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Pyrogenic carbon emission from a large wildfire in Oregon, United States

John Campbell,[1] Dan Donato,[1] David Azuma,[2] and Beverly Law[1]

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[1] We used a ground-based approach to compute the pyrogenic carbon emissions from the Biscuit Fire, an exceptionally large wildfire, which in 2002 burned over 200,000 ha of mixed conifer forest in southwestern Oregon. A combination of federal inventory data and supplementary ground measurements afforded the estimation of preburn densities for 25 separate carbon pools at 180 independent locations in the burn area. Average combustion factors for each of these pools were then compiled from the postburn assessment of thousands of individual trees, shrubs, and parcels of surface and ground fuel. Combustion factors were highest for litter, duff, and foliage, lowest for live woody pools. Combustion factors also increased with burn severity as independently assessed from remote imagery, endorsing the use of such imagery in scaling emissions to fire area. We estimate the total pyrogenic carbon emissions from the Biscuit Fire to be between 3.5 and 4.4 Tg C (17 and 22 Mg C ha^{-1}) depending on uncertainty in our ability to estimate preburn litter pools and mineral soil combustion with a central estimate of 3.8 Tg C (19 Mg C ha^{-1}). We estimate that this flux is approximately 16 times the annual net ecosystem production of this landscape prior to the wildfire and may have reduced mean net biome production across the state of Oregon by nearly half in the year 2002.

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1. Introduction

[2] Efforts to quantify carbon exchange between terrestrial vegetation and the atmosphere have typically focused on patterns of photosynthesis and respiration. While complex in nature, basic mechanistic understanding of physiology and soil processes has been used in models to predict vegetation responses over broad spatial and temporal domains. In contrast, pyrogenic releases of carbon from vegetation to the atmosphere, while physically simple, are inherently stochastic and therefore not typically included in most process-based models [*Schimel and Baker*, 2002; *Arora and Boer*, 2005].

[3] This deficiency in global vegetation modeling was made apparent following the El Niño of 1997–1998 when an anomalous two-fold increase in global atmospheric CO_2 enrichment was attributed to pyrogenic emissions from Southeast Asian wildfires [*Page et al.*, 2002; *van der Werf et al.*, 2004]. Interest in this phenomenon, combined with advances in remote detection of wildfire [*Lentile et al.*, 2006], concerns over fuel-driven increases in fire frequency and severity in the western United States [*Schoennagel et al.*, 2004], and possible feedbacks between global warming and wildfire frequency [*Westerling et al.*, 2006] has resulted in a number of large-scale, bottom-up efforts to quantify pyrogenic emissions from Africa [*Barbosa et al.*, 1999], Alaska [*French et al.*, 2002; *Kasischke and Bruhwiler*, 2002; *French et al.*, 2004], Siberia [*Soja et al.*, 2004], China [*Lü et al.*, 2006], and North America [*Wiedinmyer et al.*, 2006]. All of these studies use the same general measure-and-multiply approach popularized by *Seiler and Crutzen* [1980], where pyrogenic emissions are calculated as the product of four parameters: area burned, fuel density (biomass per unit area), combustion factor (fraction of biomass consumed by fire), and emission factor (mass of a given chemical species released per mass of fuel consumed). For the most part, the area affected by fire can be accurately assessed either remotely or from inventories and there is general agreement on the emission factors for carbon and other airborne pollutants. However, while most studies recognize the need to vary the inputs of fuel density by vegetation type and the combustion factors by fire severity, the ground data needed to parameterize these functions has been deeply lacking. This is especially true for combustion factors that are compiled from a limited source of widely varying data [see *Peterson and Sandberg*, 1988; *Soja et al.*, 2004; *Wiedinmyer et al.*, 2006] and simple assumptions on how these factors vary with respect to an operationally defined fire severity classification. To improve our regional and global estimates of pyrogenic emissions, it is necessary to improve the specificity and accuracy of our

[1]Department of Forest Science, Oregon State University, Corvallis, Oregon, USA.
[2]Forest Sciences Laboratory, U.S. Forest Service, Portland, Oregon, USA.

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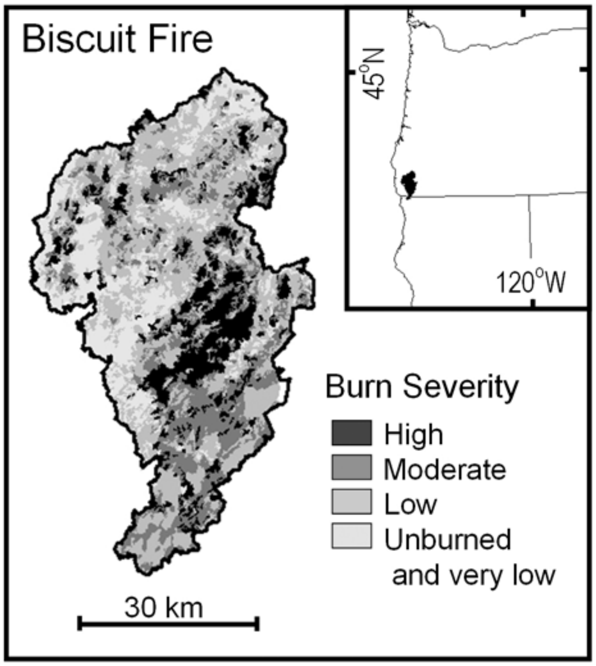

Figure 1. The Biscuit Fire. The Biscuit Fire burned at a mix of severities over 200,000 ha of forest in the Siskiyou Mountains of southwestern Oregon and northern California in the summer of 2002 making it the largest contiguous wildfire in Oregon history. The severity classes shown are those of the remotely derived 2002 BAER classification.

estimates of fuel density and combustion factors beyond what is generally available [*Houghton et al.*, 2000], especially for temperate ecosystems where quantification of fire effects lags behind that of boreal systems.

[4] In this study we consider an exceptionally large wildfire, the Biscuit Fire, which in 2002 burned over 200,000 ha of mixed conifer forest in southwestern Oregon. Carbon emissions from a fire this large are likely to contribute sizably to the annual carbon budget of the region [*Law et al.*, 2004]. Accurate quantification of this flux has been limited by our understanding of the amount of fuel present and the fraction actually combusted. Conveniently, however, the Biscuit perimeter encompassed 180 systematically located U.S. Department of Agriculture (USDA) Forest Service inventory plots. Structural measurements made on these plots before and after the fire, combined with biomass measurements on additional plots, now afford an assessment of preburn fuel density and combustion factors across a combination of forest types, ages, and burn severities unprecedented for a single fire.

