Supplemental Material for Harmon et al. 2022. Combustion of Aboveground Wood from Live Trees in Megafires, CA, USA. Forests.

S.1. Theoretical Analysis of Combustion Losses

We used information about the proportions of parts and the form of tree boles to assess how much and which woody parts of a tree would be missing based on various levels of total aboveground fire consumption. If the smallest woody parts (i.e., twigs and branches) were consumed first and the largest ones (i.e., the tree base) last, then branches would be combusted before boles. As far as stems are concerned, smaller diameter tops would likely be lost before larger diameter bases. Although both height and diameter of boles are combusted by fires we considered losses as either solely length- or diameter-related. Given these rules we removed parts as the proportion of aboveground mass consumed increased.

Branches typically comprise 16-40% of the aboveground woody biomass in conifer species with this proportion decreasing with diameter [22] (Figure S1). Therefore, for larger diameter trees a consumption rate of over 16% implies that the branches would have been completely consumed by fire. For consumption rates above this level the bole must also have been consumed in part.

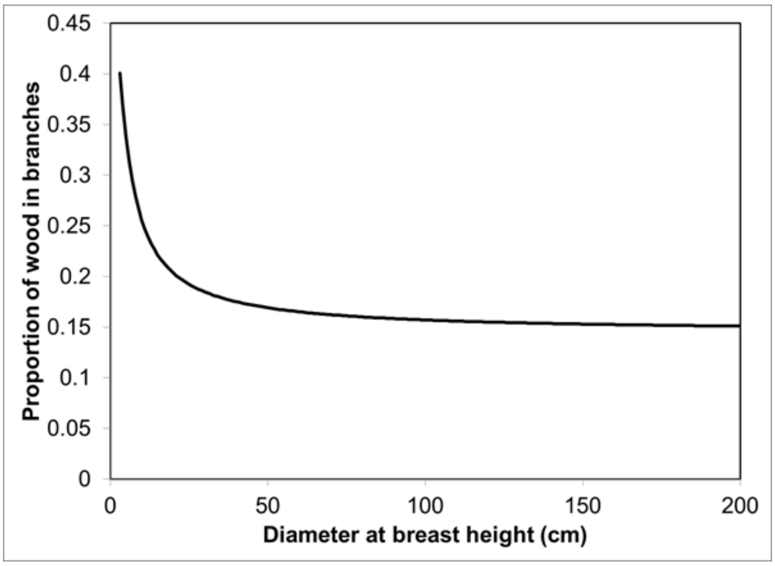


Figure S1. Relationship for conifers between the proportion of aboveground woody parts in branches and tree diameter at breast height (based on equations in [22].

Assuming the losses from boles start at the top, where the diameter is smallest, we calculated the height remaining for a given level of live aboveground consumption. For example, if 50% of the aboveground woody biomass was consumed and 16% of the aboveground portion of trees was in branches, then 41% of the bole mass would have to have been consumed and 59% would remain. If boles have a conical form, then 64% of the bole length would have to be missing for this amount of stem mass to have to be consumed (Figure S2). Alternatively, if only the diameter was removed along the bole, then 41% of the diameter would have to been consumed and 59% would remain. For consumption losses as high as estimated by Garcia et al. [18], which ranged up to 85%, then 82% of the bole mass would have to be consumed. This implies that either 90% of the bole length would have to be missing or 82% of the diameter missing.

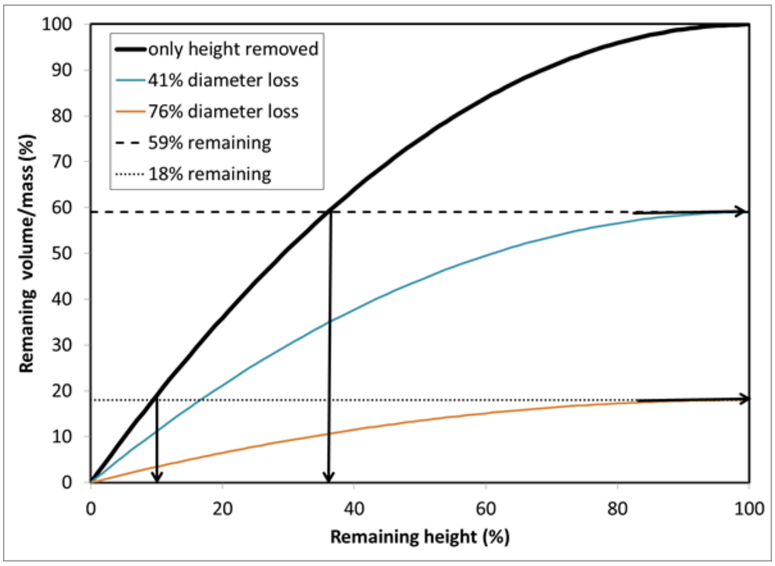


Figure S2. Amount of stem volume remaining for a given level of cumulative stem height lost or percentage of diameter lost along boles. The arrows indicate the solution for a given amount of volume mass remaining when either height (vertical) or diameter (horizontal) is lost.

Although one could use alternative bole forms and examine various combinations of height or diameter loss, the fundamental conclusion is that very little of the height or diameter of boles would remain if fire consumption was as high as Garcia et al [18] have asserted. These high rates of fire consumption also contrast with the amount of tree branches and boles that visually remain after even the most severe fires (Figure S3).

(a) (b)

Figure S3. Images of the Rim Fire from (a) December 2017 and (b) May 2018 indicate that substantial amounts of aboveground woody biomass remained even in high severity fire patches where all the trees were killed.

S-2. Additional Methods

S.2.1. Branch Models

Branches were divided into branch order segments, analogous to stream orders [41]. In the case of conifer branches, first order branch segments are the outermost, leaf bearing twigs. When two twigs join they form a second order branch segment (Figure S4). Further, when two second order segments join they form a third order branch segment, etc. Although just two branch segments of lower orders joining result in an increase in branch segment order, the bifurcation ratio often exceeds 2. For example, below 12 first order segments and three 2nd are on the hypothetical branch giving a bifurcation ratio of 4 (i.e., 12/3).

