fire

Article

Simulated Fire Behavior and Fine-Scale Forest Structure Following Conifer Removal in Aspen-Conifer Forests in the Lake Tahoe Basin, USA

Justin P. Ziegler [1,*], Chad M. Hoffman [1], Brandon M. Collins [2,3], Jonathan W. Long [3], Christa M. Dagley [4] and William Mell [5]

1 Department of Forest & Rangeland Stewardship, Colorado State University, Fort Collins, CO 80523, USA; C.Hoffman@colostate.edu
2 Center for Fire Research and Outreach, University of California, Berkeley, CA 94720, USA; bcollins@berkeley.edu
3 Pacific Southwest Research Station, USDA Forest Service, Davis, CA 95618, USA; jonathan.w.long@usda.gov
4 Department of Forestry and Wildland Resources, Humboldt State University, Arcata, CA 95521, USA; cd104@humboldt.edu
5 Pacific Northwest Research Station, USDA Forest Service, Seattle, WA 98103, USA; william.mell@usda.gov
* Correspondence: Justin.Ziegler@Colostate.edu

Received: 28 July 2020; Accepted: 8 September 2020; Published: 9 September 2020

Abstract: Quaking aspen is found in western forests of the United States and is currently at risk of loss due to conifer competition at within-stand scales. Wildfires in these forests are impactful owing to conifer infilling during prolonged fire suppression post-Euro-American settlement. Here, restoration cuttings seek to impact wildfire behavior and aspen growing conditions. In this study, we explored how actual and hypothetical cuttings with a range of conifer removal intensity altered surface fuel and overstory structure at stand and fine scales. We then simulated wildfires, examining fire behavior and effects on post-fire forest structures around aspen trees. We found that conifer removal constrained by lower upper diameter limits (<56 cm) had marginal effects on surface fuel and overstory structure, likely failing to enhance resource conditions sufficiently to sustain aspen. Increasing the diameter limit also led to a higher likelihood of fire spread and a higher rate of spread, owing to greater within-canopy wind speed, though crown fire activity decreased. Our simulations suggest heavier treatments could facilitate reintroduction of fire while also dampening the effects of wildfires on forest structure. Cutting specifications that relax diameter limits and remove a substantial portion of conifer overstory could better promote aspen restoration and mitigate fire hazard.

Keywords: forest restoration; fire behavior; point pattern; wildland-urban interface; Fire Dynamics Simulator

1. Introduction

Land management activities for over a century have led to significant changes in forest structure and ecosystem processes in mixed conifer-quaking aspen (*Populus tremuloides* Michx.) forests where wildland fire once regulated forest developmental pathways [1–4]. In these forests, low- and mixed-severity fires produced openings sufficiently large to modify microclimates, thus yielding fine-scale diversity of growing environments and regeneration niches [3,5,6]. However, lack of fires through suppression, as well as droughtiness, and livestock herbivory have reduced aspen vigor and recruitment, leading to replacement by conifers [1,7–10].

Loss of aspen within mixed forests is particularly acute in regions like the Lake Tahoe Basin of the western US, where aspen trees are typically found in relatively small (<1.5 ha) patches. Despite covering less than 2% of the Lake Tahoe Basin [7], forest managers and scientists have identified these mixed stands as a critical component in an otherwise conifer-dominated landscape due to their relative scarcity, high biological diversity, influence on hydrological processes, esthetics, and impact on landscape scale fire behavior and severity [7,11]. Studies of these forests across the greater Sierra Nevada (including the Lake Tahoe Basin) have suggested that up to 70% of stands with aspen are at moderate or high risk of being wholly replaced by shade-tolerant conifers (e.g., *Abies* spp.) [7].

The replacement of aspen by shade-tolerant conifers can alter potential fire behavior and effects. Previous simulation studies suggest the impact of conifer encroachment on fire behavior partially depends upon wind speed [11]. Under low wind speeds, surface fire spread may be limited in pure aspen stands, resulting in incomplete fire spread [12], while greater surface fuel loads associated with conifer encroachment can facilitate fire spread. Under moderate wind speeds, the lower crown base heights of conifers are thought to increase the potential for passive crown fires [11]. However, under extreme weather, crown fire behavior may occur regardless of the presence or absence of conifers. The potential shifts in fire behavior and severity under different burning conditions is an essential consideration in designing treatments in mixed stands as this differentially shapes future stand structure.

Given the relative rarity of, high biological diversity near, and vulnerability of aspen, land managers are increasingly interested in restoration treatments to promote aspen while reducing fire hazard [9,13,14]. As aspen and conifers interact at fine scales on the order of meters [4,15], removing conifers proximate to aspen can reduce shading and promote suckering of new ramets [16]. Forest managers employ heuristics including reducing conifer cover to less than 25% and removing conifers within 1.5 tree lengths of existing aspen [7,14,17]. However, constraints can limit the degree of conifer removal [14]. Operational constraints such as mesic soils can limit cutting methods and therefore limit cutting intensity, while regulatory and social constraints often limit the maximum size of conifers to be removed [9,13,18,19]. Consequently, the effectiveness of aspen restoration treatments in lowering wildfire hazard or reducing conifer density may be limited [7].

These constraints lead to concern over whether these partial conifer removal treatments can sufficiently meet hazard reduction goals and reduce conifer encroachment. In this study, we simulated conifer removal of varying intensities and modeled consequent fire behavior across a range of wind speeds. We examined restoration treatment effects on (1) stand structure, (2) the behavior of potential wildfires, and (3) stand structure following conifer removal and wildfire. We assessed forest structure both at the stand scale and around existing aspen ramets. Our approach addresses whether cutting constraints lead to undesirable fire behavior and conifer stocking, and whether there are circumstances under which wildfire effects might complement aspen restoration treatments.

2. Materials and Methods

2.1. Study Sites and Data Collection

The Lake Tahoe Basin lies in the Sierra Nevada of California and Nevada, USA (39°05′ N latitude, 120°02′ W longitude), and is approximately 134,000 ha with an elevation range between 1900 to 3050 m. The Lake Tahoe Basin is classified as 55% montane, with vegetation types ranging from high elevation subalpine forests and meadows to Great Basin shrublands, 38% aquatic, and 7% developed land [20]. The climate is described as a Mediterranean continental climate with warm, dry summers and cold, wet winters. The mean annual precipitation ranges from 56 to 144 cm across the basin, with most precipitation falling as snow [21]. Forest soils in the Lake Tahoe Basin are generally derived from granite and have distinct *O* soil strata and sandy loam textures [22].

Our study site selection was based on availability of prior data and the desirability to inform the Lake Tahoe West Restoration Partnership (LTWRP), a collaborative group of stakeholders and the USDA Forest Service Lake Tahoe Basin Management Unit. In this study, we used three 1 ha plots distributed on the western and southern ends of the Lake Tahoe Basin: Barker Pass Road (BP2), Ward Creek (WA38), and Christmas Valley (CV05). These plots were a subset of nine aspen-conifer forest plots previously reported by Berrill et al. [14]. Forest managers decided these three plots were most representative of the landscape managed by the LTWRP.

These plots were rectangular, measuring 142.86 m × 70 m for BP2 and 200 m × 50 m for WA38 and CV05. All aspen with a diameter at breast height (dbh) above 10 cm and conifer trees with a dbh above 20 cm were mapped and had the following information recorded: species, dbh, tree height, and crown base height [18]. Coniferous species on these sites included lodgepole and Jeffrey pine (*Pinus contorta* Douglas ex Loudon var. murrayana (Balf.) Engelm.; *P. jeffreyi* Grev. & Balf.) and white and red fir (*Abies concolor* (Gord. & Glend.) Lindl. ex Hildebr.; *A. magnifica* A. Murr.).