[5] Our objectives were to: (1) Determine combustion factors (as a probability distribution) for each of 25 different forest carbon pools representing different fuel types. (2) Assess variation in the above combustion factors as a function of remotely sensed burn severity. (3) Combine the combustion factors with estimates of preburn fuel densities and burn area by severity to estimate fire-wide pyrogenic carbon emission. (4) Assess the utility of federal inventory plots as a method of compiling much needed fuel density and combustion factors. Results are then considered in the context of regional carbon fluxes over time for the same forest and throughout the region in the year of the fire.

2. Methods

2.1. Study Sites

[6] The Biscuit Fire burned at a mix of severities across 200,000 ha of forest in the Siskiyou Mountains of southwestern Oregon and northern California in the summer of 2002, making it the largest contiguous wildfire on record for Oregon (see Figures 1 and 2). The Siskiyou Mountains are characterized by a variety of forest types from Douglas-fir/western hemlock/bigleaf maple communities on mesic sites, to Douglas-fir/tanoak on drier sites, to Jeffrey pine on ultramafic substrates [see *Whittaker*, 1960].

[7] Within the perimeter of the Biscuit Fire there are 180 regularly spaced permanent federal inventory plots (i.e., systematic sample design). In these one-hectare plots (referred to hence forth as inventory plots), metrics to quantify biomass, composition, and various structural attributes have been collected in approximate 10-year intervals since 1970 [see *USDA*, 1995]. The most recent measurements before the Biscuit Fire were made between 1993 and 1997. A 2003–2004 measurement cycle in the years following the fire was then conducted in which additional metrics quantifying fire effects were collected [see *USDA*, 2003].

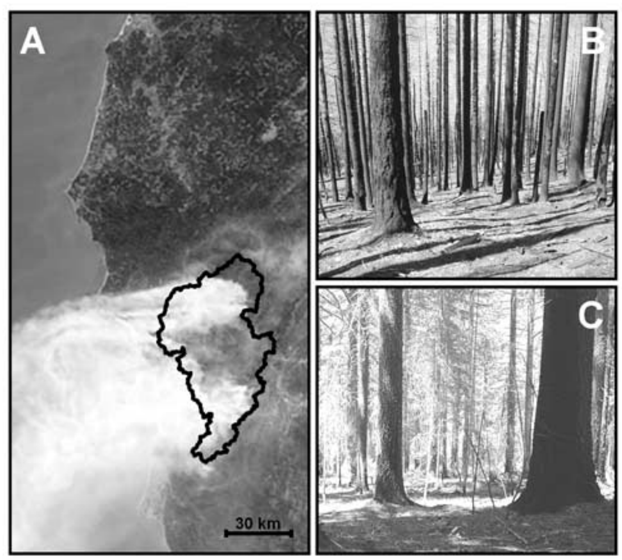

Figure 2. Images from the Biscuit Fire showing (a) the smoke plume drifting over the Pacific Ocean, (b) a forest stand which burned at high severity, and (c) a forest stand which burned at low severity. The black line on Figure 2a denotes the final perimeter of the fire. Even in the most severely burned stands in the Biscuit, where mortality reached 100% and fine surface fuels were completely combusted, tree boles and fine branches remained largely intact. Typical low severity burn in the Biscuit was characterized by bole scorching, minimal canopy mortality, and partial consumption of understory vegetation and ground fuels. Photo for Figure 2a provided by NASA Visible Earth (http://visibleearth.nasa.gov/); photos for Figures 2b and 2c courtesy of Joe Fontaine and Dan Donato.

[8] While data from the inventory plots provided detailed measurements of fire effects on the boles and crowns of most trees, as well as most detritus pools, they did not include fire effects on coarse woody detritus and smaller woody stems killed in the fire. To assess the effects of the Biscuit Fire on these carbon pools, we made pertinent measurements (see below) in 2004 on 54 additional one-hectare plots (referred to hence forth as supplementary plots) randomly located within 54 independent forest stands deliberately distributed across burn severities, including areas unaffected by fire.

2.2. Pyrogenic Emissions

[9] Following the approach of *Seiler and Crutzen* [1980], pyrogenic carbon emissions from the Biscuit Fire were computed according to equation (1):

$$PE = \sum_{i=1,j=1}^{n} A_i \left(D_{ij} \cdot CF_{ij} \right) \quad (1)$$

where PE is pyrogenic emission in mass of carbon, A is the area affected by burn severity class i, D is the preburn carbon density in mass per unit area of carbon pool j averaged across plots of burn severity i, and CF (hence forth referred to as combustion factor) is the fraction of preburn carbon pool j combusted in burn severity class i. In this study we recognize four burn severities: high, moderate, low, and unburned/very low; and 25 separate carbon pools separated by tissue type, growth form, size class, and mortality status.

2.3. Pool-Specific Combustion Factors

[10] The methods for calculating combustion factors specific to various carbon pools are shown in Table 1. We used two basic approaches for arriving upon combustion factors: (1) a back-calculation method where combustion factors are calculated solely from postburn measurements of charring and perceived loss of foliage and branches, and (2) a before-and-after method where combustion factors are calculated as the difference between preburn and postburn mass. As a general rule, the combustion factor of large carbon pools and those that experience low fractional combustion (i.e., live stem wood) are more precisely assessed using the back-calculation method since the sampling error associated with before-and-after comparisons would result in unacceptably low signal-to-noise ratios. Conversely, the combustion factor of smaller carbon pools and those that experience high fractional combustion (i.e., fine woody debris and surface litter) are more precisely assessed using the before-and-after method since postburn measurements reveal little regarding the preburn pool size.

[11] For each separate carbon pool, combustion factors were assessed at the finest possible scale (see Table 1). For instance, since the impacts of fire on foliage, bark, and stem wood were measured separately on each tree, combustion factors for these pools were computed separately for each tree. When measurements represented plot-level average responses (e.g., downed wood), combustion factors were computed at the plot level.

