All scores		All scores		<9		≥ 9	
Composite resistant score									
<i>Mean and statistical significant differences among FRSA classes</i>									
Single-story—commercial thin	<i>P</i> -value	$\bar{x}$	Sig.	$\bar{x}$	Sig.	$\bar{x}$	Sig.	$\bar{x}$	Sig.
Composite resistant score	<.0001	4.6	c	6.9	b	7.1	b	10.2	a
Top height (m)	<.0001	23	a	23	a	19	b	23	a
Quadratic mean diameter (cm)	<.0001	24.6	c	26.2	b	18.8	d	31.0	a
Canopy base height (m)	<.0001	7	b	7	b	5	c	9	a
Canopy bulk density (kg m ⁻³)	<.0001	0.12	a	0.09	b	0.10	b	0.5	c
Total cover (percent)	<.0001	52	a	49	b	51	ab	39	c
Basal area (m ² ha ⁻¹)	<.0001	34	a	32	a	26	b	24	b
Trees ha ⁻¹	<.0001	191	a	157	b	199	a	77	c
Overstory									
Nominal diameter (cm) ^a	<.0001	42.3	b	44.2	ab	32.3	c	47.0	a
Nominal height (m)	<.0001	22	b	23	b	17	c	25	a
Canopy base height (m)	<.0001	8	b	8	b	6	c	11	a
Crown cover (percent)	<.0001	47	a	47	a	46	a	34	b
Multistory—improvement cut									
Composite resistance score	<.0001	4.9	c	7.4	c	7.4	c	9.9	a
Top height (m)	<.0001	23	a	24	a	20	b	23	a
Quadratic mean diameter (cm)	<.0001	21.1	b	23.3	a	18.0	c	23.9	a
Canopy base height (m)	<.0001	8	b	6	ab	4	c	7	a
Canopy bulk density (kg m ⁻³)	<.0001	0.09	a	0.08	b	0.09	ab	0.05	c
Total cover (percent)	<.0001	50	a	48	a	51	a	42	b
Basal area (m ² ha ⁻¹)	.0002	28	ab	30	a	25	b	25	b
Trees ha ⁻¹	.0915	189	a	181	a	186	a	127	a
Overstory									
Nominal diameter (cm)	<.0001	51.3	b	56.4	a	40.6	c	58.4	a
Nominal height (m)	<.0001	26	b	29	a	21	c	30	a
Canopy base height (m)	<.0001	12	c	13	b	9	d	14	a
Canopy cover (percent)	.0042	31	a	34	a	31	a	26	b
Midstory									
Nominal diameter (cm)	<.0001	13.7	bc	14.7	ab	10.9	c	16.8	a
Nominal height (m)	<.0001	8	bc	8	b	7	c	10	a
Canopy base height (m)	<.0001	3	bc	4	ab	3	c	4	a
Canopy cover (percent)	.0417	21	a	20	ab	20	ab	16	b

Note: FRSA, fire-resistant species abundance; Sig., significance. FRSA 1 has <25 percent fire-resistant species, FRSA2 has 25–74.9 percent fire-resistant species, FRSA 3 has ≥ 75 percent fire-resistant species and a composite resistance score <9, and FRSA 4 has ≥ 75 percent fire-resistant species and a fire-resistance score ≥ 9 points. Lower-case letters identify statistical difference among FRSA within each forest structure characteristic. Limited space prevented us from including English units.

^aNominal diameter and height are calculated as the average diameter and height of nine sample trees (four trees above) and (four trees below) the 70th percentile tree (Dixon 2018).

forests required to sustain mycorrhizae habitat ranged from 20 to 50 Mg ha⁻¹ (10 to 20 tons ac⁻¹), we selected the midpoint of this range as the threshold for surface fuel treatment.

To account for the ladder fuels that develop after harvest operations from reduced canopy density, we added regeneration via the “Natural” keyword in FFE-FVS 10 and 20 years after treatment, using parameters developed via REPUTE (Vandendriesche 2010), an FVS postprocessing program that facilitates adding seedlings and saplings into growth projections. Seedling recruitment is determined by species and stand density index in relation to species-specific maximum stand density index, and small saplings are added using a distribution pattern computed from current stand size and density conditions (Vandendriesche 2010). The REPUTE program processes output files from the Fvsstand Alone Program (Vandendriesche 1997) to develop regeneration keywords. The Natural keyword parameters are determined via association with the composite distribution matrix of observed small sapling frequencies of all the stands (grouped by forest type), compiled in the Fvsstand Alone Program output. Regeneration is triggered by the vegetation state (a size/density classification based on stand density index, quadratic mean diameter, and canopy cover) as each projection cycle is processed.

The basis for a reference trajectory for each stand was devised by defining a “grow-only” prescription under which no trees were cut. All stand-treatment combinations were evaluated from pretreatment year 1 to post-treatment year 2, then projected forward through three, 10-year growth cycles (to 10, 20, and 30 years after treatment) to evaluate the longevity of fuel treatments relative to the grow-only, disturbance-free scenario.

FFE-FVS model output includes several kinds of data tables useful for assessing fire resistance (Figure 1), including a “cutlist” (useful for estimating treatment costs and wood production value) and several containing forest structure, composition, and fire potential attributes calculated by FFE-FVS either as standard output or via analyst-devised “compute” keywords.

We did not simulate prescribed fire for several reasons. First, the species in some forests are not fire-resistant (e.g., hardwoods and conifers with thin bark), so if we applied prescribed fire after the “mechanical” treatment, trees in the residual stand would most likely be killed. Second, surface fuel measurements collected by FIA are not directly convertible to surface fuel models. FFE-FVS’s default fuel model assignments are typically quite different from field-estimated fuel models recorded on FIA plots. Third, although often advocated, prescribed fire is not always applied, for various reasons. For example, Schultz et al. (2018) identified several barriers that prevent prescribed fire such as air quality, particularly in Oregon, Washington, and California; limited funding and capacity; interagency dynamics; and other land-management considerations. Others (e.g., Kolden 2019) cited lack of social acceptance, limited incentives to burn, risk aversion, treatment longevity, and leaders finding innovative alternatives that sidestep the challenges associated with burning. We also sought to estimate the longevity of the effectiveness achieved via mechanical treatment, followed by a consistently applied surface fuel treatment (i.e., pile-and-burn, if warranted), to provide managers with guidance on an appropriate interval for effectiveness monitoring and possible treatment maintenance activity (e.g., via prescribed fire or mechanical or hand removal of surface and ladder fuels).

Task 5: Evaluating Treatment Effectiveness

Short-term treatment effectiveness was evaluated within the context of current condition as represented by FRSA classes and addressed two questions. (1) What is the distribution of forest area by FRSA, and how do the classes differ in forest structure characteristics? (2) Which of the nine treatments achieved the greatest increase in CRS in each FRSA class?

Treatment longevity was evaluated, by FRSA, by comparing how a stand’s fire-resistance characteristics responded to the most frequently superior treatment for its stand type (single- or multistory) relative to a grow-only trajectory. Resistance metrics were evaluated pretreatment (year 1), after treatment (year 2), and 10, 20, and 30 years after treatment. To compare a typically unsuccessful treatment to a typically successful one, we highlight differences between two ICs, over time, in the shift in fuel strata gap relative to grow-only.

Treatment accomplishment that lacks staying power may offer little, if any, practical forest-restoration benefit, and learning of this from a model could avoid significant misallocation of management resources. To assess practical effectiveness, we crafted metrics that essentially integrate treatment accomplishment and longevity: 20-year mean resistance subscore and composite score differences relative to grow-only. A treatment that elevates resistance a great deal, but only for a few years before a grow-only scenario catches up and exceeds its resistance, will not be attractive under this metric, whereas one that achieves a smaller, but lasting, gain will fare better. We chose a 20-year time frame for this metric because (1) our analyses, and others (e.g., Vaillant et al. 2015, Tinkham et al. 2016), indicate that treatment benefits can rarely be expected to last much beyond two decades, and (2) consistently achieving a more frequent (e.g., 10-year) treatment maintenance interval (e.g., either mechanical thinning re-treatments or surface fuel disposal “tune-ups”) across millions of forested acres (hectares) may be unrealistic given the barriers associated with treatments like prescribed fire (Schultz et al. 2018), so this can be thought of as a temporal expectation of, or requirement for, treatment effectiveness.