We simulated three thin-from-below cuttings to assess the effects of varying conifer removal, including a light, medium, and heavy cutting, removing conifers up to 36 cm, 56 cm, and 76 cm dbh, respectively. We chose these scenarios in consultation with local land managers to span a range of either implemented or desirable cutting intensities in the Lake Tahoe Basin. In addition to these hypothetical scenarios, we evaluated the impacts of actual treatments that occurred on two of the sites (WA38 and CV05) based on re-inventoried post-treatment field data. These two observed treatments emphasized removing conifers to benefit aspen and lowering fire behavior and effects. The maximum size limit for conifer removal for the observed cutting treatments was 35 cm and 30 cm on sites WA38 and CV05, respectively.

2.2. *Simulated Fire Behavior and Effects on Conifers*

We simulated fire behavior with the Wildland urban-interface Fire Dynamics Simulator (WFDS) version 9977 [23]. WFDS is a physics-based computational model of wildland fire, which extends the Fire Dynamics Simulator (FDS) developed by the National Institute of Standards and Technology [24] to include vegetative fuel. WFDS simulates the spatial and temporal dynamics of wildland fire through the explicit representation of fire-atmosphere-fuel dynamics [25]. This is achieved by implementing computational fluid dynamics methods to solve the conservation of mass, momentum, and energy equations along with models for radiative heat transfer, thermal degradation of fuel, and gas-phase combustion. Wildland fuels are described in the model in three dimensions based on their geometry (e.g., crown base height, width, length, and shape) and their bulk properties (e.g., bulk density, and fuel moisture). Additional references provide model details and verification and validation studies [24,26–34].

We simulated potential fire behavior and effects for each site and cutting intensity under three wind speeds, defined by different inlet open wind speeds. In all simulations, we used an overall domain size measuring 1000 m × 320 m × 100 m in the x, y, and z dimensions, respectively. Similar to other studies using WFDS [35], the domain design (Figure 1) contained four critical parts: (1) a wind development zone located at x = [0, 400] m; (2) an ignition burner at x = [400, 430] m, y = [100, 220] m; (3) our area of interest, defined by the size of the study sites and beginning at x = 500 m; and (4) the outflow zone extending to the outlet at x = 1000 m. The domain was discretized into 2 m^3 cells, except the volume above the area of interest, which was discretized at a 1 m^3 resolution. We parameterized the inlet wind field using a standard logarithmic wind profile with the open wind speed (z = 40 m) as either 6, 12, or 18 m/s representing our low, moderate, and high wind speed scenarios, respectively. The side and top boundaries were simulated as no flux, no slip surfaces, and the outflow boundary was open, allowing free atmospheric exchange into or out of the domain. The bottom boundary was flat (i.e., no slope).

For each simulation, we populated the area of interest with the tree list of a given study site's cutting scenario. We represented conifer and aspen trees as right circular cones and cylinders, respectively, defined by their location, tree height, crown base height, and crown width. Crown width was estimated using dbh-based, species-specific allometry [36,37]. We populated the rest of each simulation's domain with additional trees to ensure the wind fields in our area of interest were representative of analogous forests. Those additional trees were randomly distributed using a log-gaussian Cox point process model fit on the observed aspen and conifer trees within the area of interest [38]. A point process model ensured that the locations of randomly placed trees emulated the tree spatial pattern of measured trees.

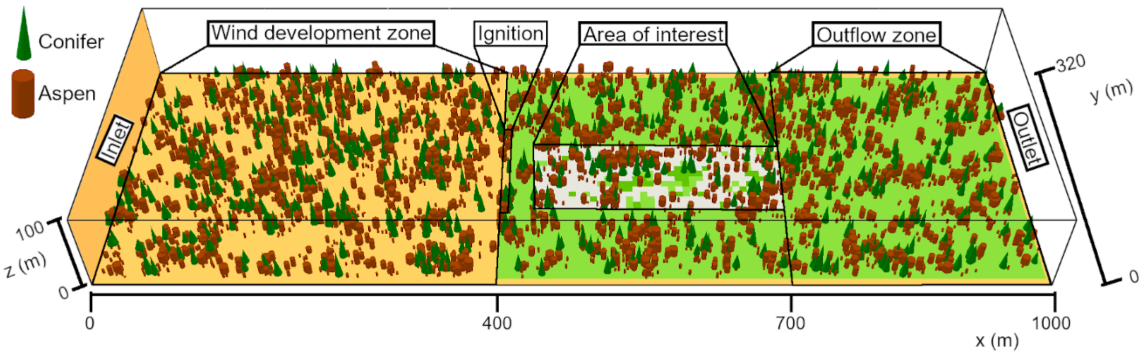

Figure 1. Example Wildland urban-interface Fire Dynamics Simulator domain used in this study, highlighting regions within the domain.

We simulated surface fuels as a heterogeneous mixture of fuelbeds based on the local density of the overstory species composition. These fuelbeds were developed locally for use in the Lake Tahoe Basin [39]. To this end, we first estimated the density of trees within three species categories, aspen (quaking aspen), fir (red fir), or pine (lodgepole pine and white fir), in each 1 m^2 cell using a spatial smoothing algorithm that includes a Gaussian kernel with a standard deviation of 1 m^2 and an edge correction scheme [38]. A fuelbed type exists for Jeffrey pine [39], but no cell was dominated by Jeffrey pine. Next, we categorized each 1 m^2 cell according to whichever category's smoothed density was greatest. Finally, we related each of these categories to a customized fuelbed (Table 1).

Table 1. Surface and fuel parameters used to populate Wildland urban-interface Fire Dynamics Simulator (WFDS) simulations.

Fuel Type/Parameter [1]	Value
Crown	
Foliar moisture content (%)	100
Surface area/Volume (m^{-1})	4000
Drag coefficient	0.25
Bulk density (kg m^{-3})—Aspen	0.19
Bulk density (kg m^{-3})—Lodgepole pine	0.50
Bulk density (kg m^{-3})—Red fir	1.20
Bulk density (kg m^{-3})—White fir	0.70
Surface—All	
Drag coefficient	0.15
Moisture content (%)	6.0
Surface—Aspen	
Surface area/Volume (m^{-1})	5350
Load (kg m^{-2})	0.9
Height (m)	0.07
Surface—Fir	
Surface area/Volume (m^{-1})	6197
Load (kg m^{-2})	2.6
Height (m)	0.16
Surface—Pine	
Surface area/Volume (m^{-1})	8149
Load (kg m^{-2})	1.4
Height (m)	0.10

[1] Surface fuelbed types for aspen, fir, and pine were adapted from LT094 quaking aspen forest, LT032 overmature red fir forest, and LT0044 overmature lodgepole pine, respectively [39], and load includes downed, dead woody fuels 0–0.64 cm in diameter and litter.

We measured mid-flame wind speed, mean rate of fire spread, and total canopy consumption within the area of interest of each simulation. Omitting the simulations on the observed treatments, we assessed the impacts of cutting intensity, wind speed, and their interaction on these three measurements using mixed-effects ANOVAs; sites were included as a random variable. For all tests in this study, $\alpha = 0.05$.

2.3. Effects of Conifer Removal and Fire on Stand Structure

We used individual tree crown consumption as a proxy for mortality, assuming conifers with any amount of crown consumption were killed. Though many factors, including necrosis of tissues, deformation of xylem, and post-fire plant stressors, affect the likelihood of fire-induced tree mortality [40], several studies have suggested that crown consumption is a powerful predictor of conifer mortality [40–42].

We tracked spatially averaged stand metrics and local aspen-centric metrics to investigate the effects of cuttings and subsequent fires on forest structure. First, we examined changes in basal area, trees per hectare, and canopy cover at the stand scale. Canopy cover was calculated as the percent of area occupied by the sum of non-overlapping projected crown areas. Next, to assess local effects of conifer removal on aspen, we calculated the proportion of aspen that have a conifer present within 1.5 tree lengths and the stand density index (SDI) of those conifers. We used mixed-effects ANOVAs, where the dependent variable was the change from pre-fire to post-fire for each of the forest structure metrics. Fixed variables included cutting intensity, wind speed, and their interaction; study site was a random variable.