[12] Unlike tissue combustion in larger trees, much of the losses in smaller trees (<7 cm DBH; diameter at 1.37 m above ground) occurs as a result of complete tree combustion. To quantify the incidence of complete combustion of small diameter trees, the frequency of small conifers was compared between burned and unburned plots. The apparent deficit of small diameter trees in burned plots was attributed to complete combustion (see Table 1). Similarly, we investigated the need to account for complete combustion of stumps and other coarse woody detritus, which was not assessed in the postburn inventory. However, despite anecdotal evidence of complete combustion of stumps and logs, there was no detectable difference in these pools between burned and unburned plots; consequently carbon losses due to their complete combustion are believed to be trivial.

2.4. Preburn Carbon Density

[13] Preburn carbon density for each recognized carbon pool was computed for each inventory plot using preburn survey data and a combination of allometric scaling equations appropriate for species in the region. Tree bole mass was estimated with species- and site-specific allometric equations relating stem diameter to volume and species-specific wood density values [*van Tuyl et al.*, 2005]. Foliage and bark mass were estimated directly from species- and site-specific allometric equations [*Means et al.*, 1994]. The mass of downed woody detritus was computed from line intercept data using geometric scaling and species-specific wood density values [*Harmon and Sexton*, 1996]. Biomass of small hardwoods (including shrubs) was determined using allometric equations derived empirically from tissue harvests made in the region of the Biscuit Fire: stem mass in g = 2203(1 − exp(−0.0002(shrub volume in dm^3))); foliage mass in g = 6498(1 − exp(−0.0001(shrub volume in dm^3))). Ocular estimates of total grass and forb coverage was converted to biomass using 4.0 g m^{-2}, which is the average mass per unit coverage reported for common local species [*Means et al.*, 1994].

[14] Because litter and duff masses were not recorded on the inventory plots prior to the fire, it was necessary to estimate preburn masses for these pools from samples collected in 2004 from locations distributed throughout the Biscuit area but unaffected by fire. Recognizing that these preburn carbon pools varied across the forests affected by the Biscuit, we originally set out to collect unburned litter and duff samples from a variety of cover types and apply these cover type-specific masses to each inventory plot according to the plot's location on a cover type map. However, upon collecting these samples it became apparent that both inaccuracies in the cover type map and variability in forest floor (soil O-horizon) depth within forest type were leading to false accuracy. Considering this, we decided to aggregate forest types on the Biscuit into the two most distinct classes: (1) low biomass forests growing on ultramafic (serpentine) substrates, and (2) higher biomass forests growing on nonultramafic substrates. Sampling involved the collection of six-inch-diameter parcels of forest floor from 8 to 32 points from each of 43 independent plots distributed throughout the Biscuit perimeter (11 in ultramafic sites, 32 in nonultramafic sites). Samples were dried, separated into duff and litter, and produced four separate values: 1691 and 993 g m^{-2} for litter and duff on ultramafic substrates, respectively; 2000 and 1399 g m^{-2} for litter and

Table 1. Methods and Decision Rules for Computing Combustion Factors for Various Carbon Pools[a]

Carbon Pool	Method for Deriving Combustion Factor	Sample Size and Source
Foliage (large live trees)	The fraction of foliage reported missing from each tree via ocular estimate was equated to the fraction combusted and then corrected to account for foliage killed and dropped but not combusted based on postburn measurements of new litter accumulation.	13,000 trees in inventory plots
Branch (large live trees)	The fraction of branch and twigs reported missing from each tree via ocular estimate in the inventory records was equated to the fraction combusted.	13,000 trees in inventory plots
Bark (large live trees)	Computed for each tree as the product of: fraction of bole surface charred (derived from fire scar measurements), fraction of bark depth charred (determined through supplementary measurements to average 0.29 independent of fire severity), and fraction of mass loss resulting from charring (assumed to be 0.9, 0.5, 0.4 for high, moderate, and low severity plots, respectively crudely extrapolated from *Czimczik et al.* [2002] and assuming a maximum bark temperature of 500°C).	13,000 trees in inventory plots
Bole (large live trees)	No bole wood consumption was reported in either the inventory or supplementary plots for these larger live trees. Therefore, combustion was assumed to be negligible.	not applicable
Bole, bark, branch, and foliage (small live conifers)	Based on a comparison of density and size class distribution between burned and unburned plots, complete combustion of all tissues was determined to occur at a frequency of 0.6, 0.6, and 0.4 for high, moderate, and low severity plots, respectively. Bark, branch, and foliage loss for trees not fully combusted was assumed to be equal to that of larger trees.	430 trees in supplementary plots
Bole, bark, branch, and foliage (small live hardwoods)	Tissue combustion was determined for each stem as the difference between postburn volume (computed allometricly from basal diameter and stem height) and preburn volume (extrapolated allometricly from postburn basal diameter).	480 trees in supplementary plots
Bole, bark, branch, (standing dead trees)	Tissue combustion was computed by the same methods used for live trees except that in cases where bark was absent surface char was assessed as wood rather than bark combustion. Field records of char depth, while variable, indicate no difference between live and dead trees.	1,200 trees in inventory plots
Downed dead wood (large)	A lack of data on char severity for large downed wood prevented direct assessment. Instead the combustion factors for large downed wood was assumed to be twice that of standing dead wood.	not applicable
Downed dead wood (medium and small)	Fraction combusted was determined for each plot as the difference between preburn and postburn debris volume (determined line intercept transects).	180 inventory plots
Litter (O_i-horizon, including leaf litter and woody fragments <0.51 cm diameter)	Computed occular estimates of burn effects on 13.5m2 plots as $(a + 0.5b)/c$ where, a is the sum area of all sublitter surfaces indicating total litter combustion (light and deeply charred duff, mineral soil and rock), b is the area over which litter was reported as lightly charred, and c is total area believed to be covered by litter prior to the fire (the sum of all surfaces covered by uncharred litter, lightly charred litter, and all sublitter surfaces showing some charring).	720 inventory subplots
Duff (O_e and O_a - horizon)	Computed from postburn surveys with the same equation used for litter substituting duff char values for that of litter and referring only to subduff layers as indicators of duff loss.	720 inventory subplots
Mineral soil (A and B - horizon including fine roots to 10 cm)	Combustion of mineral soil C was assessed only when postburn surveys reported either a deeply charred mineral surface (in which case all C in the top 4 cm of soil was presumed combusted) or a moderately charred mineral surface (in which case all C in the top 2 cm of soil was presumed combusted).	720 inventory subplots

[a]Large refers to >7.62 cm DBH for trees and fragment diameter for dead wood; Small refers to <7.62 cm DBH for trees and fragment diameter for dead wood. Sample size refers to the number of independent events assessed across the fire. For details regarding postfire samplinmg procedures, see *USDA* [2003].

duff on nonultramafic substrates, respectively. To verify our estimates of preburn litter and duff were reasonable, we compared our numbers to modeled estimates using the FCCS national fuel bed map and associated fuel loadings [*Sandberg et al.*, 2001; *Ottmar et al.*, 2007] (http://www.fs.fed.us/pnw/fera/fccs). As shown in Table 2, differences in cover type partitioning between that of our study and that of the FCCS do not permit comparisons at scales smaller then the entire fire. When comparing values across the entire Biscuit, our values for duff mass were lower than that of FCCS and our values for litter mass were higher than that of FCCS suggesting a discrepancy in the operational definition of litter and duff between the two methodologies. However, the sum of litter and duff (i.e., forest floor) is in general agreement between the two approaches with the FCCS predicting only 30% more mass fire wide than we estimated from our sampling.