These 20-year means were calculated for each treatment for each stand as weighted sums of score differences between treatment and grow-only at the three post-treatment years for which FFE-FVS reported the information needed to compute metrics: 1, 10, and 20 years post-treatment, to which weights of 0.25, 0.5, and 0.25 were applied (because the year 2 outcome is the best estimate for years 2–6, year 11 best represents years 7–16, and year 21 is the best information to represent years 17–21). When evaluating the potential fire-resistance benefits of treatment over the whole forest landscape, we assumed application in each stand of the treatment generating the greatest 20-year mean benefit. When none of the treatments showed an increase, the stand was assigned a grow-only trajectory.

Data Presentation and Statistical Analysis

We obtained the means by FVS simulation year (pretreatment, post-treatment, and 10, 20, and 30 years after treatment), and prescription (single-story stands had up to three CTs, multistory stand had up to six ICs, and both kinds of stands had grow-only) and FRSA class. We used these means to evaluate differences in short-term effectiveness among treatments and with respect to initial stand attributes, and to estimate how much of the forested landscape in

this region can be managed to enhance resistance to fire. To illustrate the differences among the FRSAs, and differences over time for selected treatments, we statistically tested the following hypotheses: (1) null hypothesis—there are no statistically significant differences in stand attributes (e.g., mean height, mean quadratic diameter) among the FRSAs prior to treatment; (2) null hypothesis—for the individual fire-resistance metrics, there were no statistically significant differences between treatment outcomes and the grow-only scenario, initially, and over time. We used mixed model analysis accounting for year as a repeated measure (Littell et al. 2006) using $\alpha = .01$ significance level, implemented in SAS GLIMMIX v. 9.3 (SAS Institute Inc. 2011) with each stand representing one replicate. Differences between treatment results and the grow-only scenario were tested for individual FVS simulation years 1 (pretreatment) and 2 (post-treatment), and 10, 20, and 30 years after treatment, also using $\alpha = .01$ significance level. The conservative level of significance was selected because of the large sample size.

Results

We present information on the current condition of dry mixed conifer forests along with short- and long-term outcomes of applying treatment to these forests (Figure 1). We begin with a summary of how these forests are currently partitioned among FRSA classes and how structure characteristics differ among classes, to highlight the criticality of considering pretreatment condition, both when assessing treatment needs and when setting expectations for treatment accomplishment. Next, we highlight short-term treatment outcomes, including how resistance scores change 1 year post-treatment, forest area amenable to treatment, and the extent to which treatment moves forest area into a more resistant FRSA. We then assess treatment longevity for each fire-resistance metric, over the 30 years post-treatment, and how this varies by FRSA for broadly successful treatments for single- and multistory stands, and as a point of comparison, for fuel strata gap in one less successful treatment in multistory stands. Finally, we consider the whole forest, irrespective of initial FRSA, to explore the magnitude of the shifts in CRS, individual fire-resistance metrics, and the future distribution of FRSAs that could be anticipated if integrated, multiobjective forest management were to be widely applied to dry mixed conifer forests.

Characteristics and Landscape Distribution of FRSA Classes

There were significant differences in forest structural characteristics among the FRSA classes (Table 3). For single-story stands, on which we modeled CTs, all forest characteristics differed significantly among at least some FRSA classes. FRSA 4 stands contained trees with the largest mean diameter, highest canopy base height (as estimated via FFE-FVS), lowest total cover and CBD, and lowest tree density. Several forest characteristics differed significantly between FRSA 2 and FRSA 4, including quadratic mean diameter, total cover, and basal area. FRSA 3 contained the smallest and shortest trees. Not surprisingly, given how they were defined, FRSA 4 and 3 contained >75 percent fire-resistant species, which made their composition quite different from FRSA 1 and 2.

For multistory stands, there were significant differences among FRSAs for all attributes except tree density (Table 3). Although FRSA 3 and FRSA 4 had >75 percent of basal area in fire-resistant species, both top height and quadratic mean diameter were lower in FRSA 3 (20 m, 66 ft and 18 cm, 7 in., respectively) than in FRSA

4 (23 m, 75 ft and 24 cm, 9 in., respectively). Trees in FRSA 3 were also significantly smaller than in FRSAs 1 and 2. FRSA 2 had higher CBD (0.08 kg m^{-3} , 1.28 lb ft^{-3}) and total canopy cover (48 percent) than FRSA 4, where CBD was 0.05 kg m^{-3} (0.8 lb ft^{-3}) and total canopy cover was 42 percent.

Less than a third of both the single (0.96 million hectares, 2.3 million acres) and multistory (0.4 million hectares, 0.99 million acres) dry mixed conifer forests currently contain a high proportion of resistant species (≥ 75 percent of basal area—i.e., FRSA 3 and 4), with FRSA 4 (where CRS > 9) accounting for two-thirds of this area. In both single-story and multistory stands, FRSA 2 contained the most area, followed by FRSA 1, FRSA 4, and FRSA 3 (Table 4).

Short-Term Treatment Effectiveness

Treatable Area by FRSA Class

A prescription's implementation frequency depends on its residual stand density target and, to a lesser extent, its diameter limit. For example, to implement a prescription that calls for a residual basal area of $34 \text{ m}^2 \text{ ha}^{-1}$ ($148 \text{ ft}^2 \text{ acre}^{-1}$), the pretreatment basal area of a stand must exceed $34 \text{ m}^2 \text{ ha}^{-1}$. With the exception of CTs applied to stands in FRSA 4, a high proportion (at least 68 percent) of forest area was amenable to treatment implementation under every prescription, where implementation is defined as at least some tree removal (Table 4). Prescriptions IC 2, IC 9, and CT 6 were applicable on the vast majority of the forest in their respective structure categories (e.g., 89 percent of single-story forest area for CT 6 and, for both IC 2 and IC 9, 99 percent of the multistory forest in FRSA 1), primarily by virtue of their comparatively low residual basal area specifications (Table 1). These same prescriptions are notable for the frequency with which they increase CRS immediately post-treatment—e.g., in 70 percent of single-story FRSA 2 stands and in 93 percent of multistory FRSA three stands. Although, in practice, an increase in CRS is not necessarily the only criterion for selecting a prescription, as some prescriptions may achieve other desired objectives without diminishing fire resistance, for this analysis, we required a CRS increase for a treatment to be considered effective.

Treatment Evaluation

Mean pretreatment CRS and CRS increment attributable to treatment confirmed that prescriptions CT 6, IC 2, and IC 9 were most effective across all FRSA classes (Figure 4a). Both the pretreatment and post-treatment CRS differ among FRSA classes. Applying the most effective treatment to stands in FRSA 1 produced an average CRS no higher than 7, far below the average score in FRSA 4, even before treatment. The pre- and post-treatment scores in FRSAs 2 and 3 are comparable; however, post-treatment scores under IC 2 and IC 9 were slightly greater in FRSA 3, owing to the greater representation of trees of fire-resistant species that, owing to either self-pruning or to loss of lower branches from previous wildfires that they survived, more effectively elevate canopy base height.

There were notable patterns in the contribution of each subscore to the improvement in CRS (Figure 4b). Improvement in the resistant species subscore accounts for some of the increase in mean CRS in FRSA 1 and FRSA 2 because all treatments, and IC 4 and CT 6 in particular, increased the relative abundance of fire-resistant species in at least some stands enough to add a point to this subscore. Such improvements were not possible in FRSA 3 and

Table 4. Area of single- and multistoried stand types, in total, and by FRSA class (see Table 3 for descriptions).