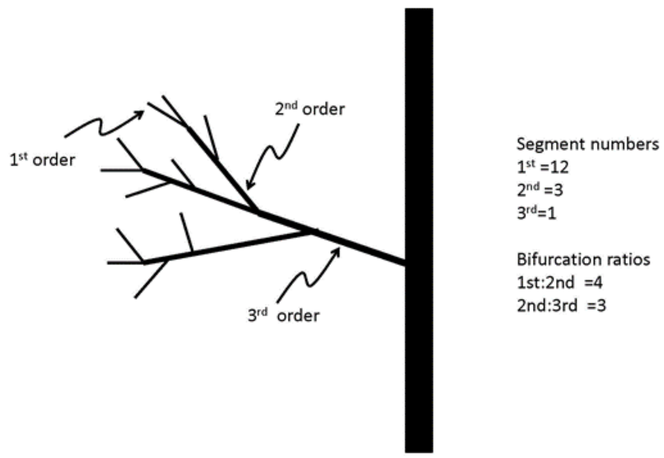
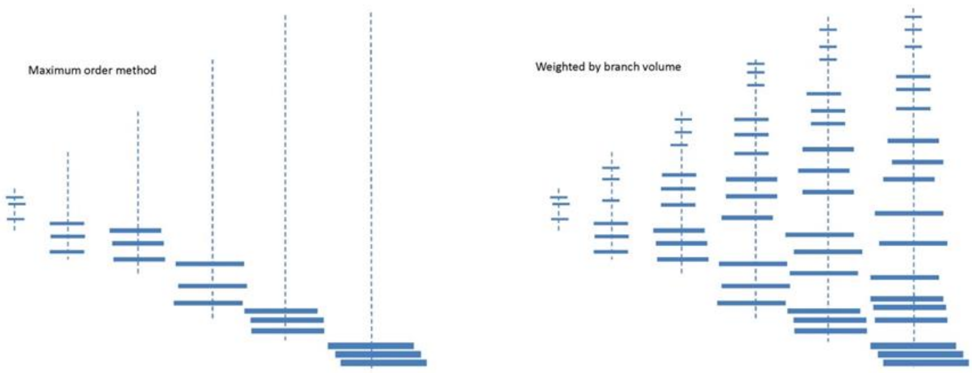


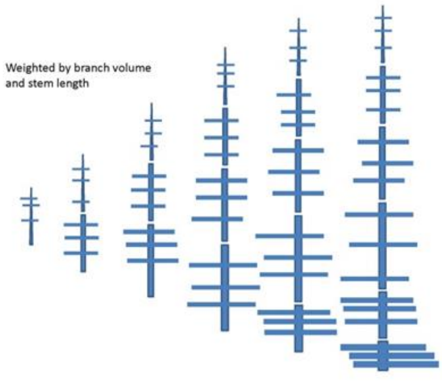
Figure S4. Schematic depiction of branch orders and bifurcation ratios.

S.2.2. Weighting of Branches for Different DBH Size Classes

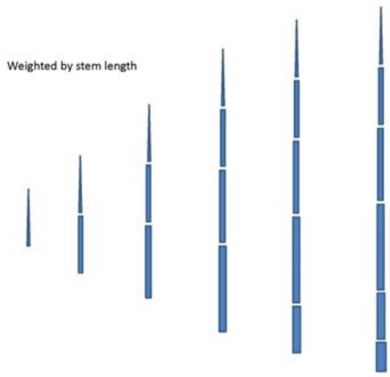
Our dissections and determinations of branch structure were at the level of individual branches and not all the branches on a tree. To estimate the proportion of branch order segments in entire trees we used several weighting methods. The first used the unweighted values from the maximum order branch found on each DBH size class (Figure S5 a). The second was to weight by the volume of branches sequentially predicted for each DBH size class (Figure S5 b). For example, in the case of a tree in DBH size class 3, the values for trees of DBH size classes 1-3 were used by weighting each by their volume. Hence branches lower on the tree had more importance than those on the top because they were larger. The third method was to weight by branch volume and bole length (Figure S5 c). The bole length was related to the difference between heights of the DBH size classes. This acknowledges that the number of branches is also important; the assumption being that the number of branches is proportional to the bole length. We did not weight by bole length alone; however, for completeness it is presented below (Figure S5 d).



(a) (b)



(c)



(d)

Figure S5. Schematic depiction of branch weighting to create a whole tree estimate abundance of branch order segments for trees of different DBH size classes: (a) the maximum order method; (b) the volume weighed method; (c) the volume-length weighted method; and (d) the length weighted method. Horizontal lines indicate branches of different length and diameter; vertical lines indicate the difference in height between DBH size classes. In effect the weighting methods envision a DBH size class to be made up of it and all smaller DBH size classes. For example, a DBH size class 3 tree would be comprised of DBH size classes 1, 2, and 3.

S.2.3. Distinguishing Between Losses from Combustion versus Decomposition

As our sampling was >4 years after the Rim Fire, some of the trees were missing branches due to fragmentation related to decomposition. To distinguish those branches lost from combustion versus fragmentation we used the following criteria. Branch ends with charring were assumed to have losses from combustion, whereas those without were assumed to have losses due to fragmentation (Figure S6). In addition we found that when higher order branches (i.e., 3rd or greater) were combusted the remaining portions had a thorn-like shape. In contrast, those lost via fragmentation had a blunt or rectangular broken end. When a tree had substantial branch loss we searched the ground around its base to determine if branches had accumulated and to examine which orders had been combusted. As our sampling occurred less than 1 year after the Creek Fire, decomposition-related fragmentation was not a concern at that site.

(a)

(b)

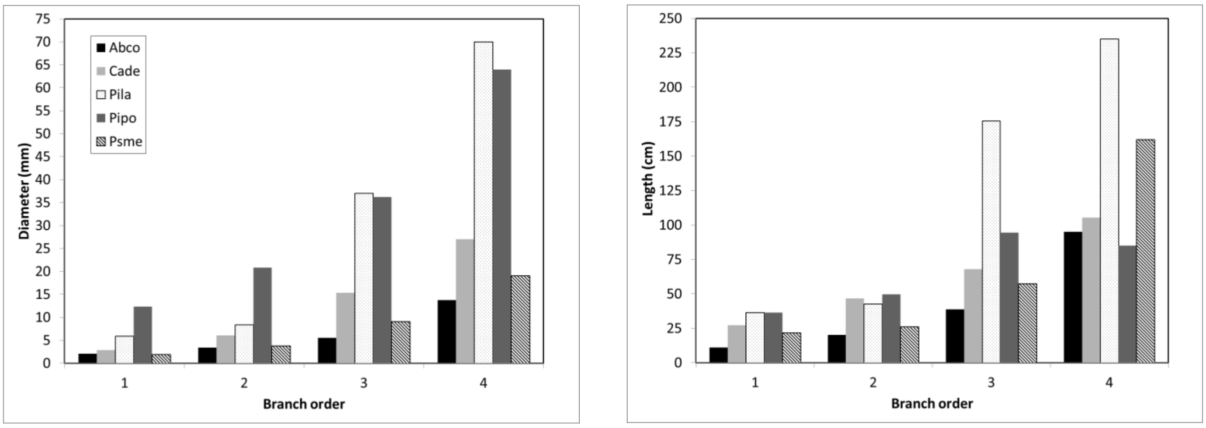
(c)

Figure S6. Examples of characteristics used to separate branches lost via combustion versus decomposition-related fragmentation: (a) branches with rectangular profiles without charring lost via decomposition-related fragmentation; (b) charring of branch stubs that had been broken off prior to fire; (c) thorn-like remnants of branches consumed in fire.