[15] A considerable portion of the Biscuit reburned the 38,000-hectare 1987 Silver Fire, introducing the possibility that fuel masses were different for these parts of the Biscuit. However, the pre-Biscuit inventory was conducted between 1993 and 1997, 6–11 a after the Silver Fire; thus most such differences were implicitly accounted for in the inventory plot data. As for litter and duff masses, which were not

Table 2. A Comparison of Modeled Forest Floor Mass to That Measured for This Study

Forest Cover Type	Fraction of Biscuit Area	Preburn C Pool, kg C ha^{-1}		
		Litter	Duff	Total Forest Floor[a]
Modeled from FCCS database[b]				
(2) W.hemlock/W.redcedar/Douglas-fir	0.53	4000	21075	25075
(7) Douglas-fir/Sugar pine/Tanoak	0.15	1277	21523	22800
(28) Ponderosa pine savanna	0.09	986	4078	5064
(38) Douglas-fir/Madrone/Tanoak	0.09	3193	8291	11484
(10,24,47,48,52,53,59) All others	0.14	2426	38596	41022
All combined and weighted by class	1.00	2989	19663	22652
From field measurements in this study				
Forest on nonultramafic substrates	0.72	10001	6993	16994
Forest on ultramafic substrates	0.28	8455	4966	13421
All combined and weighted by class	1.00	9562	6417	15979

[a]The sum of litter amd duff.
[b]Number codes correspond to mapped FCCS fuel bed types.

measured in the pre-Biscuit inventory and were derived from our supplementary sampling, the absence of unreburned Silver Fire area prohibited direct sampling of this condition to assess forest floor masses in those stands prior to reburning. We addressed this issue by collecting forest floor samples from the nearby Galice Fire, which burned the same year as the Silver Fire but did not reburn in the Biscuit. Litter and duff masses in the Galice were not discernibly different from those collected from unburned sites, suggesting that the forest floor in the Silver area had recovered to preburn levels by the time the Biscuit burned.

[16] An estimate of the carbon present in the top 10 cm of mineral soil throughout the area affected by the Biscuit was based on a rock-free soil carbon fraction of 0.10, a rock-free soil bulk density of 0.89 g cm^{-3}, a fine root mass of 0.01 g cm^{-3}, (determined from 96 soil cores taken on 3 unburned plots) and a rock fraction of 0.50 by volume chosen to represent both the typical and highly skeletal substrates present in the Siskiyou mountains. We assumed the carbon content of all pools to be 0.50 by mass (a standard approximation) except for the litter and duff pools which we assumed to be 0.40 (based on Dumas combustion of 36 field samples producing an average of 0.40 and a standard deviation of 0.08).

2.5. Binning of Data by Burn Severity

[17] To assess carbon combustion as a function of burn severity, each of the study plots was classified as one of four burn severities (e.g., high, moderate, low, or unburned/very low) based on an overlay of the Biscuit BAER (Burned Area Emergency Rehabilitation) fire severity map. The levels of severity in the BAER map were based on classification of the differenced normalized burn ratio (dNBR), a widely used index of burn severity derived from Landsat data [*Miller and Yool*, 2002; *van Wagtendonk et al.*, 2004; *Key and Benson*, 2005]. dNBR is a measure of prefire to postfire change in the ratio of near- to short-wave infrared spectral reflectance [*Key and Benson*, 2005]. BAER assessments are used by federal land management agencies for remediation reconnaissance and are independent of any of the measurements used to compute combustion in this study. Then each of the approximately 60,000 separate combustion computations made for individual trees, plots of ground cover, or debris transects were binned by the burn severity of the plot in which the record was taken and averaged to produce the values CF_{ij} in equation (1). This approach allowed us to assess the ability of BAER severity classification to detect within-fire variability in the combustion of various carbon pools and therefore the utility of BAER severity in scaling combustion factors for other fires. Similarly, to account for possible interaction between preburn carbon density and subsequent burn severity, the preburn carbon densities of each for each plot were averaged by BAER severity classification to produce the values Dij in equation (1). Finally, the total area affected by each burn severity class in the Biscuit Fire perimeter (value A_i in equation (1)) was determined from the BAER severity map to be 32, 46, 84, and 41 thousand ha for the high, moderate, low, and unburned/very low severities, respectively. While several different burn severity maps are available for the Biscuit, we chose BAER because it is among the most readily available and widely used burn severity classification for wildfires in the western United States.

3. Results

3.1. Combustion Factors

[18] The combustion factors estimated for each carbon pool and burn severity class are shown in Table 3. Discrepancies between mean and median values indicate a right skew in the event probability in high severity plots and a left skew in the lower severity plots. In other words, while combustion scales to the landscape according to the average of that experienced by individual trees or specified patches of litter, most individuals in low severity plots are affected by fire to a much lesser degree than the average of individuals located in low severity plots. Conversely, most individuals in high severity plots are affected by fire to a much greater degree than the average of individuals located in high severity.