Treatable area by CRS shift and total	Single-story: CT (3.13 million ha, 7.7 million ac)			Multistory: IC (1.21 million ha, 2.9 million ac)					
	CT 5	CT 6	CT 7	IC 1	IC 2	IC 3	IC 4	IC 8	IC 9
FRSA 1	(0.82 million ha, 2.0 million ac)			(0.30 million ha, 0.74 million ac)					
CRS increase (percent)	56	75	51	45	84	45	44	42	85
CRS no change (percent)	26	14	16	23	12	28	30	24	11
CRS decrease (percent)	2	0	0	3	3	3	4	5	3
Total (percent)	83	89	67	71	99	76	78	72	99
FRSA 2	(1.35 million ha, 3.3 million ac)			(0.50 million ha, 1.2 million ac)					
CRS increase (percent)	54	70	49	53	79	52	51	47	79
CRS no change (percent)	21	12	13	20	16	27	26	27	16
CRS decrease (percent)	2	1	0	6	2	5	7	9	2
Total (percent)	77	83	62	79	97	84	83	79	97
FRSA 3	(0.33 million ha, 0.8 million ac)			(0.13 million ha, 0.32 million ac)					
CRS increase (percent)	70	64	68	45	93	46	44	45	93
CRS no change (percent)	17	16	12	31	6	26	29	31	6
CRS decrease (percent)	0	0	0	0	0	3	3	0	0
Total (percent)	87	80	80	76	100	76	76	76	100
FRSA 4	(0.63 million ha, 1.5 million ac)			(0.27 million ha, 0.67 million ac)					
CRS increase (percent)	23	38	18	35	71	38	32	33	68
CRS no change (percent)	24	21	12	29	23	30	33	29	23
CRS decrease (percent)	2	1	0	5	3	6	9	7	5
Total (percent)	49	59	30	69	97	74	75	68	97

Note: CRS, composite resistance score; CT, commercial thin; FRSA, fire-resistant species abundance; IC, improvement cut. For each stand type, FRSA class and treatment prescription, the area for which the prescription (see Table 1 for treatment descriptions) can be implemented (defined as harvest of at least one tree). Regardless of fire-resistance outcome, for each FRSA class we report the area that had an increase in the CRS, no change in CRS, or a decrease in CRS.

*Nominal diameter and height are calculated as the average diameter and height of nine sample trees (four trees above) and (four trees below) the 70th percentile tree (Dixon 2018).

FRSA 4, which, at >75 percent fire-resistant species, already scored 3 points for resistant species. Elevating canopy base height was responsible for much of the CRS improvement in multistory stands in treatments IC 2 and IC 9, but played a smaller role in CT 6, the most effective treatment for single-story stands. Reduction in CBD was a big driver of CRS improvement in both kinds of stands with most prescriptions. We focus mainly on treatments CT 6 and IC 2 in the results we report here because they were, on average, the most effective treatments for increasing CRS and are sufficient to illustrate the important findings. Compared to the less effective treatments, they prescribed lower residual stand density in both commercial and submerchantable-sized trees.

Long-Term Treatment Effectiveness

Treatment Longevity by Resistance Metric and FRSA

For both treatment and grow-only scenarios in multistory stands, fuel strata gap and CBD were far more dynamic than resistant species or survival under IC 2 (Figure 5). As reported earlier, IC 2 was initially effective at increasing canopy base height across all the FRSAs with treatment increasing canopy base heights by 3–5 m (10–15 ft). However, the longevity of the treatment effect, defined as the difference in mean metrics between treated and grow-only, varied by FRSA. For FRSA 1 and 2, the mean canopy base height of treated stands exceeded grow-only for nearly 30 years; in FRSA 3 and 4, the mean canopy base height of treated stands became essentially indistinguishable from grow-only in 20 years. IC 2 also reduced CBD by about 0.05 kg m⁻³ (0.8 lb ft⁻³), but for a very short time (<10 years) in all but FRSA 3. In FRSA 1 and 2, treatment led to a greater CBD in less than a decade, but in FRSA 3, CBD remained reduced compared to grow-only for at least 20 years. The mean resistant species basal area percentage was virtually

unaffected by treatment in FRSA 1, where it was initially very low, and in 3 and 4, where it was initially high, and showed modest improvement (~10 percentage points) with prescription IC 2 in FRSA 2. This metric remained remarkably stable over time in all FRSAs and for both treatment and grow-only trajectories. Predicted survival was slightly elevated by treatment in all FRSAs, an effect that was largely sustained over three decades, with the greatest effect in FRSA 3, where survival improved for both treatment and grow-only trajectories.

Comparing the most successful multistory prescription IC 2 with the less, although not least, successful IC 1, the mean post-treatment composite resistant score and score improvement are greater for IC 2 in every FRSA (Figure 4). Much of this difference may be attributable to the comparatively smaller increase in mean fuel strata gap achieved by IC 1 (0.6–2.1 m, 2–7 ft, vs. 3–5 m, 10–17 ft by IC 2) in every FRSA (Figure 6). Although IC 1 and IC 2 both reduced canopy density, IC 1 retains an understory of trees <12.7 cm (5 in) dbh, if present, whereas IC 2 removes any trees <15.2 cm (6 in) dbh. The retained understory in IC 1 has the effect of reducing fuel strata gap in stands that contain understory trees, relative to IC 2; it also shortens (to 7–10 years with IC 1, vs. 17–30 years with IC 2) the duration of any fuel strata gap benefit achieved, as growth of those trees will close the gap separating them from higher stories. Treatments that maintain a multistory stand structure may meet some management objectives but will not come close to achieving maximum fire resistance because the lowest story compromises, and ultimately negates, any fuel strata gap achievements.

Similar to the effect of IC 2 in multistory stands, CT 6 produced substantial (3–5 m) initial increases in fuel strata gap in single-story stands; however, the effect was short-lived (<20 years) in FRSAs 1 and 2, and very short-lived in FRSAs 3 and 4 (Figure 7). The mean fuel strata gap after 30 years remained above 6 m (20 ft) with or

