Short Communication

# Black Carbon on Coarse Woody Debris in Once- and Twice-Burned Mixed-Conifer Forest

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## ABSTRACT

One important outcome of wildfire is the production of charcoal. Charcoal is highly resistant to decomposition and its physical and chemical properties enhance soil fertility and influence nutrient cycling. We compared the amount of black C (the carbon fraction of charcoal) on coarse woody debris (CWD; ≥7.6 cm diameter) and total CWD biomass at sites burned once in a high-severity fire with sites that burned in an initial high-severity fire and then reburned eight to ten years later. Twice-burned sites contained an average of 655 kg $ha^{-1}$ of black C on CWD, significantly more ($P = 0.004$) than the 323 kg $ha^{-1}$ present in once-burned sites. Total average CWD biomass was significantly greater in once-burned sites compared to twice-burned sites ($P < 0.001$). Black C accounted for 0.7% of CWD biomass in once-burned sites and 2.9% of CWD biomass in twice-burned sites. Short-interval reburns of patches burned in an initial high-severity fire increased the amount of black C on CWD while simultaneously reducing total CWD biomass.

## RESUMEN

Un importante producto de los incendios forestales es la formación de carbón. Este carbón es altamente resistente a la descomposición, y sus propiedades físicas y químicas aumentan la fertilidad de los suelos e influencian el ciclado de nutrientes. Nosotros comparamos la cantidad de carbono negro (la fracción de carbono contenida en el carbón) en desechos forestales medianos (CWD, ≥7,6 cm de diámetro) y la biomasa total de CWD en sitios quemados una sola vez con alta severidad, con otros en que se quemaron inicialmente con alta severidad y que se volvieron a quemar nuevamente entre ocho y diez años después. Los sitios quemados dos veces contenían un promedio de 655 kg $ha^{-1}$ de carbón negro en el CWD, significativamente mayor ($P = 0.004$) que los 323 kg $ha^{-1}$ presentes en sitios quemados solo una vez. La biomasa total promedio de CWD fue significativamente mayor en los sitios quemados solo una vez que en aquellos quemados dos veces ($P < 0.001$). El carbón negro fue del 0,7% de la biomasa de CWD en sitios quemados una vez, y del 2,9% de la biomasa de CWD en sitios quemados dos veces. Los intervalos cortos entre quemas en incendios de alta severidad inicial incrementan la cantidad de carbono negro en CWD, mientras que simultáneamente reducen la biomasa total de CWD.

*Keywords:* active fire regime, Bob Marshall Wilderness, compound disturbance, reburn, self-limiting fire, surface fuels, wilderness fire, wilderness management

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## INTRODUCTION

Short-interval, high-severity wildfire reburn patches contribute to forest landscape structural (Stevens-Rumann and Morgan 2016) and compositional (Coop *et al.* 2016) diversity. While short-interval reburns are not abundant due to self-limiting fire spread (Parks *et al.* 2015), past fire suppression has likely decreased their number and area below historical levels in many landscapes. Contemporary active fire regimes in large wilderness areas in which managers allow many wildfires to burn without suppression provide an opportunity to investigate the ecological effects of short-interval, high-severity reburns (Miller and Aplet 2016).

One important outcome of wildfire is the production of charcoal. Charcoal is carbon (C)-enriched material with a highly aromatic molecular structure produced during wildfires from pyrolysis of plant biomass (Scott *et al.* 2014). Charcoal is highly resistant to decomposition, making it a stable, slow-turnover C pool when sequestered in mineral soil or deposited in aquatic or marine sediments (Scott *et al.* 2014). Charcoal enhances soil fertility, soil moisture holding capacity, and influences nutrient cycling in fire-affected ecosystems (DeLuca and Aplet 2008).

Coarse woody debris (CWD; ≥7.6 cm diameter) stores 4% to 11% of aboveground C in northern Rocky Mountains mixed-conifer forests (Bisbing *et al.* 2010), and provides other important ecosystem functions, such as wildlife habitat and nutrient storage, in addition to influencing potential fire behavior and effects (Brown *et al.* 2003). Wildfires reduce CWD stocks through combustion during the fire event, but can also indirectly increase CWD stocks after fire when fire-killed trees fall to the ground. Coarse woody debris is also a substrate for charcoal formation, and pyrolysis of CWD during wildfires is a source of black C production (Wiechmann *et al.* 2015).

Relationships between recent fire history, CWD stocks, and black C formation on CWD remain poorly understood (DeLuca and Aplet 2008, Wiechmann *et al.* 2015). Addressing this knowledge gap would help managers understand tradeoffs associated with alternative fire management decisions (Brown *et al.* 2003) and contribute to the scientific basis for wilderness fire management (Miller and Aplet 2016). We therefore compared the amount of black C (the C fraction of charcoal) on CWD and total CWD biomass at sites that burned once in a high-severity fire with sites that burned in an initial high-severity fire and then reburned eight to ten years later.