[19] Nearly all 25 carbon pools show a monotonic increase in combustion factor as burn severity increases from the unburned-very low class through to the high severity class (Table 3). Such a consistent trend for ground, surface, and canopy fuels is an endorsement of the BAER severity classification for distinguishing the fraction of carbon combusted from different pools. Such trends are especially clear in the highly combustible ground and surface pools such as litter and fine woody detritus. This relationship between remotely assessed fire severity and ground and

Table 3. Average (and Median) Combustion Factors by Carbon Pool and Burn Severity

Forest Carbon Pool (Fuel Type)	Combustion Factor[a] High Severity		Moderate Severity		Low Severity		Unburned and Very-Low Severity	
Foliage								
Large conifers	0.69	(0.98)	0.27	(0.01)	0.08	(0.00)	0.02	(0.00)
Large hardwoods	0.58	(0.87)	0.29	(0.00)	0.12	(0.00)	0.03	(0.00)
Small conifers	0.89	(1.00)	0.76	(1.00)	0.44	(0.07)	0.01	(0.00)
Small hardwoods	1.00	(1.00)	0.80	(1.00)	0.50	(0.00)	0.00	(0.00)
Grass and forbs	1.00	(1.00)	0.76	(0.88)	0.75	(0.87)	0.70	(0.83)
Branch								
Large conifers	0.05	(0.08)	0.02	(0.00)	0.00	(0.00)	0.00	(0.00)
Large hardwoods	0.05	(0.06)	0.02	(0.00)	0.01	(0.00)	0.00	(0.00)
Small conifers	0.64	(1.00)	0.69	(1.00)	0.41	(0.00)	0.00	(0.00)
Small hardwoods	0.79	(0.81)	0.63	(0.65)	0.40	(0.41)	0.00	(0.00)
Bark								
Large conifers	0.20	(0.26)	0.06	(0.03)	0.03	(0.01)	0.01	(0.01)
Large hardwoods	0.22	(0.26)	0.11	(0.15)	0.03	(0.00)	0.01	(0.00)
Small conifers	0.70	(1.00)	0.70	(1.00)	0.42	(0.05)	0.01	(0.01)
Small hardwoods	0.79	(0.81)	0.63	(0.65)	0.40	(0.41)	0.00	(0.00)
Bole								
Large conifers	0.00	(0.00)	0.00	(0.00)	0.00	(0.00)	0.00	(0.00)
Large hardwoods	0.00	(0.00)	0.00	(0.00)	0.00	(0.00)	0.00	(0.00)
Small conifers	0.61	(1.00)	0.68	(1.00)	0.40	(0.00)	0.00	(0.00)
Small hardwoods	0.79	(0.81)	0.63	(0.65)	0.40	(0.41)	0.00	(0.00)
Dead wood								
Large standing	0.12	(0.07)	0.04	(0.03)	0.02	(0.01)	0.02	(0.00)
Small standing	0.61	(1.00)	0.68	(1.00)	0.40	(0.00)	0.00	(0.00)
Large downed	0.24	(0.14)	0.08	(0.06)	0.04	(0.02)	0.04	(0.01)
Medium downed	0.79	(1.00)	0.73	(0.83)	0.67	(0.76)	0.62	(0.67)
Small downed	0.78	(0.83)	0.58	(0.62)	0.61	(0.70)	0.62	(0.69)
Forest floor and soil[b]								
Litter	1.00	(1.00)	0.76	(0.88)	0.75	(0.87)	0.70	(0.83)
Duff	0.99	(0.99)	0.51	(0.64)	0.54	(0.75)	0.44	(0.50)
Soil to10 cm	0.08	(0.05)	0.04	(0.01)	0.04	(0.01)	0.02	(0.00)

[a]Fraction of preburn mass lost to combustion.
[b]Litter is O_i horizon, duff is O_e and O_a horizon, soil is all mineral soil to a depth of 10 cm including fine roots. For live trees, small is <7.62 cm DBH; large is >7.62 cm DBH. For dead wood, small is 0.51–2.54 cm, medium is 2.54–7.62 cm, and large is >7.62 cm diameter.

surface fuel combustion was not a foregone conclusion, as fire effects on the ground can often be decoupled from fire effects in the canopy [*Pyne et al.*, 1996; *van Wagner*, 1977]. While litter, duff, and small woody detritus combustion was lowest in the unburned-very low severity plots, the fact that the values still average 60% combustion indicate just how prevalent surface fire was across all of the Biscuit Fire. Field records confirm that, of the 41 inventory plots that were remotely classified as unburned-very low, only two showed no sign of surface fire.

[20] Combustion factors also varied expectedly among carbon pools. Pools with larger surface to volume ratios (e.g., foliage, small stems, and litter) showed consistently higher combustion factors than those with lower surface to volume ratios (e.g., large tree boles). This is consistent with most fire behavior models which equate fuel fragment size inversely to their propensity for desiccation and combustibility [*Reinhardt et al.*, 1997].

3.2. Preburn Carbon Pools

[21] Preburn carbon mass for each pool and burn severity class is shown in Table 4. As is the case with most mature forest landscapes, biomass is concentrated in the largest trees. Differences in biomass among burn severities reflect the tendency for stands with more small trees and fewer large trees to burn at higher severity, a finding consistent with that of *Azuma et al.* [2004]. Notably, this trend is reversed for dead wood in that higher severity plots had consistently lower amounts of coarse woody detritus prior to the fire. To aid in comparison with other wildfire research [e.g., *Ottmar et al.*, 2007], preburn carbon pools were also summarized according to conventional fuel categorization and expressed in total dry mass per unit area along with corresponding combustion factors in Table 5.

3.3. Total Pyrogenic Emissions and Sources

[22] Using equation (1) to combine the combustion factors of Table 3, the preburn carbon pools of Table 4, and the area exposed to each burn severity class (see methods above) yields a Biscuit-wide pyrogenic emission of 3.8 Tg C. Here, the two largest sources of pyrogenic emissions were both from the forest floor. As shown in Table 6, 31% of the total pyrogenic emissions arose from combustion of the litter layer and another 26% arose from combustion of the underlying duff and mineral soil layers. The next largest source was the combustion of dead wood which contributed 19% to total emissions. The relative contribution of different pools to total emissions was largely the same when carbon losses were computed separately by burn severity class, with the litter and duff pools being the largest contributors. However, as burn severity decreases there is a slight shift in major combustion sources from the canopy

Table 4. Average Carbon Density by Forest Carbon Pool and Burn Severity[a]