We conducted our analysis in R v3.2.3 (R Core Team 2016, Vienna, Austria), using packages nlme v3.1-144 for mixed effects ANOVAs [43], spatstat to generate log-gaussian Cox point process models and to assign surface fuels [38], sp to calculate canopy cover [44], ggplot2 for visualizations [45], and tidyverse for data wrangling [46].

3. Results

General Effects of Cutting and Fire

All three sites had a similar basal area before cutting (~50 m^2 ha^{-1}) but differed in their density (341 to 555 trees ha^{-1}) and the proportion and size of conifers present (Table 2). While the light and observed cuttings decreased tree density and increased quadratic mean diameter, other measures of forest structure were not substantially reduced until cutting intensity approached the medium and high levels of conifer removal (Table 2).

In particular, the simulated light cuttings reduced conifer density by 54% and conifer basal area by 24%, averaged across sites. Total canopy cover remained relatively high (51–63%) with conifer cover greater than 25% on all sites. Light cuttings resulted in a marginal reduction in the proportion of aspen with a conifer present within 1.5 tree lengths (1–2%) and reduced conifer SDI near aspen by 23–40%. The observed cutting treatments tended to mirror the light cutting scenarios, although the observed cuttings removed only 31% and 51% of conifers in sites CV05 and WA38, respectively.

In contrast to the light cuttings, the medium cuttings reduced conifer density by 87% (34% more than light cuttings) and conifer basal area by 61% (37% more than light cuttings) averaged across sites. Total canopy cover was reduced to 42–53%, of which conifer cover was 18–27%. Conifers within 1.5 tree lengths were present near 75–93% of aspen across the sites. The SDI of these proximate conifers ranged from 49 to 26 on average, just one-third of pre-treatment local SDI.

Heavy cuttings markedly reduced conifer abundance. After heavy cutting, only 5 to 19 conifers ha^{-1} remained, amounting to only 4% of the original conifers, or 17% of initial conifer basal area, averaged across sites. The average residual canopy cover was around 55% (average conifer canopy was 16%). Conifers were proximate to only half or slightly greater of the aspen, resulting in a local SDI reduced by 60–80% of pre-treatment values.

Table 2. Summary of forest structure and local stocking proximate to aspen pre-cutting; after simulated light (removal of conifers <36 cm dbh), medium (removal of conifers <56 cm dbh), and heavy (removal of conifers <76 cm dbh) cuttings; and in the observed post-treatment cutting. QMD and SDI are quadratic mean diameter and stand density index, respectively.

Site/Cutting Scenario	QMD (cm) [1]		Canopy Height (m) [2]		Basal Area		Tree Density		Canopy Cover (%)		Local Stocking [3]	
	All	Conifer	All	Conifer	All (m^2/ha)	% Conifer	All (ha^{-1})	% Conifer	All	Conifer	Conifer Presence (%)	Conifer SDI
BP2												
Pre-cutting	34.6	36.9	25.4	23.2	52	55	555	48	64	40	89	129
Light	37.5	50	26.2	27.5	42.4	45	385	25	60	30	88	76
Medium	35.8	71.9	26.4	31.4	30.7	24	306	6	53	18	74	26
Heavy	34	89.3	26.2	31.5	26.6	12	293	2	51	15	54	13
CV05												
Pre-cutting	43.8	41.6	29.7	29.4	51.3	51	341	57	65	35	100	134
Light	48.8	52.2	30.3	30.7	45.8	45	245	40	63	29	99	75
Medium	50.3	66.6	30.4	32.4	35.2	29	177	16	57	20	93	37
Heavy	48	81.2	30.3	32.5	27.7	9	153	3	53	14	55	18
Obs. Post	46.4	46.2	29.8	29.9	47	47	278	48	63	31	99	83
WA38												
Pre-cutting	40.5	45.8	27.9	29.7	52.7	85	410	67	56	45	93	96
Light	45.6	58.4	29.6	32.7	45	83	276	50	51	38	91	73
Medium	45.9	78	30.9	36.4	30.7	75	185	26	42	27	89	49
Heavy	41.5	96.8	29.7	37.8	21	63	155	12	36	20	50	37
Obs. Post	45.7	58.3	29.8	32.9	43.1	83	263	51	50	38	88	73

[1] Aspen QMD remained unchanged across cutting scenarios at 32.2, 46.4, and 26.8 cm in BP2, CV05, and WA38, respectively. [2] Average canopy height of aspen, across cutting scenarios, remained unchanged at 26.1, 29.7, and 21.6 m, respectively. [3] Local stocking metrics describe the percent of aspen with conifers present, and their stand density index, within 1.5 tree lengths.

Though all scenarios retained a heterogeneous mixture of fuelbed types, cuttings had a significant impact on surface fuelbed composition (Figure 2). Thirty-two, 45, and 49 percent of the surface fuels were classified as aspen fuelbeds for WA38, BP2, and CV05, respectively, before any treatment. Aspen fuelbeds became the predominant fuel type, as the cutting intensity increased, primarily at the expense of fir (Figure 2). The light and observed cutting scenarios had relatively minor effects on the proportion and patch size of aspen surface fuels. In comparison, the medium and heavy cutting scenarios increased the proportion of aspen fuelbeds by 70 to 90 percent. As fuel loads varied by fuelbed type, cuttings concomitantly reduced the average fuel loads across the study sites (Table 3); light, medium, heavy, and the observed cuttings reduced the average fuel loads by 17%, 33%, 39%, and 11%, respectively.

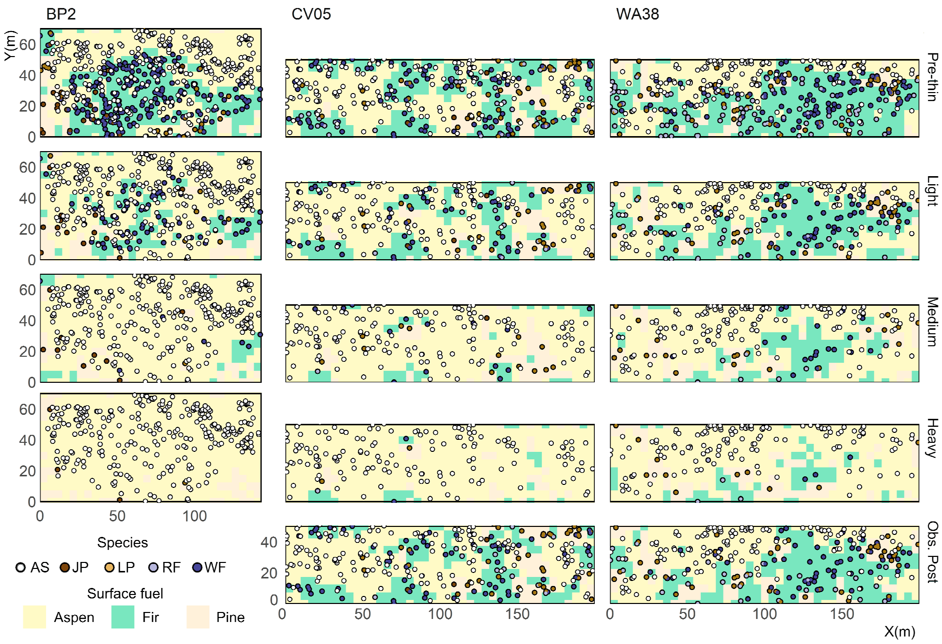

Figure 2. Maps of trees and fuelbed types across three sites (columns) and four scenarios (rows)—pre-treatment, the observed post-cutting, and light and heavy low-cuttings. Trees are colored by species and include quaking aspen (Populus tremuloides; AS), Jeffrey pine (Pinus jeffreyi; JP), red fir (Abies magnifica; RF), and white fir (Abies concolor var. lowiana; WF).

