


Communication

# Chronosequence of Fuel Loading and Fuel Depth Following Forest Rehabilitation Frill Treatment of Tanoak to Release Douglas-Fir: A Case Study from Northern California

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**Abstract:** There is concern that forest management activities such as chemical thinning may increase hazardous fuel loading and therefore increase risk of stand-replacing wildfire. Chemical thinning, often accomplished by frill treatment of unwanted trees, leaves trees standing dead for a time before they fall and become surface fuels. In coastal northern California, frill treatment is used as a forest rehabilitation treatment that removes tanoak (*Notholithocarpus densiflorus*) to release merchantable conifers from excessive competition. We studied fuel bed depth and fuel loading after frill treatment of tanoak along a 16-year chronosequence that substituted space for time. The total depth of fuel bed was separated into woody fuels, litter, and duff. The height of each layer was variable and greatest on average in post-treatment year 5 after treated tanoak had begun to break apart and fall. Initially, the evergreen tanoak trees retained their foliage for at least a year after treatment. Five years after treatment, many tanoak had fallen and transitioned to become fine- and coarse woody debris. After 11 years, the larger pieces of down wood were mostly classified as rotten. After 16 years, the fuel loading appeared roughly equivalent to pre-treatment levels, however we did not explicitly test for differences due to potential confounding between time and multiple factors such as inter-annual climate variations and site attributes. Nevertheless, our data provide some insight into changes in surface fuel characteristics due to rehabilitation treatments. These data can be used as inputs for fire behavior modeling to generate indicative predictions of fire effects such as fire severity and how these change over time since treatment.

**Keywords:** chemical thinning; fire behavior; forest restoration; fuel model; imazapyr; *Notholithocarpus densiflorus*; *Pseudotsuga menziesii*; surface fuels; wildfire

## 1. Introduction

With recent increase in the occurrence of wildfire across the Southwestern United States, it would be helpful to understand how forest management practices can alter wildfire hazards [1]. Of particular relevance are changes in surface fuels due to forest management because surface fuels are an important driver of fire behavior [2,3]. Additionally of interest is how these surface fuels might increase or decrease over the years following forest management disturbances such as partial harvesting or chemical thinning [4], especially when harvest residues are left in the forest [5]. This information would help us develop a time series of fuel loading for use in fire behavior modeling, allowing us to identify forest management interventions that result in sustained wildfire hazard mitigation [6].

Little is known about forest fuel dynamics and the associated wildfire hazard in the dry forests of California's Coast Range. Here, coastal Douglas-fir (*Pseudotsuga menziesii* var. *menziesii*) forests

are widespread, but have a history of conifer harvesting that allowed hardwoods of little commercial value to dominate [7]. Restoration treatments are being implemented throughout the region, mainly on industrial timberlands [8]. A common forest rehabilitation treatment being implemented on a large scale is herbicide frill treatment of unwanted hardwoods [9]. This herbicide stem-injection treatment kills hardwoods to release residual conifers from competition, allowing them to grow rapidly, and does not require the cumbersome permitting and other fixed costs associated with commercial conifer harvest [4]. Another common rehabilitation treatment involves partial harvesting of merchantable conifer combined with herbicide frill treatment of unwanted hardwoods. This treatment enhances growth of residual conifers and generates revenue to offset costs of reducing the density of unwanted hardwoods such as tanoak (*Notholithocarpus densiflorus*) [8]. Without herbicide treatment, the shade-tolerant stump-sprouting tanoak quickly re-occupies available growing space and competes with conifer trees and regeneration [10–12]. The resultant change in species composition leaves these forests crowded with live, dead, and dying trees and advance regeneration of hardwoods collectively comprising hazardous surface and ladder fuels. Changes in species composition will also alter the litter layer. Douglas-fir needles are short and fall individually, resulting in compact litter. Dry tanoak litter can form a deeper and more porous litter layer. Douglas-fir and tanoak litter decomposes to 5% of the original dry weight in 7 and 9 years, respectively [13]. Additional information is needed on dynamics of woody surface fuels with and without common forest management interventions such as frill treatment of hardwoods.