Forest Carbon Pool	Carbon Density, kg C ha^{-1}				
	High Severity	Moderate Severity	Low Severity	Unburned Very Low Severity	All Burn Severities
Foliage					
Large conifers	2853	3045	3397	3670	3242
Large hardwoods	1152	234	1594	3813	1698
Small conifers	1172	3272	1746	1260	1863
Small hardwoods	378	397	431	461	417
Grass and forbs	3	2	2	3	2
Branch					
Large conifers	11421	6725	9886	11399	9858
Large hardwoods	2759	565	3964	10113	4350
Small conifers	105	117	2152	64	609
Small hardwoods	505	432	831	549	579
Bark					
Large conifers	8759	7279	12171	16587	11199
Large hardwoods	2779	565	4053	10694	4523
Small conifers	99	89	2148	52	597
Small hardwoods	18	115	67	76	69
Bole					
Large conifers	40650	38509	65120	85396	57419
Large hardwoods	19331	3991	28727	70943	30748
Small conifers	347	365	236	202	288
Small hardwoods	188	1127	711	772	700
Dead wood					
Large standing	6791	2877	7338	6701	5927
Small standing	869	554	2148	2998	1642
Large downed	6179	9003	12145	7201	9324
Medium downed	1388	1422	1933	2196	1798
Small downed	1055	1414	1499	2028	1543
Forest floor and soil					
Litter	9228	9096	9743	9929	9499
Duff	5979	5806	6655	6898	6335
Soil and roots to 10 cm	45500	45500	45500	45500	45500

[a]Values are the average of 26, 41, 66, and 43 inventory plots for high, moderate, low, and unburned-very low severity study plots, respectively, except that one Biscuit-wide value was used for soil and roots. For live trees, small is <7.62 cm DBH; large is >7.62 cm DBH. For dead wood, small is 0.51–2.54 cm, medium is 2.54–7.62 cm, and large is >7.62 cm diameter. Litter is O_i horizon; duff is O_e and O_a horizon.

to the ground and surface, reflecting the shift in fire behavior from a crown fire (which in most cases included ground and surface combustion as well) to a surface fire.

3.4. Uncertainty Assessment

[23] The sources of uncertainty in our estimates of pyrogenic emissions range from measurement uncertainty in the field, to sampling error at both the plot and landscape level, to the various quantitative assumptions regarding allometric scaling of preburn carbon pools and mass losses, to decision rules regarding the partitioning of carbon pools. Considering the difficulty in estimating combustion of subsurface carbon and that 65% of the total fire-wide carbon emissions may come from the combustion of litter, duff, and mineral soil carbon, we contend that most of the uncertainty in our estimate of total pyrogenic emissions arises from uncertainty in combustion of these pools.

[24] In the case of litter and duff, we are reasonably confident that our sample means for preburn mass for both that of ultramafic and nonultramafic substrates approach the true Biscuit-area means. Likely, most of the uncertainty arises from the assumption that combustion factors for litter

Table 5. Preburn Fuel Mass and Combustion Factors by Alternative Convention[a]

Fuel Category	Fuel Mass, Mg dry mass ha^{-1}	Combustion Factor (Fraction Combusted)			
		High Severity	Moderate Severity	Low Severity	Unburned Very Low Severity
Trees	263.2	0.08	0.07	0.03	0.00
Snags	15.7	0.18	0.14	0.11	0.01
Shrubs	3.7	0.86	0.66	0.42	0.00
Nonwoody fuel	<0.1	1.00	0.76	0.75	0.70
1 h surface fuels	6.1	1.00	0.76	0.75	0.70
10 h surface fuels	3.1	0.24	0.08	0.04	0.04
100 h surface fuels	3.6	0.79	0.73	0.67	0.62
1000+ h surface fuels	18.6	0.78	0.58	0.61	0.62
Litter	13.0	1.00	0.76	0.75	0.70
Duff	12.8	0.99	0.51	0.54	0.44

[a]Shrubs include all hardwoods <7.6 cm DBH; unlike elsewhere in paper, here litter excludes all woody fragments. Other categories follow the FCCS fuel category definitions.

Table 6. Pyrogenic Carbon Emissions by Carbon Pool and Burn Severity Class

Forest Carbon Pool	Combusted Carbon, Mg ha^{-1}				
	High Severity	Moderate Severity	Low Severity	Unburned Very Low Severity	Fire-Wide[a] Combustion, Tg C
Litter	7.4	5.5	5.8	5.4	1.00–1.24
Duff, soil and roots	8.3	4.2	4.6	3.5	0.79–1.48
Dead wood	4.8	3.1	3.7	2.9	0.72
Live wood and bark	4.1	2.1	3.0	0.4	0.49
Live foliage	4.1	3.7	1.4	0.2	0.43
Total	28.6	18.6	18.6	12.4	3.83

[a]Calculated by weighting the emissions from each burn class by the area of that burn class over the fire perimeter. Ranges shown for litter, duff, and soil reflect uncertainty in parameter estimates as described in text.

and duff computed for each of the 180 plots did not covary with the actual preburn litter and mass. For instance, if conditions were such that ground fuel consumption was moisture-limited, more litter and duff masses may equate to lower fractional combustion due to greater moisture retention. Conversely, if conditions were such that ground fuel consumption was continuity-limited rather than moisture-limited, lower litter and duff masses may equate to lower fractional combustion.

[25] While our estimate of preburn mineral soil carbon (including roots) was crudely based on samples from only three study plots, by far the most uncertain parameter was the presumed depth to which all carbon was combusted below exposed mineral surfaces identified in the inventory data as either "moderately" or "deeply" charred. Our best estimate of 2.0 and 4.0 cm, respectively, was based on the assumption that surface temperatures during the Biscuit in some cases exceeded 700°C (Bormann, personal communication), that soil temperatures during fire attenuate rapidly with depth, and that soil carbon begins to combust at 100°C [*Agee*, 1993]. However, it is also reasonable to believe that soil carbon could have completely combusted to depths of up to 5 cm or that complete combustion never exceeded 2 cm.

[26] To quantify the potential uncertainty stemming from assumptions regarding litter, duff, and mineral soil combustion, we computed an alternative maximum and minimum value for total pyrogenic emissions across the Biscuit. An alternative maximum value of 4.4 Tg was arrived upon by matching the higher litter and duff combustion factors to higher preburn litter and duff masses (i.e., a positive interaction effect), and assigning deep maximum soil C consumption depths of 3 cm and 5 cm for mineral surfaces identified as moderately and deeply charred, respectively. Similarly, an alternative minimum value of 3.5 Tg was arrived upon by matching the higher litter and duff combustion factors to lower preburn litter and duff masses (i.e., a negative interaction effect), and assigning shallow maximum soil C consumption depths of 1 cm and 2 cm for mineral surfaces identified as moderately and deeply charred, respectively. The litter and duff component of the analysis was performed by first identifying the percentile of each combustion record from the entire distribution, then multiplying each litter and duff combustion record by a preburn mass selected from the same percentile of its distribution (for maximum value), and finally multiplying each litter and duff combustion record by a preburn mass selected from the reverse percentile (100-x) of the preburn mass distribution (for minimum value).