Table 3. Characteristics of surface fuelbeds under varying cutting scenarios.

Site/Cutting	Surface Fuelbed Composition (%)			Average Fuel Load (kg/m^2)
	Aspen	Fir	Pine	
BP2				
Pre-cutting	49	41	11	1.65
Light	69	18	12	1.27
Medium	86	6	8	1.04
Heavy	90	0	10	0.95
CV05				
Pre-cutting	45	43	12	1.69
Light	58	28	14	1.44
Medium	77	10	13	1.13
Heavy	86	6	7	1.04
Obs. Post	52	33	15	1.54
WA38				
Pre-cutting	32	56	12	1.92
Light	43	40	16	1.67
Medium	62	22	16	1.36
Heavy	71	13	16	1.20
Obs. Post	42	40	18	1.67

Fire behavior varied among the cutting and wind speed scenarios. Fire spread across our plots was particularly conditional on within-stand wind speeds. Before cutting, or following cuttings of low intensity, fire spread in sites BP2 and CV05 either ceased or was not uniform (Figure 3). Higher wind speeds facilitated more comprehensive fire spread in these instances. The capacity for a fire to burn throughout the plots under more intense cuttings, despite reductions in fuel load is partly explained by increases in the mid-flame wind speed (Figure 4a). Further reductions in conifer stocking led to higher mid-flame wind speeds as the canopy opened ($F_{1,30}$ = 83.10, $p < 0.001$). There was also an interaction between cutting intensity and mid-flame wind speed; when we simulated fires with higher open wind speeds, greater cutting intensities led to even greater mid-flame wind speeds ($F_{1,30}$ = 18.71, $p < 0.001$). Accordingly, rate of fire spread increased with greater intensity of cutting ($F_{1,30}$ = 45.68, $p < 0.001$), and greater wind speed ($F_{1,30}$ = 79.59, $p < 0.001$); however, there was no clear interaction between intensity of cutting and wind speed ($F_{1,30}$ = 2.64, p = 0.115). Visual inspection of the rate of fire spread shows a tendency for spread rate to slightly diminish under heavy cutting relative to medium cutting. This indicates a crossover point regarding a trade-off between higher mid-flame wind speeds and lower surface fuel load associated with aspen (Figure 4b).

Despite increased mid-flame wind speeds associated with cutting and rate of fire spread, we found the amount of canopy consumption decreased greatly with cutting intensity ($F_{1,30}$ = 58.75, $p < 0.001$), particularly between light and medium cuttings (Figure 4c). This occurred despite slight increases of canopy consumption with greater wind speed ($F_{1,30}$ = 4.2, p = 0.049). Though the effect size was marginal, visual inspection of Figure 4c suggests that greater cutting intensity was more effective at reducing canopy consumption when wind speed increased ($F_{1,30}$ = 3.34, p = 0.077). Last, we note that fire behavior within the observed cuttings was generally similar to either the light cuttings or pre-cutting scenarios.

The effect of fire on conifer mortality varied across cutting and wind speed scenarios (Figure 5). Fires reduced conifer canopy cover least when study sites had been cut more heavily ($F_{1,30}$ = 94.56, $p < 0.001$) or under low wind speeds ($F_{1,30}$ = 4.00, p = 0.050). Further, the effect of cutting intensity depended on wind speed ($F_{1,30}$ = 4.46, p = 0.040); when cuttings were lighter, or in the pre-cutting scenario, canopy consumption increased with greater wind speeds (Figure 5a). When cutting intensity was greater, the magnitude of open wind speed had little effect.

Though fires did reduce conifer cover, particularly following no or light cuttings, conifers were still near quaking aspen. Figure 5b shows that fires slightly reduced the proportion of aspen with local conifer presence; this reduction did not vary with cutting intensity ($F_{1,30}$ = 2.07, p = 0.160) nor did cutting intensity interact with wind speed ($F_{1,30}$ = 0.92, p = 0.344). Only the effect of wind speed was impactful ($F_{1,30}$ = 6.53, p = 0.016) with greater wind speed leading to decreases in post-fire conifer proximate to aspen.

Cutting intensity did, however, influence the local stocking around aspen post-fire (Figure 5c). Fires decreased local SDI most under lighter cuttings ($F_{1,30}$ = 7.84, p = 0.009) and greater wind speeds ($F_{1,30}$ = 6.91, p = 0.013). In addition, local SDI was most impacted by fire in the cases of no or light cutting and when wind speed was greater ($F_{1,30}$ = 9.23, p = 0.005). For all these metrics, the effect of fire after observed cuttings was similar to light cuttings (Figure 5).

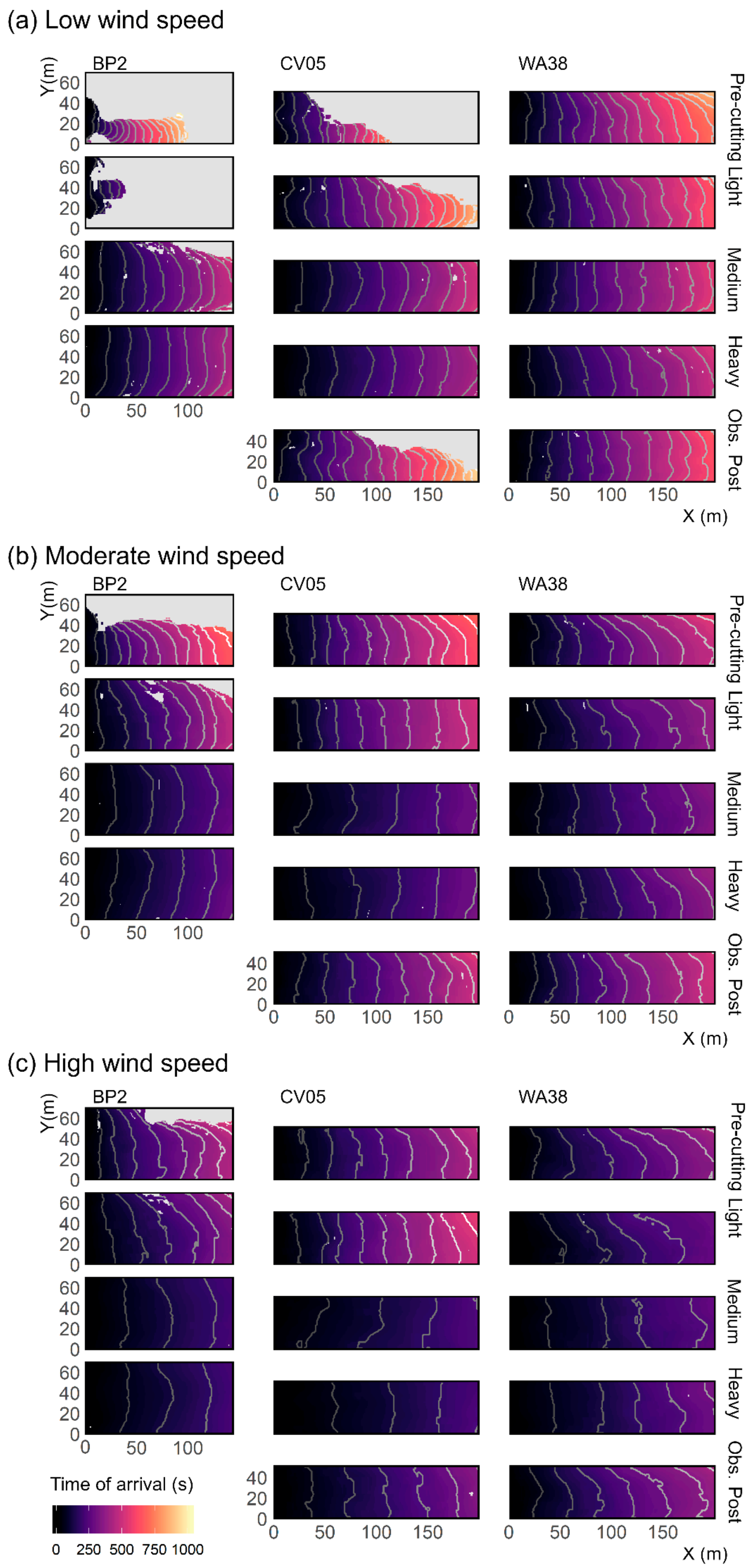

Figure 3. Maps of fire spread (from left to right) among each site and cutting scenario under (**a**) low, (**b**) moderate, and (**c**) high open wind speeds. Contours are time of arrival at 60 s intervals.