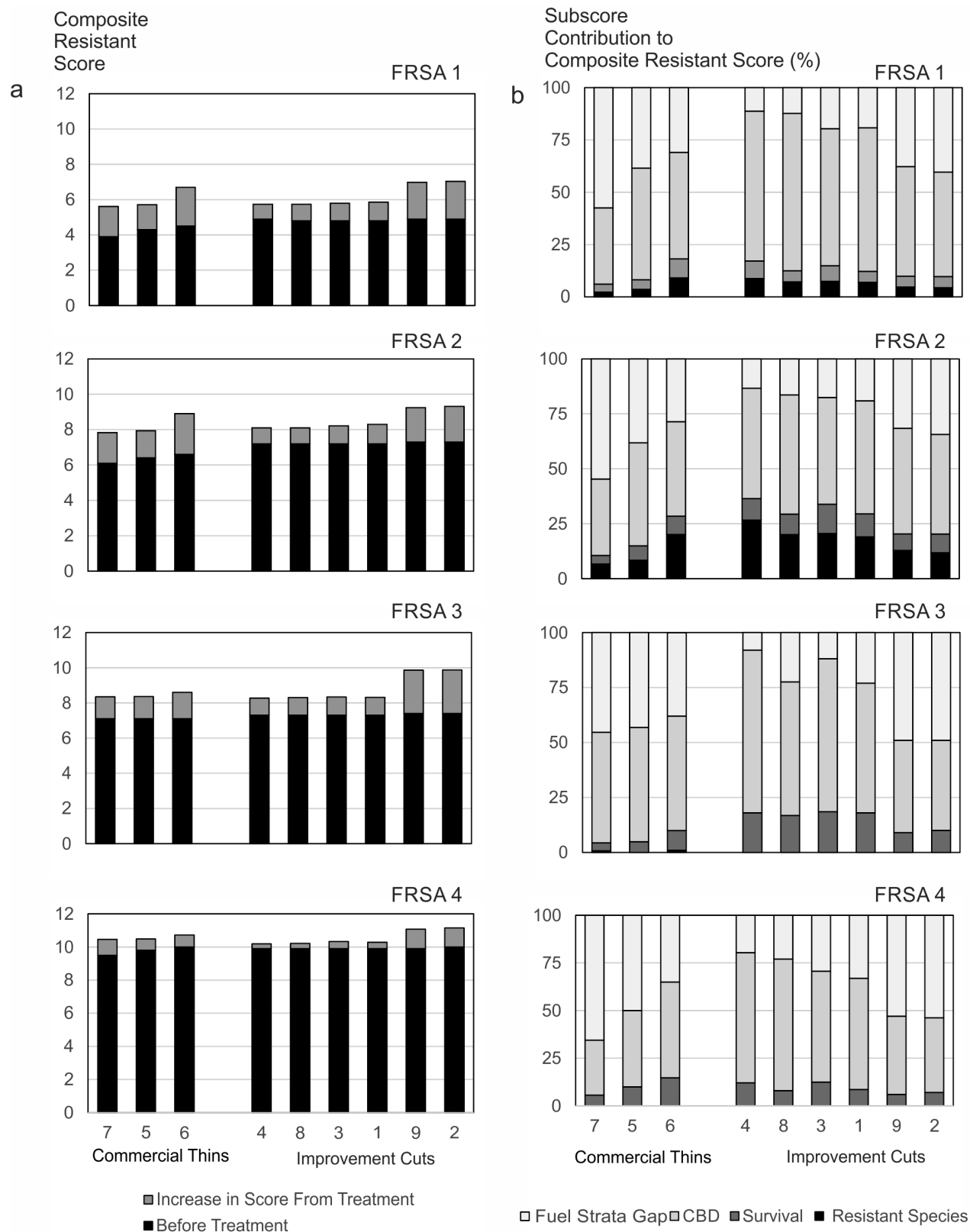


Figure 4. For stand-treatment combinations where treatment increased composite resistance score (CRS), (a) mean before treatment CRS (black), and mean CRS increment immediately after treatment (gray), and post-treatment total score (combined score of the black and gray) by Fire-Resistant Species Abundance (FRSA) class (1 [low] to 4 [high])—see Table 3 for FRSA class descriptions—and prescription parameters—see Table 1 treatment codes and descriptions. Within commercial thins and improvement cuts, treatments appear in ascending order by post-treatment CRS; and (b) proportion of CRS increment attributable to each subscore element, in ascending order of shade intensity (light to dark) from fuel strata gap, canopy bulk density (CBD), proportion of stand volume expected to survive a fire with 6- to 8-ft flame lengths (survival), and proportion of basal area in fire-resistant species (resistant species).

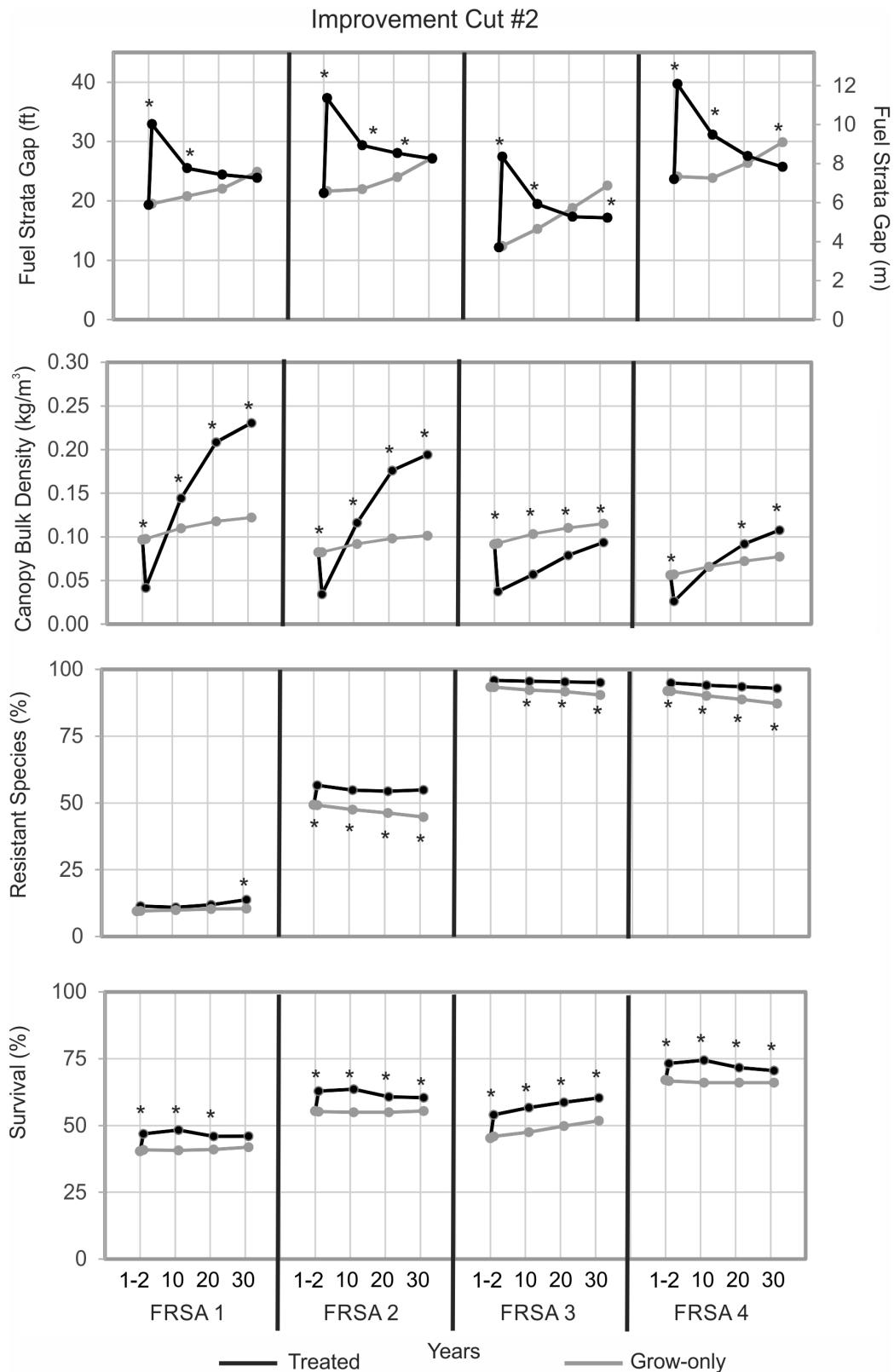


Figure 5. Thirty-year projections, by FRSA class, of mean, hazard-related stand attributes underlying composite resistant score (CRS) subscores in multistory stands for two scenarios: (1) treated in year 1 by implementing the IC 2 (improvement cut 2—refer to prescription parameters in Table 1) prescription, and (2) grow-only (projected without any treatment). Attributes are fuel strata gap, canopy bulk density, percentage of stand basal area in fire-resistant species, and percentage of tree volume predicted to survive a fire with 6- to 8-ft flame lengths. Significance is indicated by "*" between grow-only and treatment for each year evaluated at $\alpha = .01$.

without treatment. In FRSA 4, it exceeded 9 m (30 ft), making these forests particularly resistant to crown ignition under all but the most extreme surface fuel models (e.g., TU 5), slopes, and fire

weather. This prescription attained substantial, although short-lived, reductions in CBD in FRSA 1 and 2, and smaller, but longer-lasting, reductions in FRSA 3 and 4. FRSA 4 stands had quite a low