Herbicide frill treatment of tanoak and other unwanted hardwoods is currently most effective when using the forestry herbicide imazapyr [14]. Treated tanoak can remain standing for many years after being killed. After treatment, the evergreen hardwoods retain their brown, dead foliage for upwards of a year [15]. Next, after the leaves fall, progressively larger twigs and branches break and fall. Eventually entire stems break and fall, becoming surface fuels. It is common for tanoak stems to break around breast height where the frill treatment axe cuts appear to physically weaken the stem and provide an entry point for wood-decomposing fungi (Figure 1). However, the timeline for breakdown and decomposition of these surface fuels has not been reported [9].



**Figure 1.** Fallen tanoak stems originating from stump sprout clumps, five years after forest rehabilitation frill treatment and enrichment planting of coast redwood (*Sequoia sempervirens*) outside its natural range to supplement natural regeneration of Douglas-fir seeding in from forest edge in background.

## 2. Materials and Methods

### 2.1. Site Description

We studied surface fuels along a single chronosequence at two sites 26 km apart on the California Coast Range in Humboldt County. The two sites have similar climate, topography (i.e., upper slope and ridge), vegetation, elevation (665 vs. 870 m a.s.l.), and distance from the Pacific Ocean (28 vs. 25 km). The climate is Mediterranean, with cool wet winters and warm dry summers. At this distance from the coast, there is less coastal fog and therefore higher summer temperatures and more frequent fire, especially on ridges and at higher elevations due to lightning ignitions. These areas had been historically burned throughout the year by Native Americans until the mid-1860s. Before active fire suppression in the 1900s and early 2000s, fire intervals varied from 10–16 years [13]. These Douglas-fir/tanoak forests were 40–45 years old at the time of sampling. The understory was dominated by evergreen huckleberry (*Vaccinium ovatum*), salal (*Gaultheria shallon*), and poison oak (*Toxicodendron diversilobum*).

At Lupton Creek (40°53'50.29" N, 123°49'36.77" W), we sampled surface fuels in two no-treatment control areas representing pre-treatment fuel loads (basal area 34 m<sup>2</sup>/ha and 26 cm average diameter at breast height (DBH)). We also sampled surface fuels in two adjacent areas within 12 months after partial harvesting of conifers and frill treatment of hardwoods (basal area 22 m<sup>2</sup>/ha and 36 cm DBH, excluding treated hardwoods) (Figure 2). At Little Pine Creek (41°8'14.08" N, 123°50'56.50" W), we studied fuels in three stands that received rehabilitation frill treatment in 2002, 2007, and 2013 (i.e., 5-, 11-, and 16 years after frill treatment) (Figure 3). Average residual tree size was similar at both sites, but the rehabilitation hardwood frill treatments were implemented without commercial conifer harvest at Little Pine Creek because there was not enough conifer basal area for harvest (i.e., conifer basal area <23 m<sup>2</sup>/ha).



**Figure 2.** Prolonged retention of dead foliage on hardwoods standing dead after frill treatment and down hardwoods cut by feller buncher during partial harvest of Douglas-fir 12 months earlier at Lupton Creek.



**Figure 3.** Chronosequence of surface fuels after frill treatment of tanoak at Little Pine Creek.

At Lupton Creek, we installed 10-m Brown's planar intercept transects [16] oriented at randomly-selected cardinal directions (N, S, E, or W) that all terminated at one randomly-selected corner of a 0.2-ha square fixed-area forest inventory plot. The two no-treatment control plots each had three transects for a total of six transects. The treatment plots had 2–3 transects for a total of five transects. At Little Pine Creek, we installed five 10-m Brown's fuel transects in each stand at random start locations with random azimuth, giving fuel depth and loading for a single stand that underwent rehabilitation frill treatment in 2002, a second stand treated in 2007, and a third stand treated in 2013, for a total of 15 transects. Fuels data were collected in autumn of 2018.