S.3. Additional Analyses, Figures, and Tables

S.3.1. Dissected Branches

The dimensions and bifurcation ratios of dissected branches are presented in Figure S7 and Tables S1 and S2.



(**a**) (**b**)

Figure S7. Mean dimensions of branch orders of dissected branches for different tree species (a) mid-length diameter; and (b) segment length. Abco-*A. concolor*; Cade-*C. decurrens*; Pila-*P. lambertinana*; Pipo- *P. ponderosa*; Psme- *P. menziesii.*

Table S1. Dimensions of dissected branch segments for five species in Rim Fire, Sierra Nevada Mountains, CA.

Branch order	Diameter (mm)	Length (cm)	N
	Abies concolor		
1	2.0 (0.1)[1]	11.2 (0.7)	60
2	3.4 (0.2)	20.1 (1.5)	60
3	5.5 (0.6)	38.8 (6.1)	22
4	13.8 (1.1)	95.0 (12.1)	20
	Calocedrus decurrens		
1	2.9 (0.2)	27.4 (2.4)	49
2	6.1 (0.2)	46.6 (2.5)	78
3	15.3 (0.9)	68.1 (8.7)	38
4	27.0 (2.3)	105.3 (12.0)	12
	Pinus lambertiana		
1	5.9 (1.0)	36.2 (5.0)	10
2	8.3 (1.5)	42.6 (6.4)	10
3	37.0 (4.2)	175.5 (35.7)	2
4	70.0 (NA)	235.0 (NA)	1

	Pinus ponderosa		
1	12.3 (0.3)	36.6 (2.5)	84
2	20.9 (0.7)	49.7 (4.7)	84
3	36.2 (1.9)	94.5 (9.3)	39
4	64.0 (NA)	85.0 (NA)	1
	Pseudotsuga menziesii		
1	1.9 (0.1)	21.7 (2.7)	20
2	3.7 (0.5)	26.1 (4.3)	20
3	9.0 (1.2)	57.4 (14.4)	5
4	19.0 (0.5)	162.0 (0.5)	8

Notes: [1] mean (standard error)

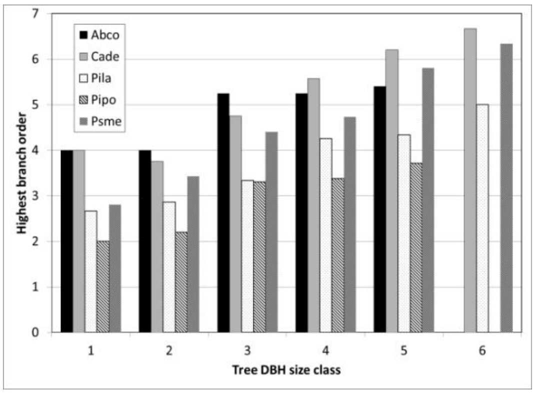
Table S2. Bifurcation ratios for dissected tree branches for five species in Rim Fire, Sierra Nevada Mountains, CA.

Branch orders	**Bifurcation Ratio**		
	Mean	**Minimum**	**Maximum**
	Abies concolor		
1 to 2	4.7	4.1	6.4
2 to 3	7.8	4.7	9.7
3 to 4	4.2	3.0	5.0
	Calocedrus decurrens		
1 to 2	7.5	4.7	11.0
2 to 3	4.6	2.6	6.5
3 to 4	3.5	2.0	5.0
	Pinus lambertiana		
1 to 2	3.1	NA	NA
2 to 3	25.5	NA	NA
3 to 4	2.0	NA	NA
	Pinus ponderosa		
1 to 2	6.0	3.2	8.5
2 to 3	4.3	3.0	6.0
3 to 4	2.0	NA	NA
	Pseudotsuga menziesii		
1 to 2	5.7	4.6	6.9
2 to 3	10.3	9.7	11.0
3 to 4	2.5	2.0	3.0

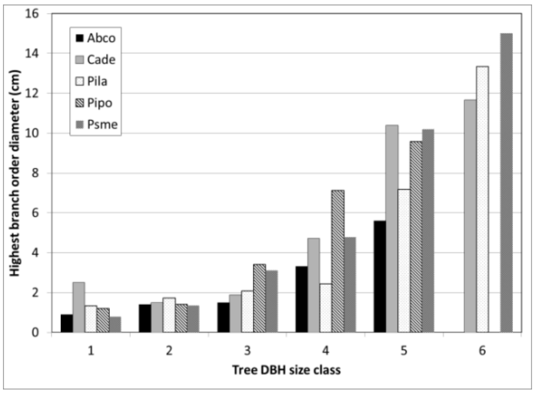
S.3.2. Branch Structures

We found that as tree DBH size class increased the average of the highest branch order present, the diameter, and the length increased (Figure S8a). For the maximum branch order present General Linear Modelling (Proc GLM [25]) of DBH size classes 1-5 indicated that DBH-size class and species were highly significant ($p < 0.01$). For maximum diameter, maximum branch length, and length of the highest branch order segment, both DBH-size class and species and their interactions were either highly significant or significant (i.e., the interaction term for maximum diameter was significant). The significant interactions were related to different rates of increase among species as DBH size class increased.

A. concolor and *C. decurrens* had highest branch orders present in the smallest DBH size classes (order 4), whereas *P. ponderosa* had the lowest (order 2). For the largest DBH size classes *C. decurrens* and *P. menziesii* had the highest number of branch orders present (> order 6) and P. ponderosa the least (≈order 4). Maximum branch diameters ranged between 8±3.1 and 15±0.3 cm, the smallest for *A. concolor* and the largest for *P. menziesii* (Figure S8b). The total maximum length for the largest DBH size class ranged between 4.1±0.3 m for P. ponderosa and 7.7±0.2 m for *P. menziesii* (Figure S8c). The average length of the highest branch order segment for the largest DBH size classes ranged between 1.7±0.4 m for *C. decurrens* and 3.3±0.3 m for *P. lambertiana* (Figure Sd).