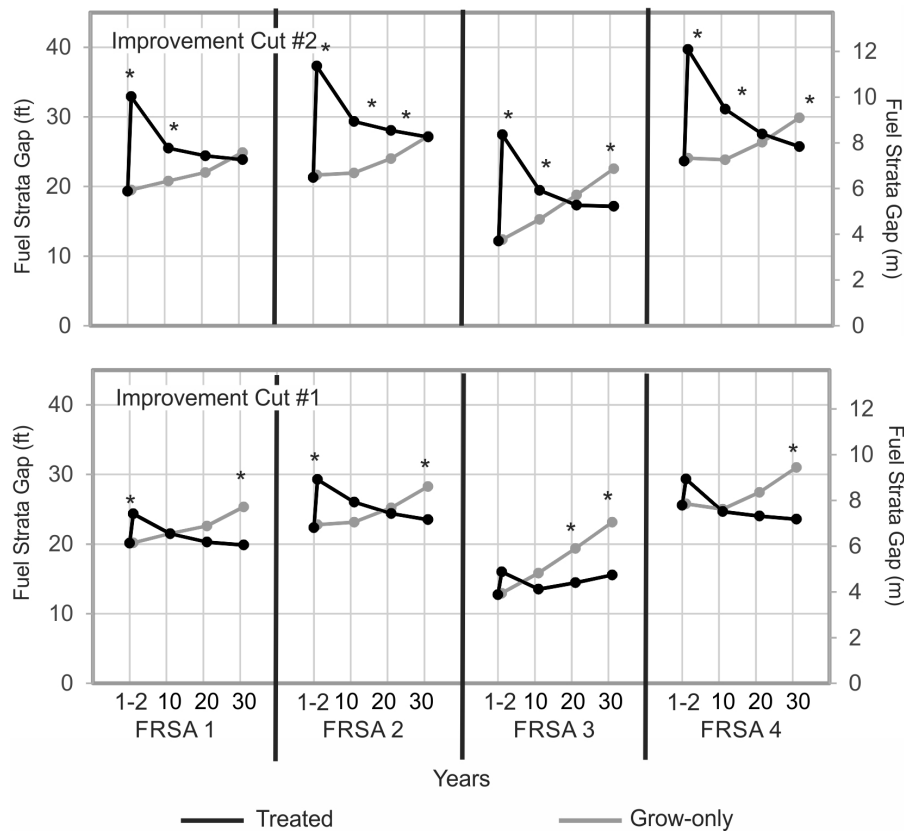


Figure 6. Thirty-year projections, by Fire-Resistant Species Abundance (FRSA) class, of mean fuel strata gap in multistory stands treated with prescription IC 2 (improvement cut 2; refer to prescription parameters in Table 1), which specifies removal of all trees less than 6 in. in diameter at breast height (dbh), and IC 1, which allows up to 150 trees per acre under 5 inches dbh to remain, for two scenarios: (1) treated in year 1, and (2) grow-only (projected without treatment). Significance is indicated by “*” between grow-only and treatment for each year evaluated at $\alpha = .01$.

CBD, regardless of whether or not they were treated, because the resistant species that grow there have a lower crown density than the fire-intolerant species common in FRSA 1 and 2, and because trees in these stands are older, larger, and more widely separated than those in FRSA 3. The mean CBD in FRSA 4 (treated and untreated), and in FRSA 3 (treated), was held below 0.10 kg m^{-3} (1.6 lb ft^{-3}).

Treatment impacts on the resistant species subscore were similar in single- and multistory stands, with modest impact in FRSAs 1, 3, and 4, and quite a substantial impact in FRSA 2, the class where resistant species basal area percentage was initially between 25 and 75 (Figures 5 and 7). It is difficult to define cutting rules that appreciably change species composition in stands with few resistant species, and in those with mostly resistant species. As with multistory stands, this metric remained relatively static for treated stands across all FRSAs. Survival in FRSA 3 increased over time whether or not treatments were implemented, likely because these trees grew larger, enhancing their survival prospects. Treatment effects in all FRSAs were somewhat more modest than in multistory stands, but similar in their sustainability over time.

Landscape Treatment Effectiveness

Although CT 6 and IC 2 most frequently generated the greatest immediate increase in CRS, other treatments also improved CRS scores for some stands, and expanded the area for which treatment could achieve a CRS increase. As described earlier, even the best

treatments rarely remained effective for as long as 30 years, on average. Considering treatment accomplishment over a two-decade span as the mean change in CRS over 20 years, relative to untreated forest, directly incorporates treatment longevity in the definition of success. Thus, although the short-term effect analyses found that treatment could increase CRS above the grow-only value on about 85 percent of the area, improvement in 20-year weighted average CRS could be achieved on only 50–60 percent for both single- and multistory stands.

The histograms in Figure 8 show a net rightward shift for each subscore, although with a large concentration of no change, relative to grow-only—most of these “no change” cases are stands for which grow-only was assigned as the best prescription. There are also a few cases where scores for fuel strata gap decreased or CBD should be increased (Figure 8a and b), most likely because of regeneration during the 20-year period following treatment, as previously discussed. Treatment-induced changes in subscores for resistant species and survival volume were uncommon compared to fuel strata gap and CBD, and almost never negative, probably because any regeneration, even if consequential to canopy height and cover, would be small in basal area and volume compared to the residual stand, and have little effect on these scores (Figure 8c and d).

Choosing the treatment with the maximum 20-year weighted average CRS does shift 50 (single-story) to 60 (multistory) percent of stands to a higher 20-year weighted average CRS than grow-only,

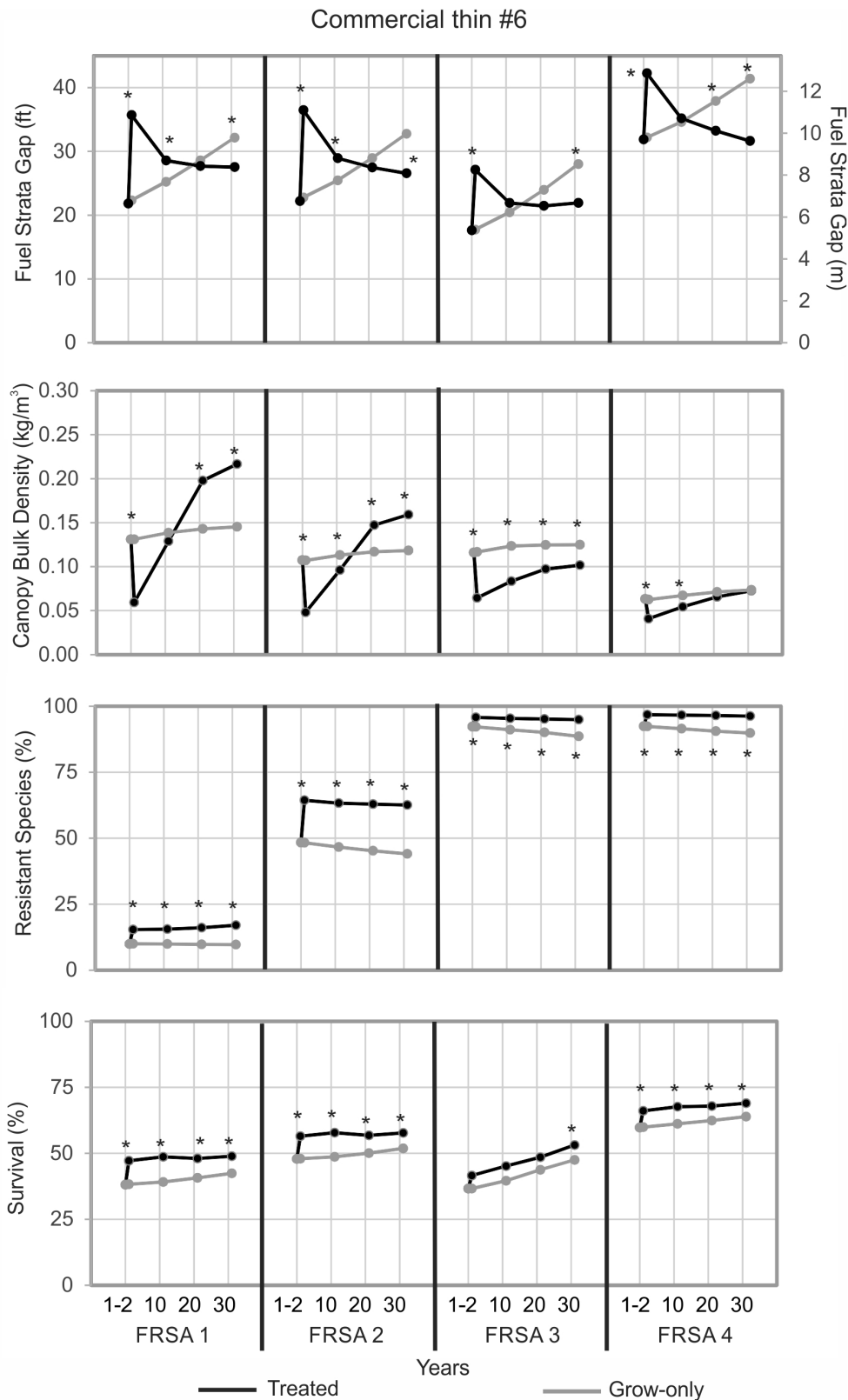


Figure 7. Thirty-year projections, by Fire-Resistant Species Abundance (FRSA) class, of mean, hazard-related stand attributes underlying composite resistant score (CRS) subscores in single-story stands for two scenarios: (1) treated in year 1 by implementing prescription CT 6 (commercial thin 6; refer to prescription parameters in Table 1), and (2) grow-only (projected without treatment). Attributes are fuel strata gap, canopy bulk density, percentage of stand basal area in fire-resistant species, and percentage of tree volume predicted to survive a fire with 6- to 8-ft flame lengths. Significance is indicated by "*" between grow-only and treatment for each year evaluated at $\alpha = .01$.