## 2.2. Fuel Loading Conversion

The Brown's transect woody fuels data were converted to tons per acre using Equation (1):

$$\text{Fuel Loading} = \frac{(11.64 \times n \times d^2 \times s \times a \times c)}{L} \quad (1)$$

where  $n$  is the total number of fuel intersections over all sample points,  $d^2$  is the squared average diameter (in<sup>2</sup>) of 1000-hr fuel pieces (Equation (2)),  $c$  is the slope correction factor (Equation (3)),  $a$  is the non-horizontal angle correction factor,  $s$  is the specific gravity of the materials, and  $L$  is the length of the transect (ft) [16].

$$d^2 = \frac{\sum (DBH^2)}{n} \quad (2)$$

$$c = \sqrt{1 + \left(\frac{\%Slope}{100}\right)^2} \quad (3)$$

To calculate litter and duff loadings, the average depth was multiplied by the bulk density of litter (2.75 lbs/ft<sup>3</sup>) or duff (5.5 lbs/ft<sup>3</sup>), and converted to tons/acre [16] using Equation (4):

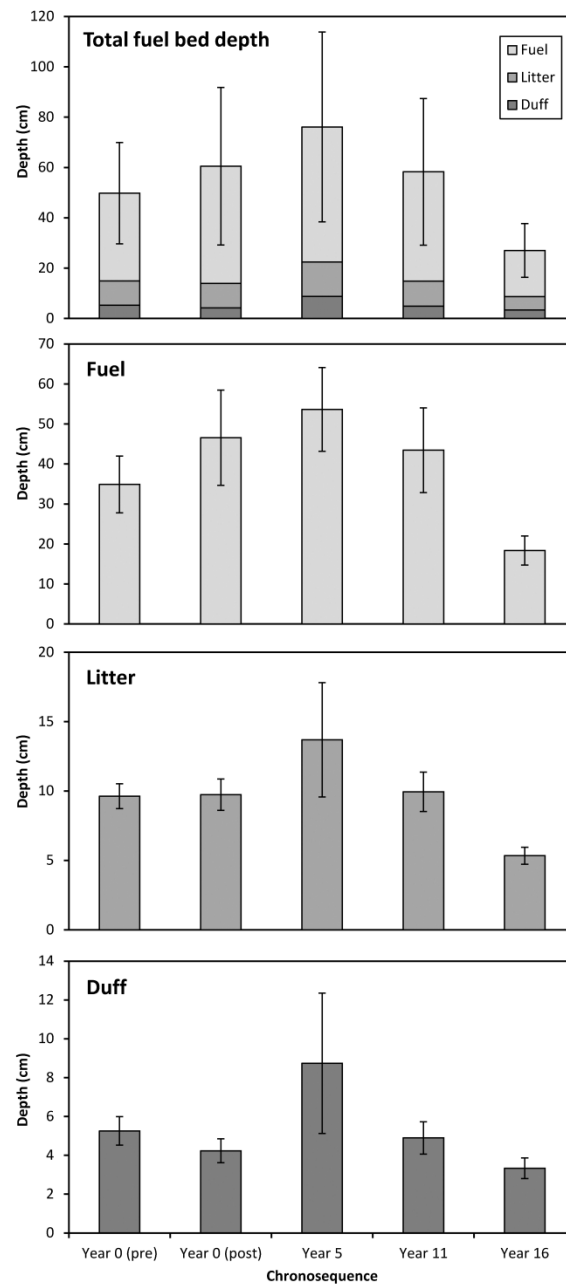
$$\text{Fuel loading} = \text{avg.depth(in.)} \times (\text{bulk density} \left(\frac{\text{lb}}{\text{ft}^3}\right) \left(\frac{1\text{ft}}{12\text{in}}\right) \left(\frac{1\text{ton}}{2000\text{lb}}\right) \left(\frac{43560\text{ft}^2}{1\text{acre}}\right)) \quad (4)$$

The tons per acre values (English units; Appendix A, Table A1) which are used for fire and fuels modeling in the USA were converted to tons per hectare for publication. Then, for all fuels transects representing each time point in the chronosequence, we calculated the mean and standard error by fuel size class and type. Sample size for standard error calculations was  $n = 5$  (or  $n = 6$  for no-treatment control plots) for fuel loading, and  $n = 15$  (or  $n = 18$  for controls) for fuel depth measured at three points along each transect.