[27] Because the combustion data come from a regular sampling scheme, and because the severity map was used only to bin (not measure) combustion factors, the particular burn severity classification used to bin the plots has little influence on our estimate of fire-wide emissions. The effect of burn severity classification on the estimate of fire-wide emissions arises only from potential covariance between burn severity and preburn carbon density. To investigate this source of uncertainty, we computed an alternative estimate of fire-wide emissions using all the same combustion data but treating all plots as a single burn severity class (equation (1) without the i designation). The resulting estimate of fire-wide pyrogenic emissions was different by only 10%. Because any alternative severity classification would likely have more in common with the BAER classification than no classification at all, it is reasonable to assume that the use of an alternative severity classification would result in a discrepancy in total pyrogenic emissions much smaller than 10%.

4. Discussion

4.1. Comparisons With Other Studies

[28] Overall, the combustion factors reported here for litter and duff (0.70–1.00 for litter and 0.40–1.00 for duff depending on fire severity) are similar to those reported or used by others modeling fire emissions. *Wiedinmyer et al.* [2006] used litter combustion factors of 0.8 to 0.9 depending on tree cover when modeling combustion across North America, *Soja et al.* [2004] used litter combustion factors of 0.2 to 1.0 depending on fire severity when modeling combustion across Siberia, and *Michalek et al.* [2000] used combined litter and humus combustion factors of 0.2 to 0.9 depending on fire severity when modeling combustion for a black spruce forest in Alaska.

[29] Our combustion factors for tree stems (<0.01–0.03 for stems >7.6 cm DBH and <0.01–0.71 for stems <7.6 cm DBH, depending on fire severity) are somewhat lower than values commonly used by modelers. *Wiedinmyer et al.* [2006] used a woody fuel combustion factor of 0.30 when modeling high severity combustion across North America, *Soja et al.* [2004] used a tree combustion factor of 0.30 when modeling high severity combustion across Siberia, and *Lü et al.* [2006] used a tree combustion factor of 0.10 for temperate forests of China. While the definition of woody fuel varies among these studies, the application of these combustion factors to the Biscuit Fire would lead to a large overestimation of pyrogenic emissions, in part because a significant portion of the biomass is in large trees that experience very little wood combustion. Notably, the com-

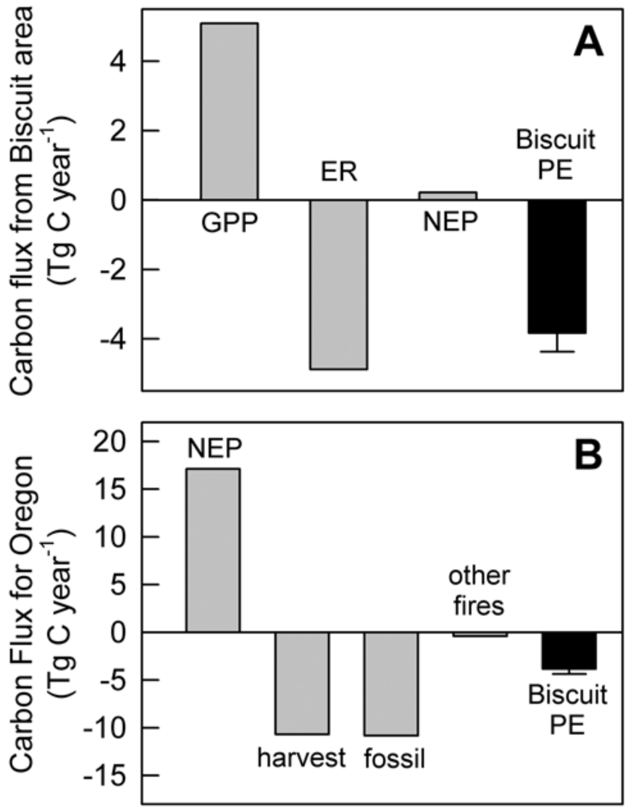

Figure 3. Pyrogenic carbon emissions from the 2002 Biscuit Fire (PE) compared with simulated ecosystem fluxes from (a) the forest present prior to the fire and (b) simulated biome fluxes across Oregon. GPP is Gross Ecosystem Production, NEP is Net Ecosystem Production, ER is total Ecosystem Respiration, and harvest is the sum of both forest product and crop removals. Data for all grey bars are from simulations by *Turner et al.* [2007] averaging the years 1996–2000 except fossil emissions which represent 2000 values from *Blasing et al.* [2004]. Error bar on Biscuit PE covers the upper alternative estimate described in this study.

bustion factors we report here for high severity fire are very similar to those reported for western Washington state, United States, by *Fahnestock and Agee* [1983], who, using no more than expert knowledge, estimated combustion factors to be 0.05, 0.10, 0.75, 0.30, and 0.80 for stems, branches, understory vegetation, dead wood, and forest floor, respectively, in high-severity wildfire.

[30] The latest AP-42, a document used by the U.S. Environmental Protection Agency in estimating air pollution, reports values for fuel loading (mass of fuel typically consumed by wildfire) of 135 and 40 Mg ha^{-1} for Oregon and California forests, respectively. Applying the former of these two values to the Biscuit would yield a total pyrogenic emission of about 14 Tg C (four times that reported in this study). However, applying the latter of these two values to the Biscuit would yield a total pyrogenic emission of about 4 Tg C (just outside our upper estimate). The discrepancy between values for Oregon and California can be traced to *Yamate* [1973], who first compiled fuel loading values for forests of the United States from what were regionally different approaches to estimating forest fuels.

4.2. Utility of Inventory Data

[31] Only through the use of federal inventory data were we able to assess pool-specific carbon losses over an area as large and diverse as that affected by the Biscuit Fire. The addition of fire-related measurements to the normal suite of inventory metrics was done primarily to predict delayed mortality, validate fire behavior models, and monitor the effects of fire on soil. These measurements also proved very useful in making estimates of pyrogenic emissions. The largest limitation to the inventory data used in this study is the absence of preburn litter and duff mass. While one can, as we did, use cover type to assign each plot a regional average value, only by matching observations of combustion to preburn measurements made at the same location can one confidently account for interactions that may exist between preburn mass and the subsequent combustion factor. The addition of litter and duff depth to the standard inventory protocol would go a long way toward improving our ability to estimate carbon losses.