(a)



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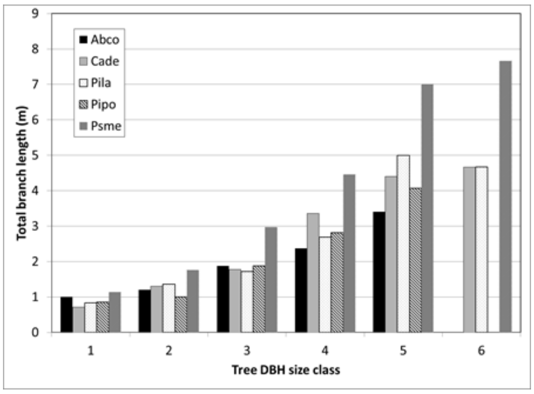

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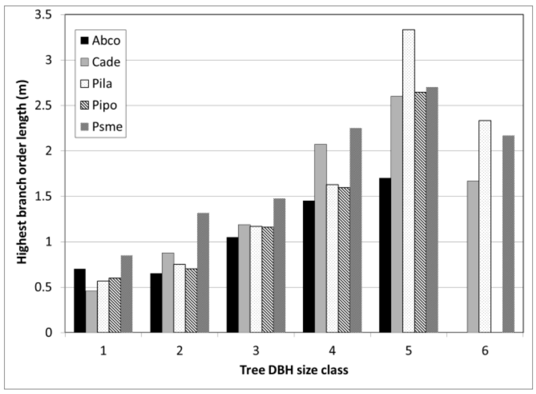
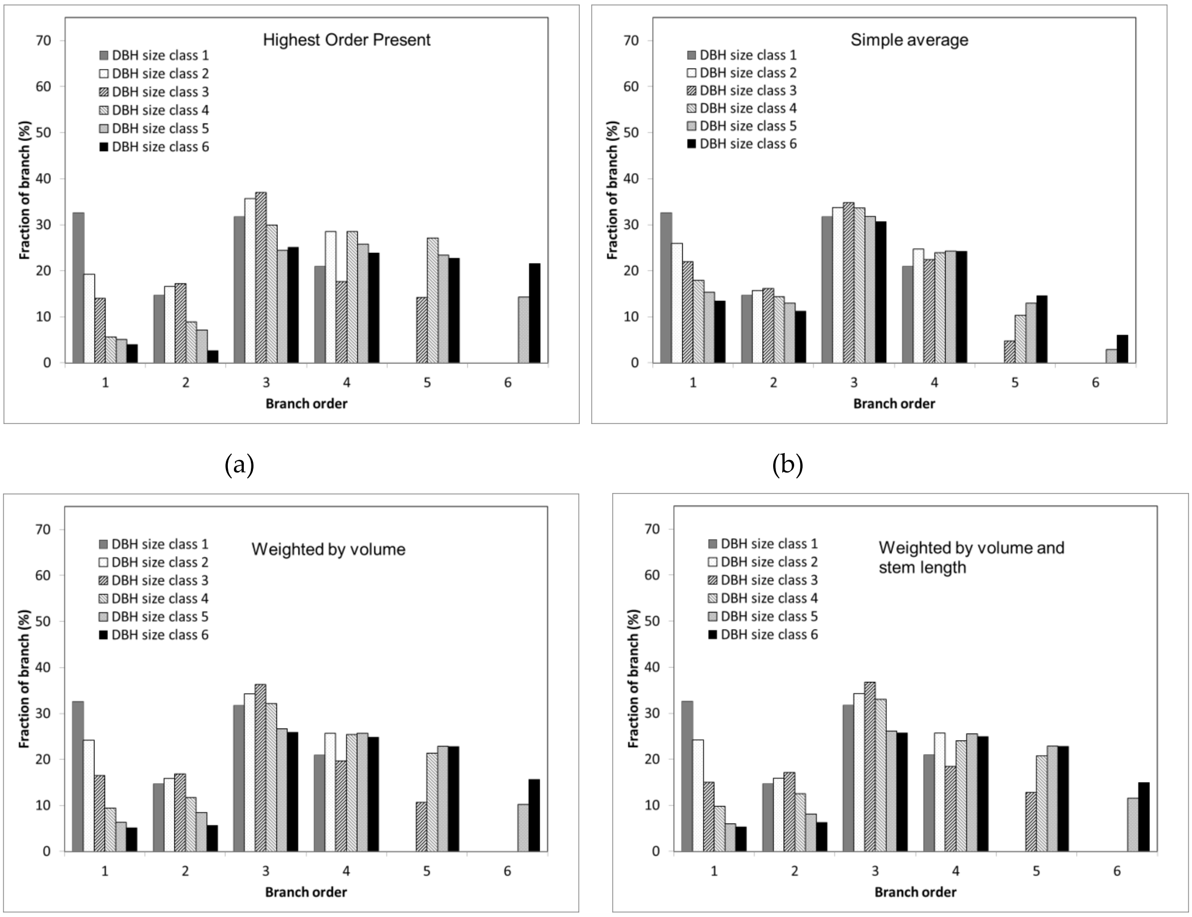


(d)

Figure S8. Changes in branch structure among species and DBH size classes ((1: 1.0-4.9, 2: 5.0-9.9, 3: 10.0-24.9, 4: 25.0-49.9, 55: 0.0-99.9, 6: >100 cm)) adjacent to the Rim Fire, California: (a) highest branch order; (b) diameter of highest branch order present; (c) total length of highest order branches; and (d) length of highest order branch segment. Abco-*A. concolor*; Cade-*C. decurrens*; Pila-*P. lambertinana*; Pipo- *P. ponderosa*; Psme- *P. menziesii*. DBH size class 6 was not sampled for Abco or Pipo.

S.3.3. Sensitivity of Branch Models to Weighting Method

As indicated in section S.2 we used three different methods to construct tree-level branch models including using the proportions of orders found on the highest order branches, weighting these by branch volume, and weighting by branch volume and bole length. We also considered, but ultimately did not use, a simple averaging method that did not weight branches by volume or length. Although the predictions of branch order segments differed (Figure S9) the overall differences were quite small and unlikely to greatly influence estimates of branch combustion rates.