## 3. Results

### 3.1. Fuel Depth

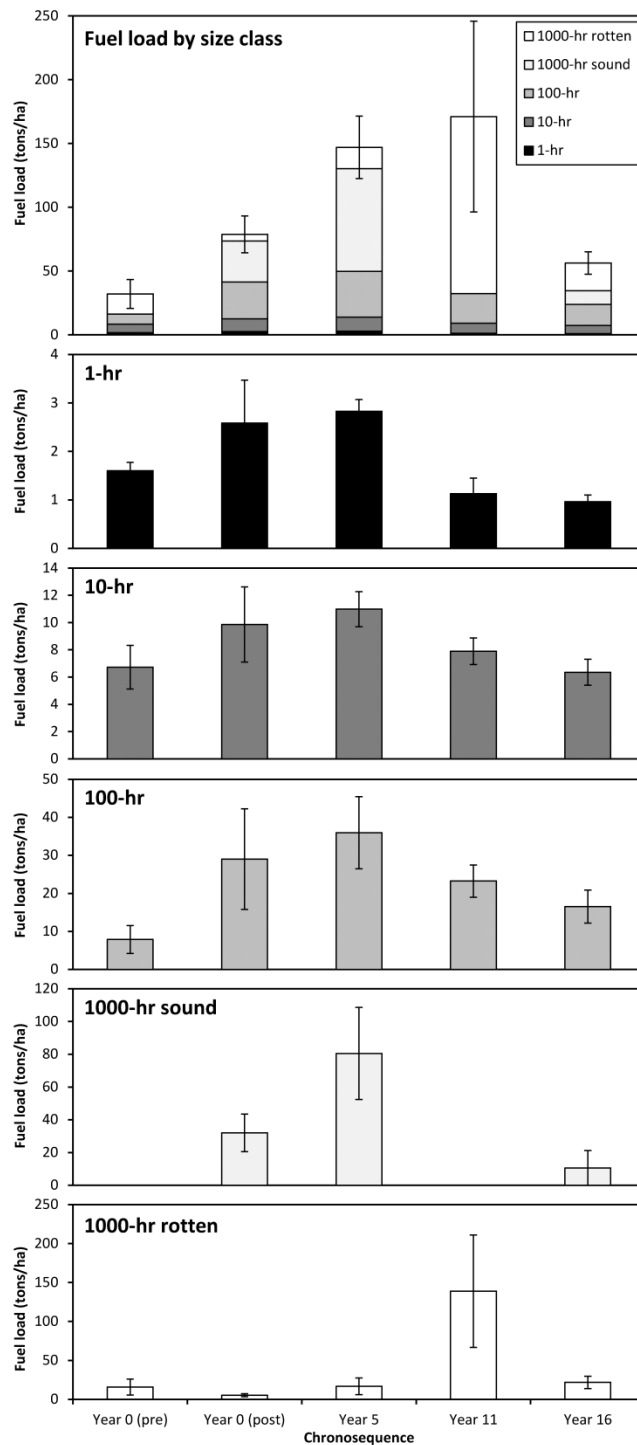
The depth of fuels was lower immediately after partial harvesting than before harvest. In the rehabilitation stands receiving herbicide frill treatment, fuel bed depth was greatest in post-treatment year 5, then lower in year 11, and lowest in year 16 (Figure 4).



**Figure 4.** Average fuel bed depth for duff, litter and woody fuels combined, and separately, showing means and standard errors for each stage in chronosequence: pre-treatment and post-treatment year 0 (partial harvest and frill treatment) at Lupton Creek, and year 5, 11, and 16 after frill treatment rehabilitation treatments (no harvest) at Little Pine Creek.

### 3.2. Fuel Loading

The average fuel loading for all transects was much greater in year 5 than immediately pre- or post-treatment. Fuel loading was greatest at post-treatment year 11. In year 16, the average fuel loading was higher than pre-treatment but lower than the post-treatment year-0 fuel load. The representation of 1-h, 10-h, 100-h and 1000-h fuels changed at each time point in the chronosequence. The loading of heavier fuels was greatest in year 5. After this time, the 1000-h fuels appeared to transition rapidly from sound to rotten. However, large standard errors indicated that fuel loading varied spatially and temporally (Figure 5).