[32] The second most valuable addition to inventory measurement with respect to pyrogenic emissions would be to extend the measurement of dead trees to include those less than 7.6 cm DBH. As determined from data collected in our supplementary plots, a great deal of the mortality and combustion occurred in this smaller size class. If the purpose of postburn inventory is to be expanded to include estimates of pyrogenic emissions of carbon or any another chemical species, it would be highly recommended to modify federal inventory protocols to include assessment of the smaller fire-killed trees. As interest grows in monitoring the effects of and recovery from fire in forests of the western United States, it is likely that federal inventory data will be increasingly relied upon.

4.3. Regional Significance of Biscuit Emissions

[33] One way to consider the importance of pyrogenic emissions from the Biscuit Fire is to compare it to fluxes from the same parcel of ground prior to the fire. As illustrated in Figure 3a, the estimated 3.8 Tg of C released as a result of combustion during the fire is nearly equal to the annual gross primary production, and approximately 18 times the annual net ecosystem production, simulated for an equal area of forest in the same Klamath-Siskiyou ecoregion (data from simulations by *Turner et al.* [2007]). Clearly pyrogenic emissions from a disturbance of this magnitude are an important part of any forest carbon budget. Nevertheless, one must realize that over 60% of the combustion comes from litter, foliage, and small downed wood, all of which are believed to have mean residence times of 10–20 years [*Law et al.*, 2001]. While some fraction of the combusted surface fuels would, without fire, find its way into long-term soil carbon pools, a sizable fraction of the pyrogenic emissions may be thought of as being destined for biogenic emission (i.e., through decay) within 1 to 2 decades with or without fire. Moreover, the proportion of these higher turn-over pools that is combusted should equate to a subsequent reduction in the heterotrophic respiration of these pools until they become recharged by new litter and branch fall. Conversely, carbon pools with

longer residence times, such as the stems of larger trees, contributed proportionally less to the pyrogenic emissions.

[34] Preliminary calculations suggest that the biomass killed but not combusted by the Biscuit Fire approaches 11 Tg C. As this material decays, the protracted biogenic emissions initiated by the Biscuit Fire should eventually exceed the one-time pyrogenic emission. However, considering that the majority of this fire mortality is in the form of large tree boles, uncertainties in the aerial decay rates of fire-killed trees, the rates at which these trees fall to the ground, and any decompositional effects of charring make it difficult to predict just how this biogenic loss will play out.

[35] Another way to consider the importance of pyrogenic emissions from the Biscuit Fire is to compare this one-time flux to regional fluxes in the same year. As illustrated in Figure 3b, the 3.8 Tg C estimated to have been released by the Biscuit Fire in this study is equal to approximately one third of the 10.8 Tg C reported to be released annually through fossil fuel burning in Oregon [*Blasing et al.*, 2004]. Furthermore, our estimate pyrogenic emission from the Biscuit Fire reduces estimates of Net Biome Production in Oregon (Net Ecosystem Production minus timber and crop harvest removals minus average fire emissions) in 2002 by more than half from 6.2 to 2.4 according process simulations made by *Turner et al.* [2007].

4.4. Future Research

[36] In this paper we estimate the pyrogenic carbon emissions from a particularly large fire in Oregon primarily for the purpose of determining the significance of this historical disturbance event to the carbon balance of the region, but also to explore the utility of federal inventory to do so. Undoubtedly, the most reliable way to extend these computations to future wildfires in the region would be to conduct similar ground measurements on these fires. However, the vast majority of fires in the western United States do not burn large enough to affect an appropriately large number of inventory plots that cover a range of variability in severity and preburn carbon pools. So, in the short term, combustion factors reported here could be applied to other Oregon fires with the assumption that they would be more accurate than other literature values that are derived largely from boreal fires. The observation that BAER severity classification consistently ranked the combustion factors of nearly all 24 preburn carbon pools (Table 3) suggests that it, as well as other classifications derived from remote imagery, may scale combustion factors across fires on comparable forests with acceptable accuracy. Only additional ground studies will be able to confirm this.

[37] One important direction for future work is to better quantify combustive losses from litter, duff, and mineral soil, as this was a primary source of uncertainty in our computations. Especially valuable would be repeated measures of litter and duff mass at the same sample points before and after a fire, as only these studies would reveal any covariance between preburn mass and fraction combusted (a potentially important interactive term not accounted for in equation (1)). Quantifying carbon combustion from mineral soil poses its own challenges. In a meta analysis including eight forest wildfire studies, *Johnson and Curtis* [2001] found substantial variability in the impacts of wildfire on A-horizon carbon content with an overall tendency for this pool to increase following wildfire, which was attributed to additions of charcoal and hydrophobic organic matter. The potential for wildfire to enrich soil carbon, combined with uncertainty surrounding postburn erosion and the sampling error ubiquitous to soil carbon quantification, unfortunately renders the before-after approach for assessing carbon combustion from mineral soil less tractable than it is for litter and duff. For these reasons the mechanistic modeling of soil carbon combustion from fire temperature (as done very crudely in this study) holds more promise than empirical approaches quantifying pyrogenic emissions from forest soils.

[38] Fine scale estimates of fuel loads, fuel consumption, and carbon production across the continental United States, Hawaii and Alaska continue to be improved by the FCCS (Fuel Characteristic Classification System) and fire behavior modles such as Consume 3.0 [*Sandberg et al.*, 2001; *Ottmar et al.*, 2007] (http://www.fs.fed.eu/pnw/fera/research/smoke). Future efforts to assess pyrogenic losses will likely be carried out through the use of process-based fire behavior models parameterized with these or similar fuel load layers, and driven by the sort of high precision remote imagery that can measure the intensity and duration of surface energy flux during the course of a wildfire [*Riggan et al.*, 2004]. These sophisticated approaches will still require independent estimates of fuel consumption like those that can be provided by prefire and postfire inventory.

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D. Azuma, Forest Sciences Laboratory, U.S. Forest Service, Portland, OR 97208, USA.
J. Campbell, D. Donato, and B. Law, Department of Forest Science, Oregon State University, Corvallis, OR 97331, USA. (john.campbell@oregonstate.edu)