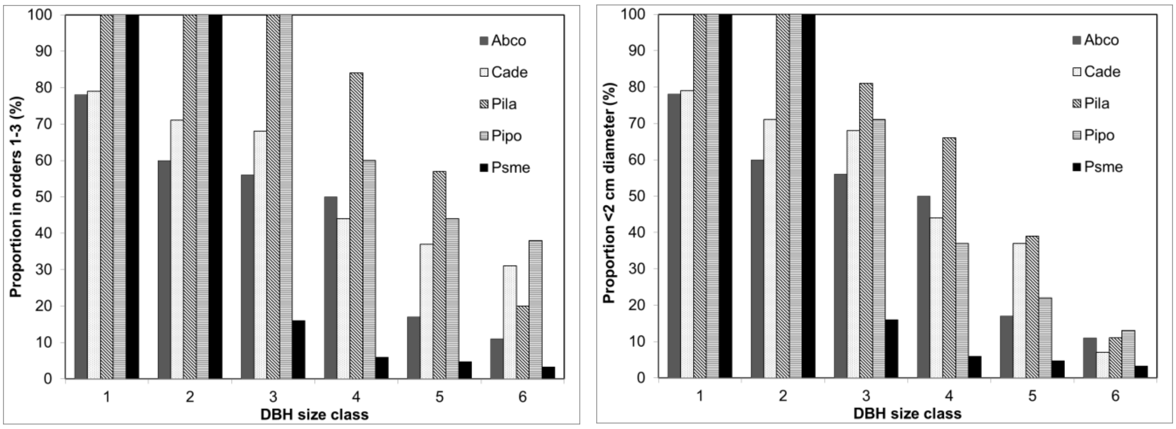


(a) (b) (c) (d)

Figure S9. Comparison of the different models used to estimate branch order contributions for *C. decurrens*. (a) maximum order model; (b) simple, unweighted average; (c) volume weighted model; and (d) volume and length weighted model. The simple average was not used in any subsequent analysis and is presented for comparative purposes only. DBH size classes are the same as Figure S8.

S.3.4. Proportion of Branches Likely Subject to Combustion

To place an upper limit on branch consumption by fire we assumed the branch orders (1-3) and diameters (<2 cm) were combusted. Using these criteria we determined the proportion of branches likely subject combustion (Figure S10). Both criteria indicate that for trees <25 cm DBH a high proportion of branches have the potential to be consumed by fire. However, for tree >25 cm DBH (DBH size classes 4-6) most tree species would have <60% of their branches subject to fire consumption.

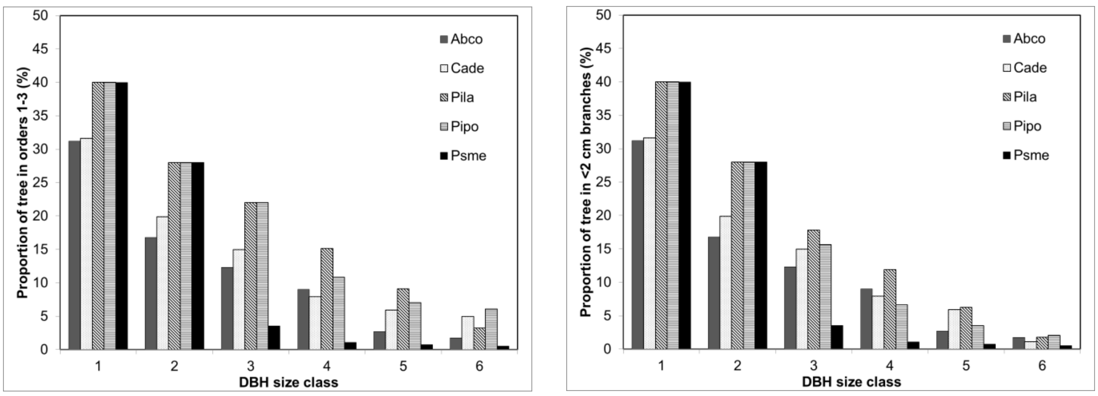


(a) (b)

Figure S10 Theoretical maximum branch combustion possible based on: (a) branch orders observed to be consumed or (b) the maximum branch diameters to be consumed. DBH size classes and species codes are the same as for Figure S8.

C.3.5. Proportion of Aboveground Woody Biomass Likely Subject to Combustion

We determined the proportion of aboveground woody biomass likely combusted by adjusting the fraction of branches subject to combustion by the fraction of aboveground woody biomass in branches ([22]; Figure S1). Using the mid-point of each of the DBH size classes we found that, for trees 1-5 cm DBH, 40% of the aboveground woody biomass was in branches. The proportion of woody biomass in branches decreases substantially once trees reach >10 cm DBH (≤22%). For trees >50 cm DBH we found that 16% of the aboveground woody biomass was in branches. The fires consuming either all of branch orders 1-3 or all branches < 2 cm diameter would therefore only consume 40% of the woody aboveground biomass of the smallest trees, but for most species and DBH size classes <25% would be consumed (Figure S11). For the largest trees, <10% (and in most cases <5%) of the tree had the potential to be consumed if the maximum fraction of branches consumed was as in Figure S10.



(a) (b)

Figure S11. Proportion of tree aboveground woody biomass in: (a) branch order segments 1-3; and (b) branch segments <2 cm diameter. DBH size classes and species codes are the same as for Figure S8.

S.3.6. Combustion of Branches at Tree-level

The combustion of branches and boles at the tree-level is shown in Figure S12. The parameters for the non-linear regression models for branch combustion are presented in Table S3.