**Figure 5.** Average fuel loading for all size classes combined, and separated by fuel size class, showing means and standard errors for each stage in chronosequence: pre-treatment and post-treatment year 0 (partial harvest and frill treatment) at Lupton Creek, and year 5, 11, and 16 after frill treatment rehabilitation treatments (no harvest) at Little Pine Creek.

#### 4. Discussion

The forest rehabilitation frill treatment chronosequence exhibited a rise-peak-fall in surface fuels of all types and size classes over a 16-year period. We did not record associated forest inventory data showing how the treatment introduced space between residual conifer tree crowns, shifted species composition from tanoak to Douglas-fir dominance, and initiated a patchy new cohort of

natural regeneration. In combination with surface fuel load, these factors will interact to modify fire behavior and fire effects. Widely-spaced Douglas-fir are less likely to carry active crown fire [17]. The fire-resistant bark of Douglas-fir and other conifers will thicken as the trees respond to release and grow larger [18,19], making them more likely to survive fire. As the new cohort develops, it will come to represent ladder fuels that could allow fire to climb into the main canopy [20–22]. Tending of the new cohort may be adopted to release these trees from competition and allow them to grow larger and more resistant over time [23]. These simultaneous changes in fuels and forest structure must be quantified to support modeling of fire behavior and fire effects following forest rehabilitation.

There was rapid treefall and decay in the warm moist coastal climate. Much longer treefall and decay times have been reported elsewhere, and there are differences among species and according to treatment/disturbance. After partial harvesting in Ontario, Canada, white pine (*Pinus strobus*) and red pine (*P. resinosa*) snags had median fall times of 15–20 and 30 years, respectively, and trees that fell at death decayed more quickly (~55–60 years) than trees that died standing (~90 years) [24]. After wildfire in Idaho, USA, ponderosa pine (*P. ponderosa*) snags fell sooner than Douglas-fir (*Pseudotsuga menziesii*) snags, with time taken to fall reported in terms of ‘half-lives’ of 9–10 years and 15–16 years, respectively; post-fire salvage logging resulted in a roughly 20% shorter half-life [25]. In the Sierra Nevada Mountains of California, USA, conifer snags had lost all needles and twigs, and 75% of pines and 66% of true firs had lost most larger limbs, within five years of death; larger snags took longer to fall than smaller snags [26]. In Maine, USA, hardwood snags in decay class 4 (i.e., no structural integrity; bark detached or absent) averaged 9–12 years since death [27]. Throughout the eastern USA, conifer coarse wood debris decayed more slowly than hardwood, with average residence times of 57 to 124 years for conifers and from 46 to 71 years for hardwoods [28]. When compared against our data, these findings indicate that tanoak treefall and decay is relatively rapid after the rehabilitation frill treatment on California’s north coast where warm moist conditions favor decomposition [29].

The main limitation of our study was the lack of replication in our space-for-time substitution chronosequence. This prevented us from testing for differences in surface fuels at different times since treatment. It also prevents us from making inferences about the timing of any peak in surface fuel loading or fuel bed depth because it may have been by chance that we encountered more or less fuels (with more/less decay) at each site. The spatial heterogeneity of forest fuels is well known, and can prevent detection of significant differences among treatments and over time in well-replicated chronosequence studies [30,31]. Therefore we advise caution when interpreting our data, and recommend collecting additional transect data to validate or amend our findings. In the meantime, our limited data represent the best available information for surface fuels resulting from frill treatment of tanoak to restore conifer dominance in the Coast Range forests of northern California.

## 5. Conclusions

Forest rehabilitation frill treatments caused surface fuel depths and fuel loading to rise, peak, then fall within <20 years. Fuel bed depth and loading of the finer fuel size classes peaked around five years after treatment. Standard errors for fuel depth and the loading of larger fuel size classes indicated that fuel depth and fuel loading exhibited high spatial variability within each stand.

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**Conflicts of Interest:** The authors declare no conflicts of interest.



## Appendix A

**Table A1.** Average fuel loading for each time point in English units (tons/acre) formatted for entry into fire models.