if only by a few points (Figure 9a), and about half of both stand types achieve a 20-year weighted score of 9 or better (9b). However, only some of the stands that achieve an increase in CRS end up

with attribute values that would lead them to be classified as FRSA 4. There is some shift in the distribution of FRSA classes evaluated for the average of 20 post-treatment years, compared to FRSA

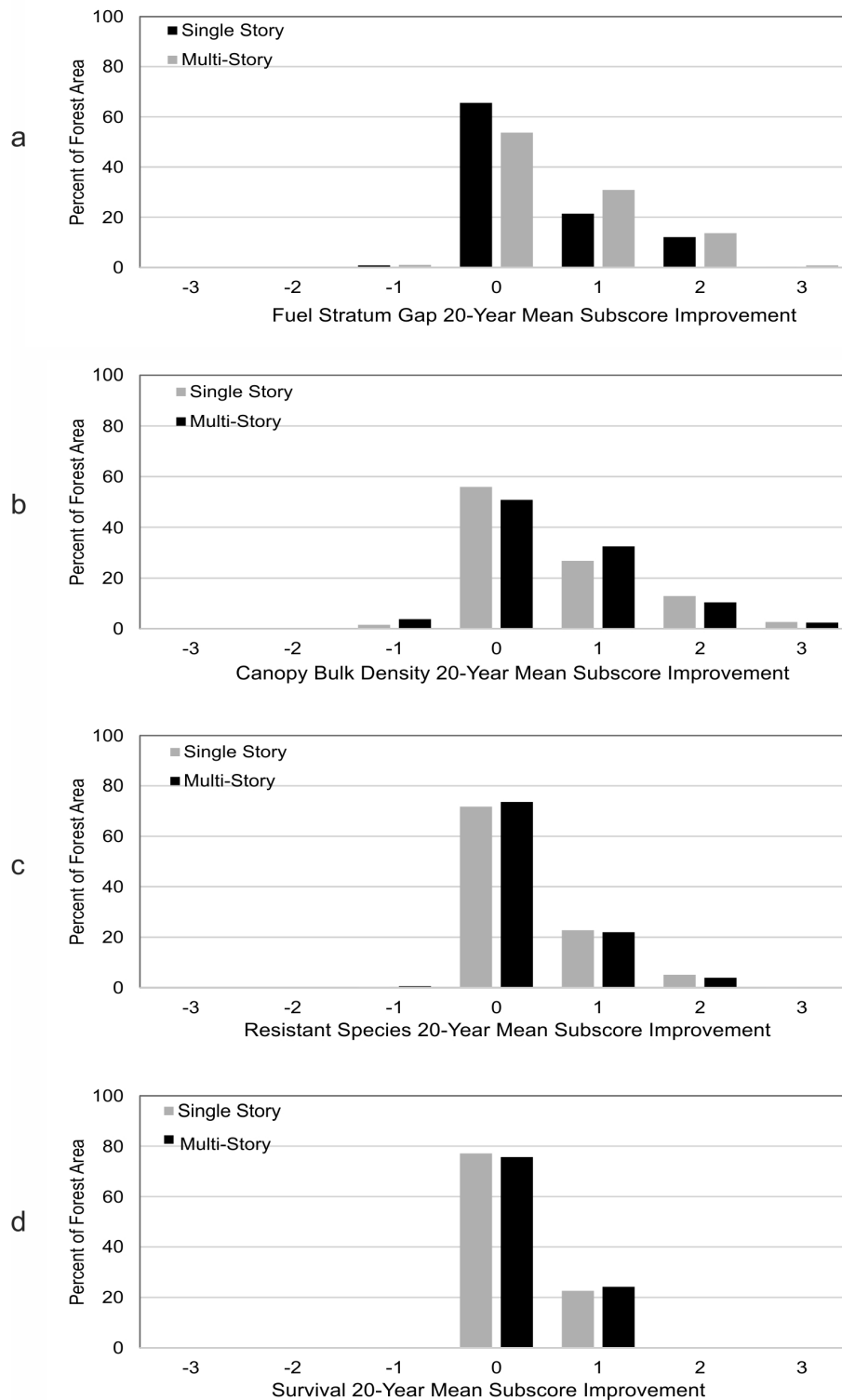


Figure 8. Histograms of the binned change in 20-year mean subscore values between the treatment that maximized 20-year mean composite resistant score (CRS) and 20-year mean grow-only for (a) fuel strata gap, (b) canopy bulk density, (c) resistant species, and (d) volume survival subscores for single- and multistory stands. Bins are constructed, for example, as 1 (0.1–1), 2 (1.1–2), etc.

assignments before treatment. For example, prior to treatment, 27–29 percent of stands were in FRSA 3 or 4. Considering the resistance metrics averaged over the 20 years following treatment, 39

percent of stands would be classified as FRSA 3 or 4. There was a substantial net increase in the area of FRSA 4 and decrease in the area of FRSA 2 (Figure 9c and d).