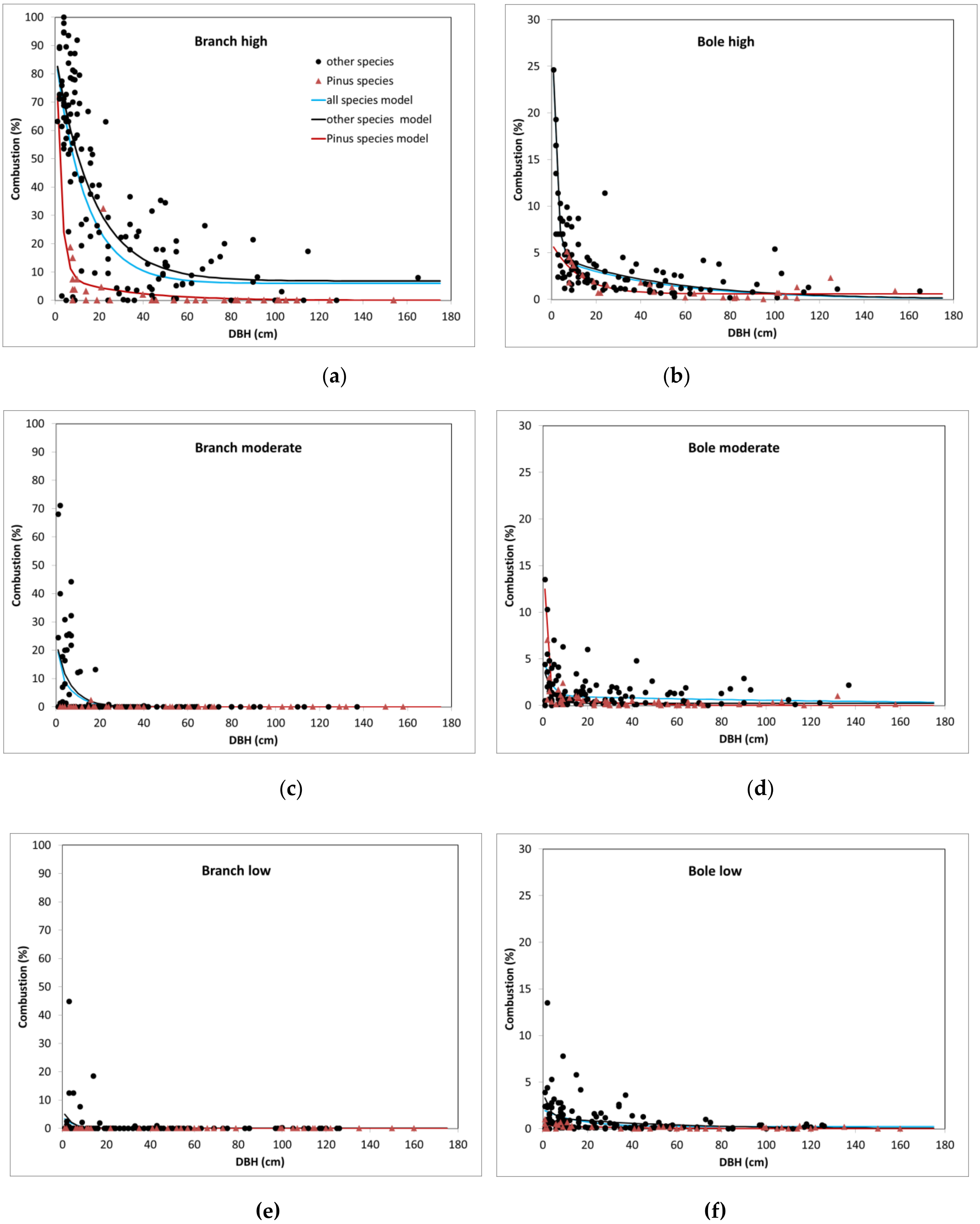


Figure S12. Branch and bole consumption as a function of fire severity and diameter at breast height for the Creek and Rim Fires, California: (a) branch consumption for high severity fire patches; (b) bole consumption for high severity patches; (c) branch consumption moderate severity;

(d) bole consumption moderate severity; (e) branch consumption low severity; and (f) bole consumption low severity.

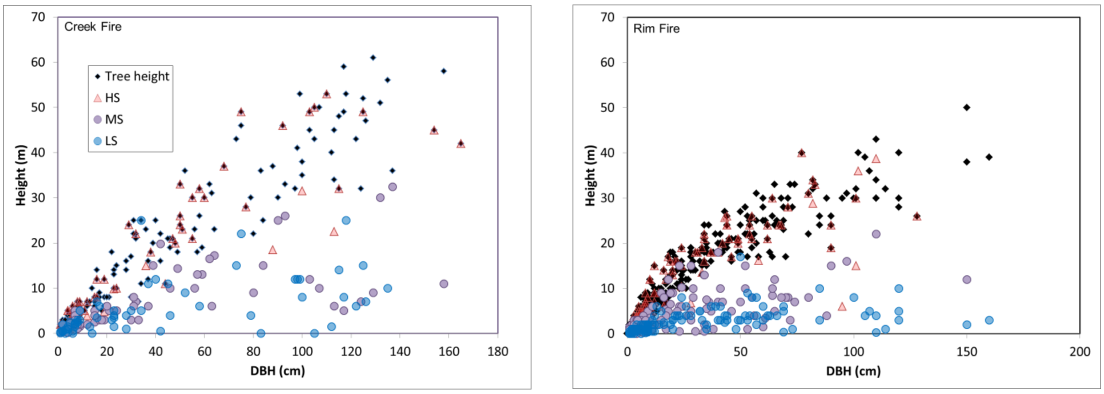
Table S3. Non-linear regressions predicting branch consumption as a function of DBH for different fire severity classes and species groups.

Species Group[1]	Combustion$_1$	Combustion$_2$	k_1	k_2	r^2	DF	N	significance[2]
			High severity					
All	68.4(15.7)	22.8(10.9)	-0.1(0)	-0.02(0.01)	0.60	4	173	***
Other	80.3(5.2)	6.9(3.8)	-0.06(0.01)		0.65	2	139	***
Pinus	100(0)	8.9(8.4)	-0.45(0.25)	-0.03(0.03)	0.30	3	33	***
			Moderate severity					
All	22.4(75.1)	15.5(10.6)	-1.34(4.16)	-0.14(0.09)	0.20	4	162	***
Other	6.0(45.6)	20.8(19.9)	-1.02(11.9)	-0.15(0.12)	0.23	4	110	***
Pinus[3]							51	NS
			Low severity					
All	4.2(1.8)		-0.20(0.12)		0.06	2	169	***
Other	6.7(3.3)	0.1(0.5)	-0.29(0.19)		0.08	2	130	**
Pinus[3]							38	NS

Notes: [1] The *Pinus* species group included *Pinus jeffryi*, *P. lambertina*, and *P. ponderosa*; The other species included *Abies concolor*, *A. procera*, *Calocedrus decurrens*, and *Pseudotsuga menziesii*. [2] Significance levels: NS-not significant; *-0.05>p>0.01;**-0.01>p>0.001>;***-0.001>p. [3] Effectively no combustion of branches.

S.3.7. Bole Charring

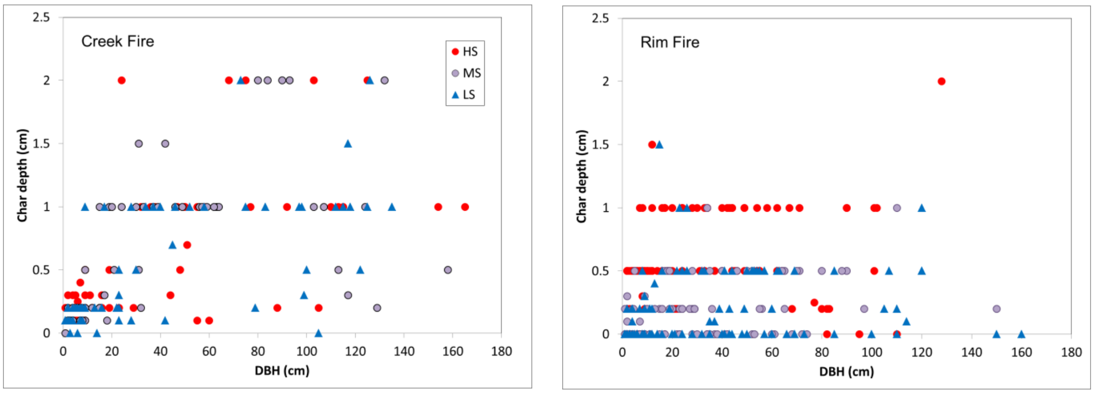
In general the height of bole charring in high severity fire patches matched that of tree height, reaching a maximum of over 50 m (Figure S13). In contrast the height of bole charring rarely exceeded 20 m in low severity patches.