	Duff	Litter	1-h	10-h	100-h	1000-h sound	1000-h rotten	Total
Year 0 (pre)	20.66	18.93	0.65	2.72	3.20	0.00	6.40	12.97
Year 0 (post)	16.64	19.13	1.05	3.99	11.75	12.98	2.11	31.87
Year 5	34.34	26.92	1.15	4.45	14.55	32.60	6.77	59.51
Year 11	19.23	19.53	0.46	3.20	9.41	0.00	56.20	69.26
Year 16	13.11	10.48	0.39	2.57	6.71	4.30	8.84	22.81

## References

1. Skinner, C.N.; Abbott, C.S.; Fry, D.L.; Stephens, S.L.; Taylor, A.H.; Trouet, V. Human and climatic influences on fire occurrence in California's North Coast Range, USA. *Fire Ecol.* **2009**, *5*, 76–99. [[CrossRef](#)]
2. Agee, J.K. *Fire Ecology of Pacific Northwest Forests*; Island Press: Washington, DC, USA, 1993.
3. Sugihara, N.G.; Van Wagendonk, J.W.; Shaffer, K.E.; Fites-Kaufman, J.; Thode, A.E. *Fire in California's Ecosystems*; University of California Press: Berkeley, CA, USA, 2006.
4. Berrill, J.-P.; Boston, K. Conifer retention and hardwood management affect interplay between harvest volume and carbon storage over 100 years in Douglas-fir/tanoak: A case study. *Math. Comp. For. Nat. Res. Sci.* **2019**, *11*, 286–293.
5. Berrill, J.-P.; Han, H.-S. Carbon, harvest yields, and residues from restoration in a mixed forest on California's Coast Range. *For. Sci.* **2017**, *63*, 128–136. [[CrossRef](#)]
6. Dagley, C.M.; Berrill, J.-P. *The Coast Range Dry Forest Restoration Experiment*; Unpublished Final Report; California Department of Forestry and Fire Protection as part of the California Climate Investments Program: Sacramento, CA, USA, 2020; 12p.
7. Sawyer, J.O.; Gray, J.; West, G.J.; Thornburgh, D.A.; Noss, R.F.; Engbeck, J.H., Jr.; Marcot, G.E.; Raymond, R. *The Redwood Forest: History, Ecology, and Conservation of the Coast Redwoods*; Chapter 2: History of Redwood and Redwood Forests. pp. 7–37; Noss, R.F., Ed.; Island Press: Washington, DC, USA, 2000; 339p.
8. Berrill, J.-P.; Howe, R.A. Multiaged redwood responds well to partial harvest and herbicide treatments. *Can. J. For. Res.* **2019**, *49*, 1425–1433. [[CrossRef](#)]
9. Valachovic, Y.S.; Lee, C.A.; Scanlon, H.; Varner, J.M.; Glebocki, R.; Graham, B.D.; Rizzo, D.M. Sudden oak death-caused changes to surface fuel loading and potential fire behavior in Douglas-fir-tanoak forests. *For. Ecol. Manag.* **2011**, *261*, 1973–1986. [[CrossRef](#)]
10. Radosovich, S.R.; Passof, P.C.; Leonard, O.A. Douglas-fir release from tanoak and Pacific madrone competition. *Weed Sci.* **1976**, *24*, 144–145. [[CrossRef](#)]
11. Harrington, T.B.; Tappeiner, J.C., II. Growth responses of young Douglas-fir and tanoak 11 years after various levels of hardwood removal and understory suppression in southwestern Oregon, USA. *For. Ecol. Manag.* **1997**, *96*, 1–11. [[CrossRef](#)]
12. Harrington, T.B. Long-term effects of tanoak competition on Douglas-fir stand development. *Can. J. For. Res.* **2009**, *39*, 765–776. [[CrossRef](#)]
13. Stephens, S.L.; Martin, R.E.; Clinton, N.E. Prehistoric fire area and emissions from California's forests, woodlands, shrublands, and grasslands. *For. Ecol. Manag.* **2007**, *251*, 205–216. [[CrossRef](#)]
14. Minogue, P.J. Introduction to imazapyr herbicide for forest vegetation management in California. *Proc. For. Veg. Manag. Conf.* **1997**, *18*, 1–7.
15. Kuljian, H.; Varner, J.M. The effects of sudden oak death on foliar moisture content and crown fire potential in tanoak. *For. Ecol. Manag.* **2010**, *259*, 2103–2110. [[CrossRef](#)]
16. Brown, J.K. *Handbook for Inventorying Downed Woody Material*; USDA Tech. Rep. INT-I6; Ogden, UT, USA, 1974; 24p.
17. Agee, J.K.; Skinner, C.N. Basic Principles of Forest Fuel Reduction Treatments. *For. Ecol. Manag.* **2005**, *211*, 83–96. [[CrossRef](#)]
18. Zeibig-Kichas, N.E.; Ardis, C.W.; Berrill, J.-P.; King, J.P. Bark thickness equations for mixed-conifer forest type in Klamath and Sierra Nevada Mountains of California. *Int. J. For. Res.* **2016**, *1864039*, 1–10. [[CrossRef](#)]