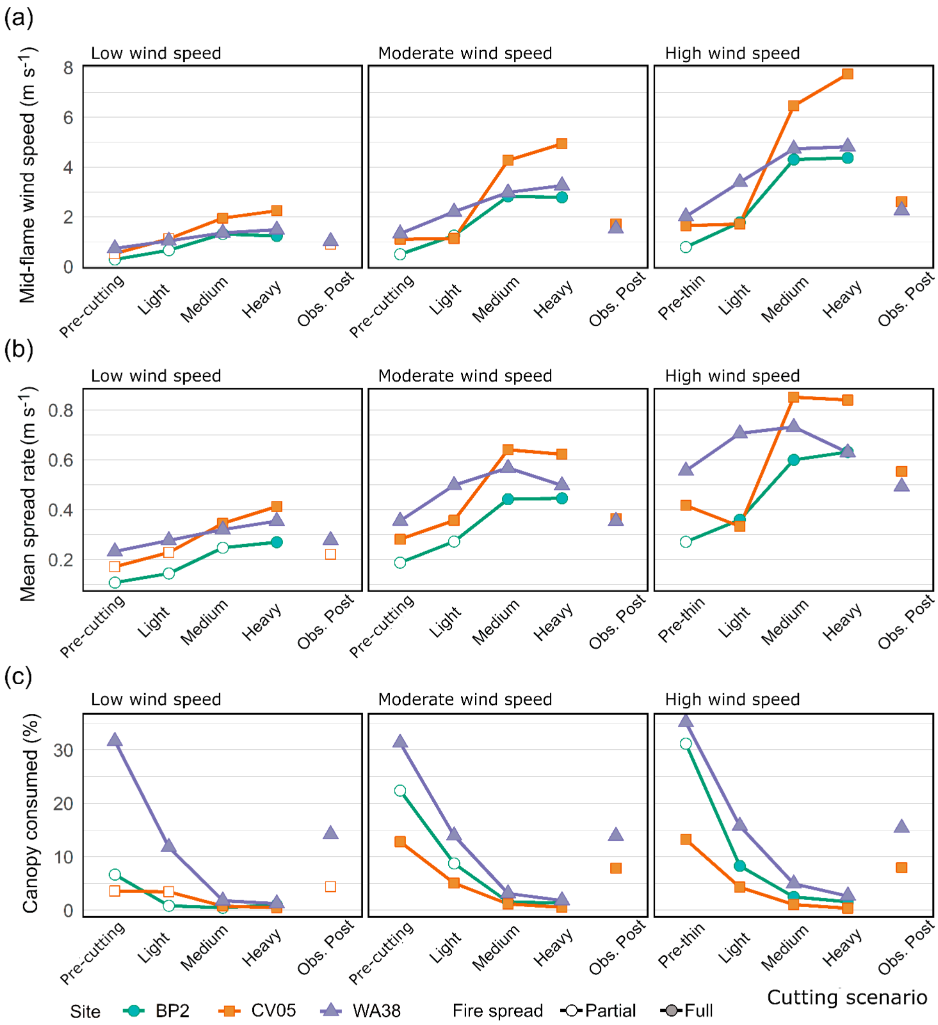

Figure 4. (**a**) Mid-flame wind speed, (**b**) mean rate of spread, and (**c**) percent of canopy consumed by site and open wind speed across five cutting scenarios; hollow and filled points indicate fires partially or fully spread across the study area, respectively.

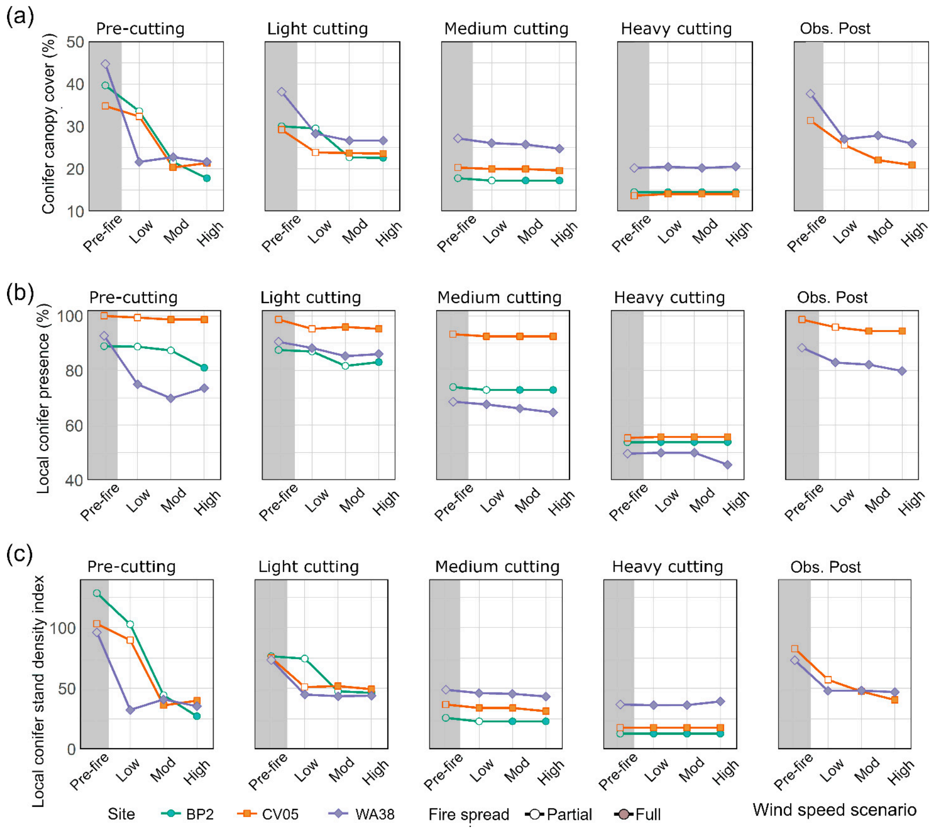

Figure 5. (**a**) Change in canopy cover, (**b**) conifer presence within 1.5 tree lengths around aspen, and (**c**) conifer stand density index within 1.5 tree lengths around aspen before fire and post-fire across open wind speeds and by cutting scenarios; hollow/filled points indicate fire spread was either partially or fully spread across the study area.

4. Discussion

Our results demonstrate how a significant removal of moderate to large conifer trees may promote restoration of aspen by alleviating conifer crowding around aspen and altering fuel and fire behavior. Even though the actual implemented treatments removed one-third to one-half of conifers, substantial changes to stand structure and simulated fires did not manifest until we simulated removal of over 80% of conifers, leaving behind less than c. 50 conifers ha^{-1} or 9 m^2 ha^{-1} basal area. Furthermore, lighter treatments did not meet several rules of thumb for aspen restoration, namely, reducing conifer cover to under 25% and removing conifer trees within 1.5 tree lengths of aspen [7,14,17]. Our results corroborate findings made by others in the Lake Tahoe Basin, which suggest that aspen restoration treatments may better meet desired ecological processes and stand dynamics by raising diameter limits [9,13,18,19].