(a) (b)

Figure S13. Bole char heights on trees compared to total tree height at: (a) Rim; and (b) Creek Fires. LS-low severity; MS-moderate severity; HS-high severity.

Radial char depth on boles did not exceed 2 cm in either the Rim or Creek Fire (Figure S14). Char depth for trees in low severity patches of the Rim Fire were often estimated as zero. However, based on measurements from the Creek Fire this was unlikely to have been the case. For trees with DBH >20 cm there was little apparent relationship between fire severity and char depth.



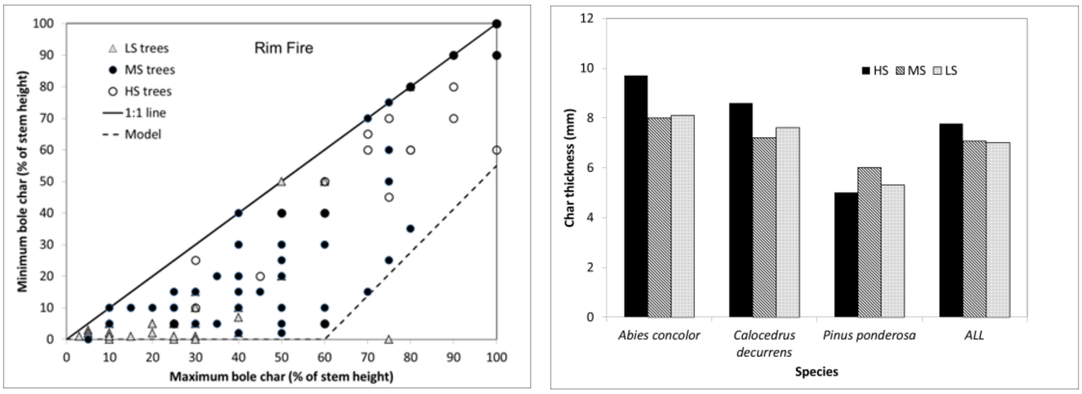
(a) (b)

Figure S14. Radial char depth at base of tree bole based on: (a) chopping into and measuring char depth on each tree at Creek Fire; and (b) visual estimates from the Rim Fire. Severity codes are the same as for Figure S13.

To gain more insight into the factors influencing bole charring two aspects were examined in detail for five individuals of each of three species of trees (*P. ponderosa*, *C. decurrens*, and *A. concolor*), in each of six DBH size classes, and each of three fire severities (i.e., low, moderate, and high). The first was the minimum versus the maximum proportion of the bole charred. The second was the radial depth of bark char at the base of the trees. For this more detailed analysis trees >20 cm DBH were selected from a stand in the Rim Fire that had burned with variable severity. The minimum and maximum char height was measured directly using a meter stick when < 3 m and estimated as a percentage of stem height for >3 m. Tree height was determined using a meter tape and clinometer. Depth of bark char was determined by using a hatchet to chop into the bark on two sides of each tree sampled. A small caliper was used to determine the depth of char.

Comparison of minimum and maximum char heights indicated that while minimum and maximum char heights were similar for many trees, there were also trees in which the minimum was considerably less than the maximum. This was particularly true for trees in low and moderate fire severity patches (Figure S15a). A model was created to predict the minimum possible char height from the maximum char height. It assumed that until the maximum char height is 60% of tree height, the minimum can be zero. As maximum char height increased the minimum increased reaching a value of 60% when the maximum char height was 100% of tree height.

The more precise depth measurements indicated that radial bark char depth ranged between 0.4 and 1.3 cm. ANOVA [25] indicated there was no significant difference in bark char depth among fire severities; in contrast there was a highly significant difference among species (Figure S15b), with *P. ponderosa* having a thinner char depth (0.54±0.04 cm) than the other two species (0.78±00.6 and 0.86±0.06 mm for *C. decurrens* and *A. concolor*, respectively).



(a) (b)

Figure S15. Bole char heights and depths for a subsample of trees on the Rim Fire: (a) the maximum versus minimum proportion of the bole charred; and (b) means depth of char at base of trees of three common species. Severity codes are the same as for Figure S13.

S.3.8. Bole Combustion

Bole combustion rates at the tree-level are presented in Figure S12. The parameters for the non-linear regressions predicting bole combustion are presented in Table S4.

Table S4. Non-linear regressions predicting bole consumption as a function of DBH for different fire severity classes and species groups.

Species Group[1]	Combustion$_1$	Combustion$_2$	k_1	k_2	r^2	DF	N	significance[2]
			High severity					
All	36.7(5.0)	4.6(0.5)	-0.63(0.08)	-0.02(0.01	0.75	4	173	***
Other	37.9(5.8)	4.8(0.6)	-0.66(0.09)	-0.02(0.01)	0.74	4	140	***
Pinus	5.5(1.6)	0.6(0.2)	-0.08(0.03)		0.66	2	32	***
			Moderate severity					
All	4.9(1.3)	1.0(0.4)	-0.35(0.14)	-0.01(0.01)	0.23	4	162	***
Other	4.6(1.4)	1.1(0.2)	-0.33(0.1)		0.18	2	110	***
Pinus[3]	25.5(34.3)	1.1(0.6)	-1.10(0.68)	-0.04(0.03)	0.50	4	51	NS