19. Berrill, J.-P.; O'Hara, K.L.; Kichas, N.E. Bark thickness in coast redwood (*Sequoia sempervirens* (D. Don) Endl.) varies according to tree- and crown size, stand structure, latitude, and genotype. *Forests* **2020**, *11*, 637. [[CrossRef](#)]
20. Stephens, S.L.; Moghaddas, J.J.; Edminster, C.; Fiedler, C.E.; Haase, S.; Harrington, M.; Keeley, J.E.; Knapp, E.E.; McIver, J.D.; Metlen, K. Fire Treatment Effects on Vegetation Structure, Fuels, and Potential Fire Severity in Western US Forests. *Ecol. Appl.* **2009**, *19*, 305–320. [[CrossRef](#)]
21. Kramer, H.A.; Collins, B.M.; Kelly, M.; Stephens, S.L. Quantifying Ladder Fuels: A New Approach Using LiDAR. *Forests* **2014**, *5*, 1432–1453. [[CrossRef](#)]
22. Kramer, H.A.; Collins, B.M.; Lake, F.K.; Jakubowski, M.K.; Stephens, S.L.; Kelly, M. Estimating Ladder Fuels: A New Approach Combining Field Photography with LiDAR. *Remote Sens.* **2016**, *8*, 766. [[CrossRef](#)]
23. O'Hara, K.L. *Multiaged Silviculture: Managing for Complex Forest Stand Structures*; Oxford University Press: Oxford, UK, 2014.
24. Vanderwel, M.C.; Malcolm, J.R.; Smith, S.M. An integrated model for snag and downed woody debris decay class transitions. *For. Ecol. Manag.* **2006**, *234*, 48–59. [[CrossRef](#)]
25. Russell, R.E.; Saab, V.A.; Dudley, J.G.; Rotella, J.J. Snag longevity in relation to wildfire and postfire salvage logging. *For. Ecol. Manag.* **2006**, *232*, 179–187. [[CrossRef](#)]
26. Raphael, M.G.; Morrison, M.L. Decay and Dynamics of Snags in the Sierra Nevada, California. *For. Sci.* **1987**, *33*, 774–783.
27. Russell, M.B.; Weiskittel, A.R. Assessing and modeling snag survival and decay dynamics for the primary species in the Acadian forest of Maine, USA. *For. Ecol. Manag.* **2012**, *284*, 230–240. [[CrossRef](#)]
28. Russell, M.B.; Woodall, C.W.; Fraver, S.; D'Amato, A.W.; Domke, G.M.; Skog, K.E. Residence times and decay rates of downed woody debris biomass/carbon in eastern US forests. *Ecosystems* **2014**, *17*, 765–777. [[CrossRef](#)]
29. Zhou, L.; Dai, L.; Gu, H.; Zhong, L. Review on the decomposition and influence factors of coarse woody debris in forest ecosystem. *J. For. Res.* **2007**, *18*, 48–54. [[CrossRef](#)]
30. Chiono, L.A.; O'Hara, K.L.; De Lasaux, M.J.; Nader, G.A.; Stephens, S.L. Development of Vegetation and Surface Fuels Following Fire Hazard Reduction Treatment. *Forests* **2012**, *3*, 700–722. [[CrossRef](#)]
31. Keane, R.E. Describing wildland surface fuel loading for fire management: A review of approaches, methods and systems. *Int. J. Wildland Fire* **2013**, *22*, 51–62. [[CrossRef](#)]



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