Fires may be complementary to aspen restoration cuttings by reducing conifer stocking, but the efficacy of fire depends on cutting intensity. Prescribed fire and managed wildfires are seen as a necessary follow-up treatment [47]; cutting competing vegetation alone increases understory light conditions but does not stimulate the suckering of new ramets as effectively as fire [48]. However, fire extinguishment occurred on two out of three sites under low open wind speeds where canopy fuels were untreated or had lighter cuttings. Interestingly, these two sites had a higher proportion of aspen surface fuels and lowest mid-flame wind speeds. These results mirror the burning experiments of Alexander and Sando [12], who found limited fire spread during prescribed fires in aspen-dominated forests. However, as conifer removal increased in our simulations, fires spread fully across our sites. Heavy cuttings were most effective at permitting fire spread, even though the resulting fires did not result in additional changes to forest structure. Fires can provide several benefits beyond controlling tree density, such as nutrient cycling and surface fuel consumption [5], in addition to stimulating aspen suckering [47]. Coupled with reduced conifer competition, these benefits would promote aspen on our study sites while also impacting their surrounding matrix of conifer-dominated stands. Facilitating restorative fire in these stands may also constrain landscape spread of undesirable high-severity fires while adding to landscape biodiversity [5]. Such effects for example were seen in the Sierra Nevada where four decades of managed wildfires resulted in a landscape mosaic of forest cover types, including the creation of aspen-dominated stands [49].

Over the range of pre-cutting to medium intensity cutting, spread rates increased with additional conifer removal. Increased fire rates of spread are a common outcome following fuel treatments because canopy removal reduces the amount of drag imposed on the wind [50]. However, in the simulations, medium and heavy cuttings altered the mode of fire spread to strictly surface fire with little crown consumption regardless of wind speed. This was due in part to (1) increases in the proportion of aspen fuelbed type in the surface fuelbed, (2) very few large conifer trees with tall crown base heights which were unlikely to torch, and (3) predominance of a less-flammable aspen overstory. This tradeoff of the rate of spread and canopy consumption is not apparent in previous fire modeling efforts within stands containing aspen which independently parameterize the fuels complex and fire weather [11]. The interdependency between fire weather and fuels inherent in fuels treatments demonstrates that reduced surface fuel load and higher crown base heights may compensate for more severe fire weather within the canopy [51].

We do not, however, expect widespread applicability of our findings across aspen restoration treatments in all aspen-conifer forests. Firstly, had cuttings removed trees throughout the canopy strata, rather than from below, mid-flame wind speed increases may have been dampened. Though this implies lower fireline intensities, this silvicultural approach would retain lower residual crown base heights and perhaps maintain some crown fire hazard. Secondly, treatments can also result in considerable additions to surface fuel loads when slash remains on site. This is often the case in remote areas [9] and may offset gains in fire behavior reduction [50,51]. Further experiments employing fuel manipulations in these dynamic ecological systems, coupled with physics-based fire modeling, can address the full suite of silvicultural and fuel management options available to managers [25].

4.1. Limitations

Although our study supplied some insight of how the intensity of conifer removal influences stand structure and potential fire behavior and effects, several limitations warrant discussion. First, we utilized a small number of sites (n = 3) in our study; while this did not introduce bias, a broader sample of mixed aspen-conifer stands will increase confidence in extrapolating our results.

Concomitant with the control provided by computational experimentation are decisions on parametrization. As our study was focused on the impact of altered fuels structures on fire behavior, topography was held constant across simulations. We expect that steeper slopes would permit fire spread even under low wind scenarios, leading to increased fire intensity and exaggerating the differences between our cutting scenarios as differences in canopy base heights become a more significant determinant of crown fire activity.

Though our simulations included heterogeneous surface fuels, our fuelbeds were represented using a single set of values for each fuelbed type. This approach is consistent with current operational methods of assessing fire behavior, though it likely resulted in a simplification of the actual spatial and temporal heterogeneity of surface fuels. Additionally, fuel moisture is a particularly important regulator of fire behavior because aspen in the overstory facilitates understory growth whose live fuel moistures can dampen fire behavior [7,52]. As we noted, heavy cuttings had lower rates of spread than medium cuttings because aspen surface fuels were most abundant despite experiencing the highest mid-flame wind speeds. Had we assigned greater fuel moistures to aspen surface fuels, we would have expected to see lower rates of spread after heavy thinning. Lastly, our design captured the expected dynamical turnover of surface fuels associated with conifer removal, though it did not account for any post-cutting slash generated. Leaving such activity fuels on the surface can increase fire behavior and severity, diminishing treatment effectiveness for a period [49]. Research in Sierra Nevada mixed conifer forest suggests activity fuels appreciable decay within seven years of cutting treatments [53]. Thus, our simulations likely underpredicted the short-term potential fire behavior and effects on these sites.

Furthermore, we assumed that post-fire conifer mortality occurred solely as a function of crown consumption. Although this approach inherently simplifies the direct and indirect causes of fire-induced tree mortality [40], previous research has indicated that conifers are likely to die with minimal crown consumption [41,42]. Further development of post-fire tree mortality models which explicitly link species level physiological response to physical properties of heat transfer that can be predicted in physics-based models such as WFDS are needed to allow for a better understanding of linkages between fire behavior and fire effects [54], thus advancing our knowledge of fuel treatment effectiveness [47] and long-term aspen health.

4.2. Future Directions

The use of physics-based modeling such as WFDS has emerged as an important tool for advancing our understanding of the complex processes and feedbacks that drive wildfire dynamics and effects [25,55]. In this study, we used a physics-based model to explore the effect of conifer removal intensity on potential fire behavior and effects across three wind speeds. While previous modeling and empirical studies have identified fire weather, surface fuelbed type, and load as critical factors of fire behavior and effects, the ability to explicitly model their interactions is unique to physics-based fire behavior models [55]. These types of models also allow us to investigate fire behavior and effects using virtual experiments. These experiments can serve as a substitute for real-world studies that would be impossible, too costly, time-consuming, or risky. Moreover, the insights from these models can motivate new, targeted experiments and assist in the interpretation of empirical observations [25]. While physics-based models provide an opportunity for advancing our understanding, it is also essential to continuously compare their results with empirical data so that we understand their limitations and uncertainties. Unfortunately, there appears to be a lack of well quantified empirical data on fire behavior in aspen-dominated forests of the Lake Tahoe Basin and, more broadly, the interior western US. To better understand model performance and advance our understanding of fire behavior and effects in mixed aspen-conifer forests, there is a need for additional documentation of fire behavior through further case studies [56] and new experiments such as those discussed by Hoffman et al. [25].

Author Contributions: Conceptualization, B.M.C., C.M.H., J.W.L., and J.P.Z.; data curation, B.M.C. and C.M.D.; formal analysis, J.P.Z.; funding acquisition, B.M.C. and C.M.H.; investigation, J.P.Z.; methodology, C.M.H. and J.P.Z.; project administration, C.M.H. and J.W.L.; resources, C.M.H. and J.P.Z.; software, C.M.H., W.M. and J.P.Z.; supervision, C.M.H.; validation, C.M.H., W.M., and J.P.Z.; visualization, J.P.Z.; writing—original draft, C.M.H. and J.P.Z.; writing—review and editing, B.M.C., C.M.D., J.W.L., C.M.H., W.M., and J.P.Z. All authors have read and agreed to the published version of the manuscript.