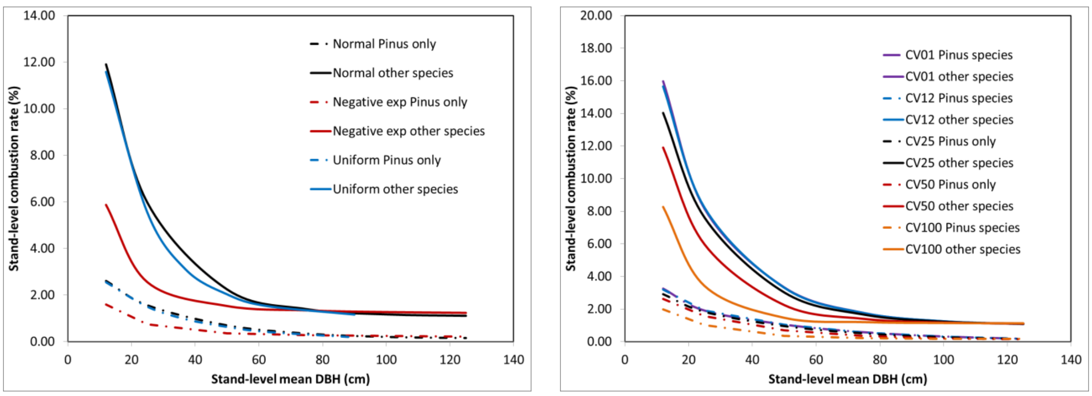
			Low Severity					
All	1.8(0.4)	0.2(0.2)	-0.06(0.03)		0.14	2	169	***
Other	3.2(1.9)	1.3(0.5)	-0.45(0.38)	-0.02(0.01)	0.17	4	130	**
Pinus[3]	2.7(3.0)	0.4(0.1)	-3(0)	-0.03(0.01)	0.34	3	38	***

Notes: [1] The *Pinus* species group included *Pinus jeffryi*, *P. lambertina*, and *P. ponderosa*; The other species included *Abies concolor*, *A. procera*, *Calocedrus decurrens*, and *Pseudotsuga menziesii*. [2] Significance levels as for Table S1: NS-not significant; *-0.05>p>0.01;**-0.01>p>0.001>;***->p>0.001

S.3.9. Sensitivity of Combustion Models to Diameter Distributions

To gain more insight into how sensitive stand-level results were to DBH size class structure, we examined three theoretical DBH size class structures: a negative exponential [42], a normal, and a uniform distribution. For each distribution a range of mean DBH was explored from 12-125 cm, calibrated so that the stand average DBH was the same for each distribution. For the normal distribution we explored sensitivity to the coefficient of variation. For the normal distributions we truncated values for DBH's below 0 cm and above 180 cm, the largest DBH we encountered in our study areas.

At the stand level the fraction of live woody aboveground mass combusted decreased with increasing average DBH and was substantially lower than that predicted for individual tree DBH. The theoretical distribution of DBH used and the species group present both had a noticeable impact on the stand-level combustion rate. For example, for a high severity fire patch in a stand with a mean DBH of 12 cm, *Pinus* species (depending on the distribution used) had a combustion rate of 1.6-2.5%; whereas other species had 5.9-11.9% (Figure S16a). Although the results for uniform and normal distributions were generally similar, at a mean DBH of 12 cm the combustion rates for negative exponential distributions were roughly half the values of these distributions (Figure S16). These differences declined as mean stand DBH increased and for mean stand DBH above 70 cm there was little difference among distributions. As the coefficient of variation increased for the normal distribution, the combustion predicted for a given mean stand DBH declined for both species groups (Figure S16b). This was likely because as the coefficient of variation increased a greater number of larger DBH trees were included. Above a mean stand DBH of 100 cm, combustion was insensitive to DBH variation; likely because large trees comprise so much of the biomass that small trees had very little effect on combustion rates.



(a) (b)

Figure S16. Stand-level combustion for theoretical and published DBH size distributions: (a) total combustion of high severity fires for different DBH distribution types; and (b) total combustion of high severity fires for differing coefficients of variation for normal distribution (e.g., CV100= coefficient of variation of 100%).

S.3.10. Foliage Consumption

Although we noted whether the crown had evidence of consumption by fire, the proportion of the crown foliage that had been combusted was not. However, combustion of foliage, at least for high severity patches, is likely to be high. We approximated the amount of foliage biomass combusted by assuming that loss of first order branches was directly proportional to foliage consumption. That is, if 100% of the first order branches were consumed, 100% of the foliage would have been consumed as well. This is highly likely in that first order branches always have associated foliage, whereas higher orders, particularly for *Pinus* species, do not.

We used a negative exponential equation to model the decline in foliage consumption as DBH increases:

$$\text{Consumption}_{foliage} = C_0\, e^{-k_{foliage} * DBH} \qquad (1\cancel{7})$$

where $k_{foliage}$ is the rate that consumption decreases as DBH increases and C_0 is the combustion rate when DBH is zero. Nonlinear regression was used to estimate these parameters and indicated values of 85.5% and 0.01 cm^{-1} for C_0 and $k_{foliage}$, respectively, for high severity fire patches. This regression was highly significant explaining 20% of the variation at the level of individual trees (Figure S17). Given that very little crown consumption occurred in low and moderate fire severity patches, we only used Equation 7 to model foliage combustion in high severity patches.

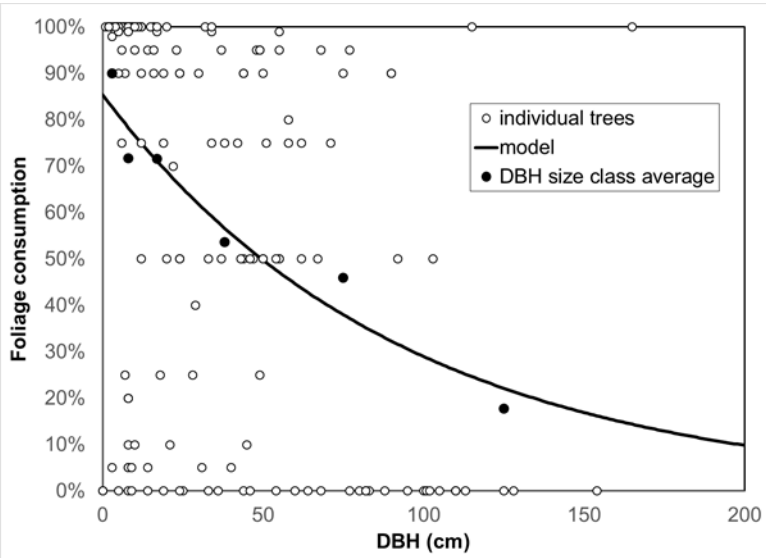


Figure S17. Relationship between diameter at breast height (DBH) of trees and the amount of foliage consumed by high severity fire patches in the Rim and Creek Fires.

Additional References

41. Leopold, L.B. 1971. Trees and streams: the efficiency of branching patterns. Journal of Theoretical Biology 31:339-354. https://doi.org/10.1016/0022-5193(71)90192-5
42. Parker, A.J., Peet, R.K. 1984. Size and age structure of conifer forests. Ecology 65: 1685–1689. https://doi.org/10.2307/1939148