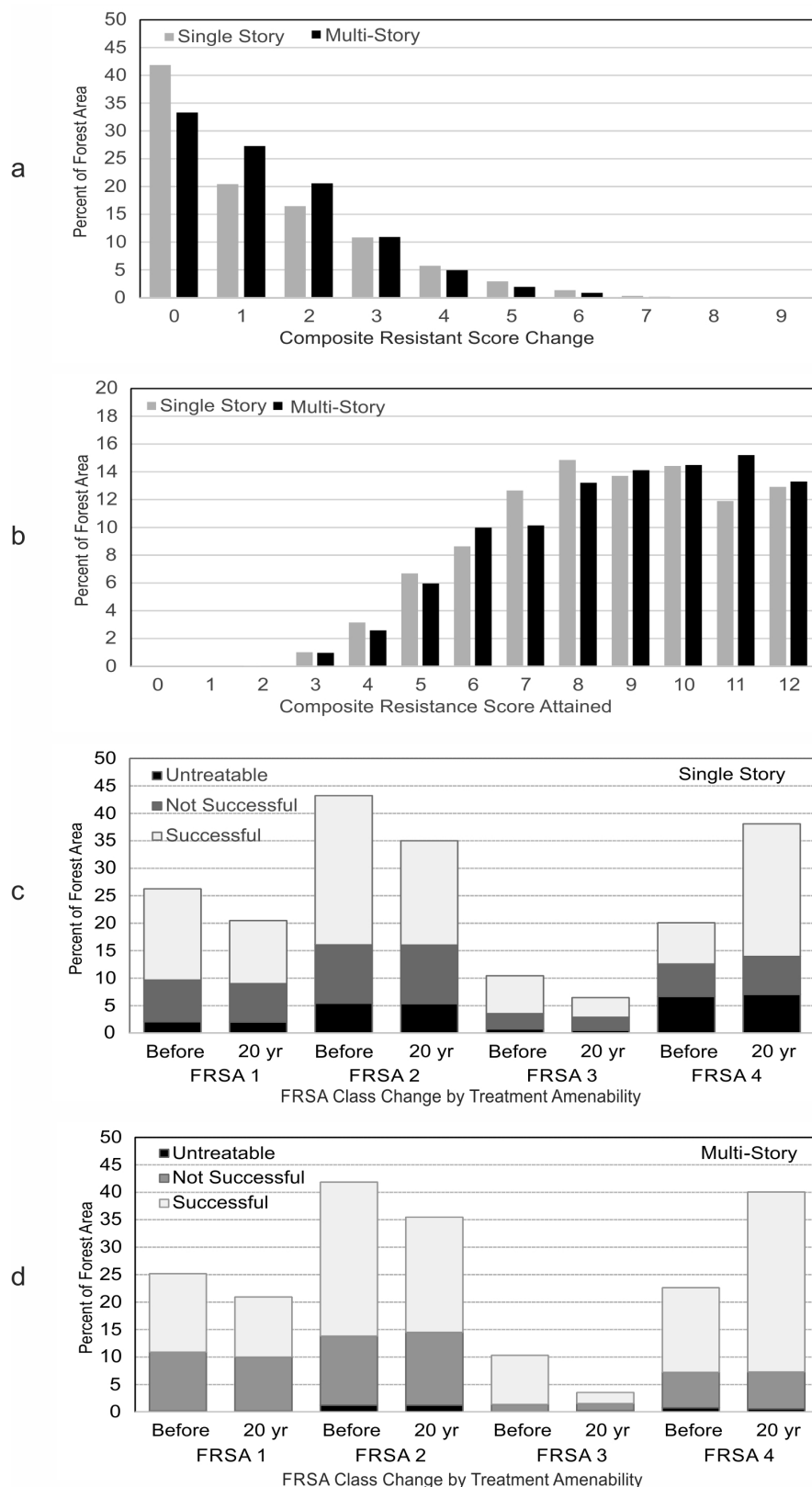


Figure 9. Histograms for single- and multistory stands of (a) difference (change) between 20-year mean Composite Resistance Scores (CRS) calculated for whichever treatment maximizes 20-year mean CRS for a stand and the 20-year mean grow-only scenario; (b) the binned 20-year mean CRS attained; (c) and (d) forest area by pretreatment (before) and 20-year mean FRSA class, decomposed via stacked bars by whether untreatable (none of the treatments would result in tree removal), unsuccessful at increasing 20-year mean CRS, or successful at increasing 20-year mean CRS, using the treatment that maximized 20-year mean CRS above the grow-only mean for (c) single-story and (d) multistory forests. 20-year mean values are binned into Fire-Resistant Species Abundance (FRSA) classes; for example, 4 represents values of 3.1–4, 3 represents 2.1–3, etc.

Discussion

Lessons Learned from the Modeling Framework

The BioSum analysis framework offers some unique fuel treatment evaluation opportunities beyond this study. It integrates (1) the FIA data that constitute a timely, regularly refreshed and representative sample of the entire forest or any subset of interest, such as particular ownerships, geographical areas, or in this case, a confluence of tree species that we label dry mixed conifer; (2) silvicultural prescriptions targeted at these subsets; and (3) FVS, a widely used stand projection system capable of predicting treatment response in its many dimensions. Although not an element of this analysis, the framework also integrates the tracking of net treatment costs, including mechanical thinning and surface fuel treatment costs and offsetting revenues from sales of wood.

Unlike a convenience sample, results can be directly extrapolated to the forested landscape—a treatment that proves effective on FIA plots representing half the forest can be regarded as effective on half the forest. The framework can be operated anywhere there are FIA data and an FVS variant, yet is also adaptable to innovation in prescriptions, harvest systems, and effectiveness metrics with respect to fire resistance or any other management objectives. Its design includes an optimization module targeted at managers and policymakers, not just scientists, to facilitate exploring, comparing, and sifting through whole libraries of prescriptions to choose the best for each situation for the identified management objectives.

The framework is not without limitations and challenges. For example, the default assumption that all nonreserved forested land is available for treatment may or may not hold. Depending on ownership, for example, there may be several objectives inherently incompatible with fuel treatment, so to account for such factors, further subsetting of plot data may be required. The lack of an endogenous regeneration module in nearly all FVS variants presents a barrier to modeling treatment longevity, which in reality depends on stochastic processes like seed crop production, weather, and disturbance. We instead relied on the REPUTE add-on to account for regeneration, without any formal assurance as to the accuracy of its mean-based predictions, although we did find the REPUTE predictions for the Inland Empire variant (Keyser 2008) reasonably consistent with those produced by the endogenous regeneration module available for that variant.

Our survival volume predictions were developed from parameters in the FOFEM model. However, only 18 species have been thoroughly investigated and parameterized, and, for some of these species, datasets contain relatively few observations for some size classes (Hood et al. 2018). More work is needed to relate tree mortality to size, species, and fire behavior. New datasets coming online via remeasurement of FIA plots that burned (Eskelson et al. 2016) offer some promise for enlarging the datasets that can be mined to develop and refine such relations, and improve the science of mortality prediction.

BioSum, like FVS, is vulnerable to some of the same critiques leveled against FVS over the years, including concerns over the accuracy of growth and mortality predictions, some of which may be amenable to calibration when suitable calibration data are available. However, because most of this plot dataset was based on initial installation visits, not remeasurement visits, we did not have the option to calibrate. When the stand projection functions fail to accurately capture growth and mortality processes, errors may amplify

as they propagate over multiple projection cycles undertaken to characterize treatment longevity. Immediate post-treatment results are free of such error propagation, as they depend only on the simulator's capacity as a prescription implementation tool (that selects trees for removal based on prescription parameters). However, as we modeled growth over time, there is the potential for errors in FVS submodels to be introduced, and to propagate with each time step. Validation is best thought of as a continuous process. The FVS steering team has developed a validation protocol and is pursuing variant testing and validation partnerships; however, validation of specific variants was outside the scope of the project on which this article is based. Recognizing the accuracy limitations of any modeling effort, we see these results as most robust when comparing among treatment scenarios, including grow-only, and believe they provide useful insight that can inform monitoring efforts that could ultimately serve to validate the conclusions of this research.

Because creativity in prescription formulation has far outpaced modeling capabilities in FFE-FVS, multistory treatment results warrant another caveat. Prescriptions received for multistory stands emphasized removal of ladder fuels under dominant and codominant trees, but FFE-FVS provides no simple tools for representing such specific spatial arrangements (Sánchez Meador et al. 2015), so modeling three colocated stories was the best approximation available. This approximation could lead FFE to understate the fuel strata gap that could be achieved outside openings. Figures 5 and 7 illustrate how rapidly the fuel strata gap decreases as stands recover, and we noted (data not shown) that small tree response to reduced overstory cover was so dramatic that understory tree cover quickly exceeded overstory cover. Based on these results, if maintaining multistoried stands is an overriding objective, it will be more difficult to maintain fire resistance, unless there is sufficient spatial separation among canopy layers. Early findings from a new generation of 3D-physics-based fire-behavior models (e.g., WFDS or FIRETEC), currently under development, suggest that spatially heterogeneous forest structures can play a role in moderating fire behavior. However, these models do not relate such moderation to specific distances among trees of specific sizes, so are not parameterized in a way that is likely to facilitate useful and specific guidance to managers on prescription development (Parsons et al. 2017, Ziegler et al. 2017).

Another issue, given that preventing transition of surface fire to crowns is the overarching objective of many fuel treatments (Agee and Skinner 2005), is the persistent difficulty in accurately representing surface fuels and the changes in such fuels that result from treatments, and the limited validation of existing models. We developed a fuel strata gap, based on the target canopy base height concept, as a workaround to characterize crown fire resistance that reduces dependence on accurately representing surface fuels. The comprehensive analysis of fuel strata gap thresholds by fuel model, slope, and windspeed identified “sweet spot” thresholds in either canopy base height or distance between canopy layers (Scott 1998, Keyes and O'Hara 2002). FFE-FVS defines a stand's canopy base height as the height at which CBD exceeds 0.011 kg m^{-3} (0.16 lb ft^{-3}), calculated using a 0.9 m (3 ft) running average, starting at ground level and moving upwards. By default, hardwoods and trees less than 1.8 m (6 ft) tall are not included in this calculation; the latter are assumed to be part of the surface fuel stratum.