Funding: This work was partially supported by a research partnership between the US Forest Service Pacific Southwest Research Station and UC Berkeley College of Natural Resources (project no. 16-JV-11272167-063), the US Forest Service Pacific Southwest Research Station and Colorado State University (project no. 17-JV-11272138-074), and the US Forest Service Pacific Northwest Research Station and Colorado State University (project no. 19-JV-11261987-085). Funding was also provided from the Lake Tahoe Basin Management Unit and through the Southern Nevada Public Lands Management Act as part of science to support the Lake Tahoe West collaborative restoration project.

Conflicts of Interest: The authors declare no conflict of interest. The funders had no role in the design of the study; in the collection, analyses, or interpretation of data; in the writing of the manuscript; or in the decision to publish the results.

References

1. Di Orio, A.P.; Callas, R.; Schaefer, R.J. Forty-eight year decline and fragmentation of aspen (*Populus tremuloides*) in the South Warner Mountains of California. *For. Ecol. Manag.* **2005**, *206*, 307–313. [CrossRef]
2. Keyser, T.L.; Smith, F.W.; Shepperd, W.D. Trembling aspen response to a mixed-severity wildfire in the Black Hills, South Dakota, USA. *Can. J. For. Res.* **2005**, *35*, 2679–2684. [CrossRef]
3. Shinneman, D.J.; Baker, W.L.; Rogers, P.C.; Kulakowski, D. Fire regimes of quaking aspen in the Mountain West. *For. Ecol. Manag.* **2013**, *299*, 22–34. [CrossRef]
4. St. Clair, S.B.; Cavard, X.; Bergeron, Y. The role of facilitation and competition in the development and resilience of aspen forests. *For. Ecol. Manag.* **2013**, *299*, 91–99. [CrossRef]
5. Hessburg, P.F.; Spies, T.A.; Perry, D.A.; Skinner, C.N.; Taylor, A.H.; Brown, P.M.; Stephens, S.L.; Larson, A.J.; Churchill, D.J.; Povak, N.A.; et al. Tamm Review: Management of mixed-severity fire regime forests in Oregon, Washington, and Northern California. *For. Ecol. Manag.* **2016**, *366*, 221–250. [CrossRef]
6. Larson, A.J.; Churchill, D. Tree spatial patterns in fire-frequent forests of western North America, including mechanisms of pattern formation and implications for designing fuel reduction and restoration treatments. *For. Ecol. Manag.* **2012**, *267*, 74–92. [CrossRef]
7. Shepperd, W.D.; Rogers, P.C.; Bartos, D.L. *Ecology, Biodiversity, Management, and Restoration of Aspen in the Sierra Nevada*; Gen. Tech. Rep. RMRS-GTR-178; United States Department of Agriculture: Fort Collins, CO, USA, 2006; p. 132. [CrossRef]
8. Bartos, D.L. Landscape dynamics of aspen and conifer forests. In Proceedings of the Sustaining Aspen in Western Landscapes Symposium Proceedings, USDA Forest-Service Proceedings RMRS-P-18, Grand Junction, CO, USA, 13–15 June 2000; Volume 13, p. 15.
9. Berrill, J.; Dagley, C.M.; Coppeto, S.A. Predicting treatment longevity after successive conifer removals in Sierra Nevada aspen restoration. *Ecol. Restor.* **2016**, *34*, 236–244. [CrossRef]
10. Krasnow, K.D.; Stephens, S.L. Evolving paradigms of aspen ecology and management: Impacts of stand condition and fire severity on vegetation dynamics. *Ecosphere* **2015**, *6*, 1–16. [CrossRef]
11. DeRose, R.J.; Leffler, A.J. Simulation of quaking aspen potential fire behavior in Northern Utah, USA. *Forests* **2014**, *5*, 3241–3256. [CrossRef]
12. Alexander, M.E.; Sando, R.W. Fire behavior and effects in aspen-northern hardwood stands. In Proceedings of the 10th Conference on Fire and Forest Meteorology, Spokane, WA, USA, 22–24 April 1980; MacIver, D.C., Auld, H., Whitewood, R., Eds.; Canadian Forest Service and Environment Canada: Ottawa, QC, Canada, 1989.
13. Berrill, J.P.; Dagley, C.M. Regeneration and recruitment correlate with stand density and composition in long-unburned aspen stands undergoing succession to conifer in the Sierra Nevada, USA. *For. Res.* **2014**, *3*. [CrossRef]
14. Berrill, J.; Dagley, C.M.; Coppeto, S.A.; Gross, S.E. Curtailing succession: Removing conifers enhances understory light and growth of young aspen in mixed stands around Lake Tahoe, California and Nevada, USA. *For. Ecol. Manag.* **2017**, *400*, 511–522. [CrossRef]
15. Ziegler, J.P.; Hoffman, C.M.; Fornwalt, P.J.; Sieg, C.H.; Battaglia, M.A.; Chambers, M.E.; Iniguez, J.M. Tree regeneration spatial patterns in ponderosa pine forests following stand-replacing fire: Influence of topography and neighbors. *Forests* **2017**, *8*, 391. [CrossRef]
16. Jones, B.E.; Rickman, T.H.; Vazquez, A.; Sado, Y.; Tate, K.W. Removal of encroaching conifers to regenerate degraded aspen stands in the Sierra Nevada. *Restor. Ecol.* **2005**, *13*, 373–379. [CrossRef]
17. Bartos, D.; Campbell, R. Decline of quaking aspen in the Interior West—Examples from Utah. *Rangelands* **1998**, *20*, 17–24.
18. Berrill, J.P.; Dagley, C.M. Geographic patterns and stand variables influencing growth and vigor of Populus tremuloides in the Sierra Nevada (USA). *ISRN For.* **2012**, *2012*, 1–9. [CrossRef]
19. Pierce, A.D.; Taylor, A.H. Competition and regeneration in quaking aspen—white fir (*Populus tremuloides—Abies concolor*) forests in the Northern Sierra. *J. Veg. Sci.* **2010**, *21*, 507–519. [CrossRef]
20. Hymanson, Z.P.; Collopy, M.W. *An Integrated Science Plan for the Lake Tahoe Basin: Conceptual Framework and Research Strategies*; General Technical Reports PSW-GTR-226; U.S. Department of Agriculture: Albany, CA, USA, 2010.
21. WRCC Western Regional Climate Center. Available online: https://wrcc.dri.edu/ (accessed on 1 July 2020).