Our sample includes stands with a canopy base height of <1.8 m, and many with a high hardwood component. Managers relying on canopy base height to mark trees do not estimate CBD to obtain it and would be better served by a metric like fuel strata gap that is amenable to field estimation. When actually applying treatments, knowledge of the surface fuel model could help guide treatment selection. However, such knowledge is generally lacking when conducting a strategic analysis of the whole forest (such as in forest or project planning). We think that managing for a fuel strata gap that achieves a high level of fire resistance with many fuel models offers a consistent and robust way to model treatment effectiveness, and that this framework makes a useful contribution to thinking about vertical stand structure in relation to fire resistance, with less dependence on harder-to-assess surface fuels.

Lessons Learned from Evaluating Fuel Treatments

Current condition is a crucial determinant of whether treatment will enhance fire resistance, and if so, for how long. Several authors (e.g., [Scott and Reinhardt 2001](#), [Agee and Skinner 2005](#), [Peterson et al. 2005](#)) emphasize the important principle that forest structure must be modified to reduce torching and crown fire potential. However, our analysis revealed that regardless of forest structure, a high proportion of basal area in fire-resistant species resulted in treatments that are more likely to maintain or enhance their fire resistance. Stands lacking resistant species (FRSA 1) have few pathways to full resilience, other than regeneration harvest that initiates a new stand better endowed with fire-resistant tree species. Classifying current condition also highlights meaningful shifts into more resilient FRSA classes that treatment can accomplish and identifies those with the greatest potential for sustained enhancement of fire resistance ([Table 5](#)). Stands in FRSA 2, some of which begin with a significant complement of resistant species,

and in FRSA 3, where resistant species dominate but the fuel strata gap has not yet grown (something that may even happen without treatment, given patience), show strong potential for resistance improvement with treatment. FRSA 4 forests are already resistant, so even the most effective treatments can do little more than maintain the existing resistance. In the long-term, the effect of stand dynamics was noted by [Keyes and Varner \(2006\)](#) as limiting longevity of fuel treatment. Similar dynamics were observed in Colorado ([Tinkham et al. 2016](#)) and Arizona ([Roccaforte et al. 2015](#)), where growing space created by treatments facilitated regeneration that reduced treatment longevity with respect to fuel strata gap, but left CBD comparatively unchanged. For FRSA 3 and 4, prescribed fire is an exceptionally valuable tool in fuels and forest management, but only to the extent that it can be applied ([Ryan et al. 2013](#)). Our results indicate that any increased fire resistance conferred by these mechanical treatments will not extend much beyond 20 years under the best circumstances, making recurring maintenance on a 20- to 30-year interval imperative for protecting the treatment investment, particularly in FRSA 4 ([Table 5](#)). Prescribed fire or other mechanical treatments such as mastication (e.g., [Stephens et al. 2009](#), [Tinkham et al. 2016](#)) are viable options.

Resistance benefits in the short term were most frequently achieved using prescriptions that harvested to the lowest residual tree density in both single- and multistory stands, and that completely removed the lowest story in multistory stands. Current conditions played an important role in determining which resistance metrics saw short-term improvement, although CBD amounted to the largest or second largest (after fuel strata gap) component of CRS improvement in every FRSA and treatment ([Figure 4b](#)). The best treatments were also startlingly effective in some FRSAs in the short term, not only at producing an immediate increase in CRS, on average ([Figure 4a](#)), but also at producing substantial shifts in area between FRSAs. For example, applying CT 6 in single-story stands shifted 32 percent of FRSA 2 forests to FRSA 3 or 4 and 28 percent of FRSA 3 forests to FRSA 4; and IC 2 moved 72 percent of FRSA 3 multistory forests to FRSA 4 ([Table 5](#)), although it is not clear how much of this shift could be expected without treatment (i.e., by waiting patiently for trees to grow). If sustainable, such FRSA shifts could really move the needle on fire resistance.

Although achieving improvements in fire resistance at the stand level is an accomplishment and an important starting-point for restoring historical fire regimes, such success must be widely replicated to reduce the impact of large, uncontrolled, uncharacteristic and unwanted fire on forested landscapes. Achieving effectiveness on only a tiny fraction of the forest does not materially influence fire at landscape scale; however, making far less than 100 percent of the forest safe from crown fire initiation can yield reduced fire sizes and mitigate effects relating to severity and smoke ([Ager et al. 2010](#), [Chiono et al. 2017](#)). As shown in [Table 4](#), treatment can be implemented on most of the forest and, except for single-story FRSA 4 stands, will produce immediate improvements in resilience as indicated by CRS. Even if treatment accomplishment is judged by the more demanding standard of mean improvement (relative to grow-only) over two decades ([Figure 9a](#)), resistance can be improved on well over half of the forest, even if gains are usually modest (a couple of points of CRS). If the best treatments are always applied (and these may sometimes be a grow-only, “patience treatment” when no active treatment can achieve a higher CRS), about half of the forest achieves a 20-year average

Table 5. Percentage of forest area, by FRSA before treatment, that would be classified in each of the four FRSA classes 1 and 30 years after treatment, for prescription commercial thin 6 (applied to single-story stands) and improvement cut 2 (applied to multistory stands).

Before treatment	Year after treatment	Post-treatment FRSA (percentage of area)			
		FRSA 1	FRSA 2	FRSA 3	FRSA 4
Commercial thin 6					
FRSA 1	1	80	20	0	0
	30	74	26	0	0
FRSA 2	1	1	71	2	26
	30	4	66	10	20
FRSA 3	1	0	0	56	44
	30	0	5	47	48
FRSA 4	1	0	0	0	100
	30	0	3	10	87
Improvement cut 2					
FRSA 1	1	86	14	0	0
	30	77	23	0	0
FRSA 2	1	2	82	1	15
	30	6	79	5	10
FRSA 3	1	0	3	17	80
	30	0	5	53	42
FRSA 4	1	0	0	0	100
	30	0	11	25	64

Note: FRSA, fire-resistant species abundance. Percentages along the diagonal (are in italics) account for area that does not experience a shift in FRSA class; percentages that represent a shift of at least 10 percent of forest area out of the current FRSA at 1 or 30 years post-treatment are shown in bold.

CRS of 9 or better (Figure 9b), which may be about the best that can be accomplished at landscape scale. It is also clear that such a treatment program produces a remarkable shift of the landscape into FRSA 4 that is sustainable for a decade or two, constituting approximately a doubling of the area capable of high resistance, even if slightly more than half of the forested area remains in FRSA 1 and 2, essentially mired there by a low endowment of resistant species. These results show promise for landscape-scale fuel treatment programs, provided they are economically feasible and matched with commitments for maintenance.

Conclusions

Although fuels management may initially appear to be a simple mission, in practice, it must integrate with other objectives and is subject to myriad constraints. This simulation-based study exposed several aspects that can limit or promote fire resistance, even before considering economic and social constraints. The greatest challenges to enhancing fire resistance via fuels management are stands that contain few if any trees of fire-resistant species. Even a well-considered treatment design incorporating commercial and noncommercial harvest and addressing surface fuels cannot achieve the level of resistance that is possible in stands largely composed of fire-resistant species. In stands dominated by fire-resistant species, but where trees are small, allowing time for trees to grow may be the best option. Forests that benefit most from treatment may be those where 25–75 percent of basal area is in fire-resistant species, and where removals of fire-vulnerable species increase the share of basal area in fire-resistant species, preferably of larger size. Unique contributions of this study include reliance on the FIA plot network as an unbiased sample of the dry mixed conifer forests across the entire forested landscape and application of manager-formulated prescriptions to develop treatment scenarios, both of which contribute to our understanding of fuel-treatment options, and factors that contribute to their short- and long-term effectiveness.

Supplementary Materials

Supplementary data are available at *Forest Science* online.

Supplement 1. Provides the methods used to select FIA plot data that represent dry mixed conifer forests.

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