22. NRCS Soil Survey of the Tahoe Basin Area, California and Nevada. Available online: https://www.nrcs.usda.gov/Internet/FSE_MANUSCRIPTS/california/CA693/0/Tahoe_CA.pdf (accessed on 1 July 2020).
23. Mell, W.E.; Maranghides, A.; McDermott, R.; Manzello, S.L. Numerical simulation and experiments of burning Douglas-fir trees. *Combust. Flame* **2009**, *156*, 2023–2041. [CrossRef]
24. McGrattan, K.; Hostikka, S.; Floyd, J.; Mcdermott, R.; Weinschenk, C.; Overholt, K. *Sixth Edition Fire Dynamics Simulator: User's Guide*; NIST Special Publication 1019; National Institute of Standards and Technology: Washington, DC, USA, 2010. [CrossRef]
25. Hoffman, C.; Sieg, C.; Linn, R.; Mell, W.; Parsons, R.; Ziegler, J.; Hiers, J. Advancing the science of wildland fire dynamics: Using process-based models. *Fire* **2018**, *1*, 32. [CrossRef]
26. Castle, D.; Mell, W.E.; Miller, F.J. Examination of the Wildland-urban interface Fire Dynamics Simulator in modeling of laboratory-scale surface-to-crown fire transition. In Proceedings of the 8th US National Combustion Meeting, Park City, UT, USA, 19–22 May 2013; Volume 4, pp. 3710–3722.
27. Hoffman, C.M.M.; Canfield, J.; Linn, R.R.R.; Mell, W.; Sieg, C.H.H.; Pimont, F.; Ziegler, J. Evaluating crown fire rate of spread predictions from physics-based models. *Fire Technol.* **2016**, *52*. [CrossRef]
28. Mueller, E.; Mell, W.; Simeoni, A. Large eddy simulation of forest canopy flow for wildland fire modeling. *Can. J. For. Res.* **2014**, *44*, 1534–1544. [CrossRef]
29. Mueller, E.; Skowronski, N.; Clark, K.; Kremens, R.; Gallagher, M.; Thomas, J.; El Houssami, M.; Filkov, A.; Butler, B.; Hom, J.; et al. Initial results from a field experiment to support the assessment of fuel treatment effectiveness in reducing wildfire intensity and spread rate. In Proceedings of the Large Wildland Fires Conference, General Technical Reports RMRS-P-73. USDA Forest Service Rocky Mountain Research Station, Fort Collins, CO, USA, 19–23 May 2014; pp. 305–308.
30. Sánchez-Monroy, X.; Mell, W.; Torres-Arenas, J.; Butler, B.W. Fire spread upslope: Numerical simulation of laboratory experiments. *Fire Saf. J.* **2019**, *108*, 102844. [CrossRef]
31. Terrei, L.; Lamorlette, A.; Ganteaume, A. Modelling the fire propagation from the fuel bed to the lower canopy of ornamental species used in wildland-urban interfaces. *Int. J. Wildl. Fire* **2019**, *28*, 113–126. [CrossRef]
32. Morandini, F.; Santoni, P.A.; Tramoni, J.B.; Mell, W.E. Experimental investigation of flammability and numerical study of combustion of shrub of rockrose under severe drought conditions. *Fire Saf. J.* **2019**, *108*, 102836. [CrossRef]
33. Mell, W.; Jenkins, M.A.; Gould, J.; Cheney, P. A physics-based approach to modelling grassland fires. *Int. J. Wildl. Fire* **2007**, *16*, 1–22. [CrossRef]
34. McGrattan, K.; Hostikka, S.; Mcdermott, R.; Floyd, J.; Weinschenk, C.; Overholt, K.; Hostikka, S.; Floyd, J.; Mcdermott, R.; Floyd, J.; et al. *Fire Dynamics Simulator Technical Reference Guide: Validation*; Nist Special Publication 1018-6; National Institute of Standards and Technology: Washington, DC, USA, 2010; Volume 3.
35. Ziegler, J.P.; Hoffman, C.; Battaglia, M.; Mell, W. Spatially explicit measurements of forest structure and fire behavior following restoration treatments in dry forests. *For. Ecol. Manag.* **2017**, *386*, 1–12. [CrossRef]
36. Gill, S.J.; Biging, G.S.; Murphy, E.C. Modeling conifer tree crown radius and estimating canopy cover. *For. Ecol. Manag.* **2000**, *126*, 405–416. [CrossRef]
37. Bechtold, W.A. Largest-crown-width prediction models for 53 species in the Western United States. *West. J. Appl. For.* **2004**, *19*, 245–251. [CrossRef]
38. Baddeley, A.; Rubak, E.; Turner, R. *Spatial Point Patterns: Methodology and Applications with R*; Chapman and Hall/CRC: Boca Raton, FL, USA, 2015. [CrossRef]
39. Ottmar, R.D.; Safford, H. *FCCS Fuelbeds for the Lake Tahoe Basin Management Unit: Final Report P018*; USDA Forest Service Pacific Northwest Research Station: Incline Village, NV, USA, 2011.
40. Hood, S.M.; Varner, J.M.; Van Mantgem, P.; Cansler, C.A. Fire and tree death: Understanding and improving modeling of fire-induced tree mortality. *Environ. Res. Lett.* **2018**, *13*, 113004. [CrossRef]
41. Fowler, J.F.; Sieg, C.H.; McMillin, J.; Allen, K.K.; Negrón, J.F.; Wadleigh, L.L.; Anhold, J.A.; Gibson, K.E. Development of post-fire crown damage mortality thresholds in ponderosa pine. *Int. J. Wildl. Fire* **2010**, *19*, 583–588. [CrossRef]
42. Sieg, C.H.; McMillin, J.D.; Fowler, J.F.; Allen, K.K.; Negron, J.F.; Wadleigh, L.L.; Anhold, J.A.; Gibson, K.E. Best predictors for postfire mortality of ponderosa pine trees in the Intermountain West. *For. Sci.* **2006**, *52*, 718–728. [CrossRef]
43. Pinheiro, J.; Bates, D.; DebRoy, S.; Sarkar, D. R Core Team. nmle: Linear and Nonlinear Mixed Effects Models. 2020. Available online: https://CRAN.R-project.org/package=nlme (accessed on on 1 July 2020).

44. Pebesma, E.J.; Bivand, R.S. Classes and methods for spatial data in R. *R News* **2005**, *5*, 9–13.
45. Wickham, H. *ggplot2: Elegant Graphics for Data Analysis*; Springer: New York, NY, USA, 2016. [CrossRef]
46. Wickham, H.; Averick, M.; Bryan, J.; Chang, W.; McGowan, L.D.; François, R.; Grolemund, G.; Hayes, A.; Henry, L.; Hester, J.; et al. Welcome to the tidyverse. *J. Open Source* **2019**, *4*. [CrossRef]
47. Krasnow, K.D.; Halford, A.S.; Stephens, S.L. Aspen restoration in the eastern Sierra Nevada: Effectiveness of prescribed fire and conifer removal. *Fire Ecol.* **2012**, *8*, 104–118. [CrossRef]
48. Shepperd, W.D.; Bartos, D.L.; Mata, S.A. Above- and below-ground effects of aspen clonal regeneration and succession to conifers. *Can. J. For. Res.* **2001**, *31*, 739–745. [CrossRef]
49. Boisramé, G.F.S.; Thompson, S.E.; Kelly, M.; Cavalli, J.; Wilkin, K.M.; Stephens, S.L. Vegetation change during 40 years of repeated managed wildfires in the Sierra Nevada, California. *For. Ecol. Manag.* **2017**, *402*, 241–252. [CrossRef]
50. Reinhardt, E.D.; Keane, R.E.; Calkin, D.E.; Cohen, J.D. Objectives and considerations for wildland fuel treatment in forested ecosystems of the interior western United States. *For. Ecol. Manag.* **2008**, *256*, 1997–2006. [CrossRef]
51. Agee, J.K.; Skinner, C.N. Basic principles of forest fuel reduction treatments. *For. Ecol. Manag.* **2005**, *211*, 83–96. [CrossRef]
52. Brown, J.K.; Simmerman, D.G. *Appraising Fuels and Flammability in Western Aspen: A Prescribed Fire Guide*; Technical Report INT-205; USDA Forest Service Intermountain Reserch Station, U.S. Department of Agriculture: Ogden, UT, USA, 1986; p. 48.
53. Stephens, S.L.; Collins, B.M.; Roller, G. Fuel treatment longevity in a Sierra Nevada mixed conifer forest. *For. Ecol. Manag.* **2012**, *285*, 204–212. [CrossRef]
54. O'Brien, J.J.; Hiers, J.K.; Varner, J.M.; Hoffman, C.M.; Dickinson, M.B.; Michaletz, S.T.; Loudermilk, E.L.; Butler, B.W. Advances in mechanistic approaches to quantifying biophysical fire effects. *Curr. For. Rep.* **2018**, *4*, 161–177. [CrossRef]
55. Parsons, R.; Linn, R.; Pimont, F.; Hoffman, C.; Sauer, J.; Winterkamp, J.; Sieg, C.; Jolly, W. Numerical investigation of aggregated fuel spatial pattern impacts on fire behavior. *Land* **2017**, *6*, 43. [CrossRef]
56. Alexander, M.E.; Thomas, D.A. Wildland fire behavior case studies and analyses: Other examples, methods, reporting stands, and some practical advice. *Fire Manag. Today* **2003**, *63*, 4–12.