## METHODS

The study area includes the floor and sidewalls of the South Fork Flathead River valley in the Bob Marshall Wilderness, Montana, USA (47°38'N, 113°21'W). Upland forests of this area are composed primarily of *Larix occidentalis* Nutt., *Pseudotsuga menziesii* (Mirb.) Franco var. *glauca* (Beissn.) Franco, *Pinus contorta* Douglas ex Loudon var. *latifolia* Engelm. ex S. Watson, *Abies lasiocarpa* (Hook) Nutt. (Belote *et al.* 2015), and *Picea engelmannii* Parry ex Engelm., with limited areas of *Pinus ponderosa* Lawson & C. Lawson (Keane *et al.* 2006) Much of the study area burned in 2000 and 2003; the most recent prior fires occurred in the 1930s.

We located 10 sites in once-burned areas (five in 2000 fire only, and five in 2003 fire only), and 10 sites in twice-burned areas (five in 2013 reburn of 2003 fire, and five in 2011 reburn of 2003 fire). Sample sites were chosen randomly from patches within the initial fire that was classified as high-severity burn and at least 3 pixels × 3 pixels (90 m × 90 m) in area, using burn severity maps from the Monitoring Trends in Burn Severity program (mtbs.gov, accessed 2 April 2017).

Coarse woody debris and associated charcoal were sampled in August 2014 using the planar intercept method (Donato *et al.* 2009). Sampling transects were arranged in a 30 m × 30 m square oriented to the cardinal directions and along one interior diagonal of the square, for a total of 162.4 m of transect per site. We recorded diameter, species, decay class, and depth of char for each CWD piece that intersected the sampling plane.

Charcoal mass estimation involved first making the standard planar intercept CWD volume calculation for each CWD piece including the charred rind, as well as calculating the volume of the inner uncharred core by reducing the CWD piece radius by the measured char depth (Donato *et al.* 2009). The difference of these two cylinders is the volume of charcoal on the CWD piece. We calculated the total CWD volume using Equation 1 in Donato *et al.* (2009) and bias-corrected charcoal volume using Equations 1, 3, and 8 in Donato *et al.* (2009). We converted CWD volumes to mass estimates using species and decay class specific CWD densities (Bisbing *et al.* 2010), and estimated black C mass using Equation 4 in Donato *et al.* (2009). We tested for differences of black C mass (kg $ha^{-1}$) and total CWD biomass (kg $ha^{-1}$) between once-burned and twice-burned forests using two-sample Wilcoxon rank sum tests ($W$). Statistical analyses were performed in R version 3.1.2 (R Core Team 2014).

## RESULTS

Twice-burned sites had approximately double the amount of black C on CWD that was present in once-burned sites (Table 1), a statistically significant difference ($P$ = 0.004, $W$ = 87). Relative variability (CV; coefficient of variation) of black C was about three times higher in once-burned sites (CV = 133) than in twice-burned sites (CV = 41), with both the lowest and highest black C stocks measured in once-burned forests.

Total CWD biomass was significantly greater in once-burned sites compared to twice-burned sites ($P$ < 0.001, $W$ = 3). Once-burned sites had about double the CWD biomass present in twice-burned sites (Table 1). Relative variability of CWD biomass was similar in once-burned (CV = 32) and twice-

**Table 1.** Black (pyrogenic) carbon produced on CWD and total CWD biomass in once- and twice-burned mixed-conifer forest in the Bob Marshall Wilderness, Montana, USA.

| **Black C (kg ha$^{-1}$)** | **Once burned** ***n*** **= 10 sites** | **Twice burned** ***n*** **= 10 sites** |
|---|---|---|
| Mean | 323 | 655 |
| Median | 239 | 604 |
| CV | 133 | 41 |
| Range (minimum–maximum) | 0–1 489 | 285–1 133 |
| **Total CWD biomass (kg ha$^{-1}$)** | | |
| Mean | 45 894 | 22 755 |
| Median | 40 956 | 21 761 |
| CV | 32 | 41 |
| Range (minimum–maximum) | 26 116–75 823 | 6 001–34 787 |

burned (CV = 41) sites. In contrast, relative variability of CWD biomass was markedly lower than that of black C biomass in once-burned sites (Table 1). Black C accounted for 0.7% of CWD biomass in once-burned sites and 2.9% of CWD biomass in twice-burned sites.

## DISCUSSION

Our data show that short-interval reburns (≤10-year fire return) of patches burned in an initial high-severity fire can cause a net increase of black C on CWD, even while reducing total CWD biomass (Table 1). Managers can reduce surface fuel loads (Stevens-Rumman and Morgan 2016), promote landscape diversity (Coops *et al.* 2016), and increase black C production by allowing fires to reburn previously burned areas, including high-severity patches.

Compound disturbance sequences that increase CWD stocks available for charring in a subsequent fire—such as a windstorm, bark beetle outbreak, or high-severity wildfire—appear to promote black C formation on CWD. Donato *et al.* (2009) estimated that a single high-severity fire (in 2002) produced 204 kg ha$^{-1}$ of black C on CWD, and found 442 kg ha$^{-1}$ of black C on CWD in portions of the same 2002 fire that reburned a 1987 stand-replacement fire. In a subalpine forest in Colorado, Buma *et al.* (2014) found that black C on CWD was marginally more abundant in areas subjected to a 1997 high-severity blowdown event followed by a 2002 wildfire (390 kg ha$^{-1}$), compared to 2002 wildfire alone (220 kg ha$^{-1}$), or combined blowdown salvage-logging wildfire disturbance (200 kg ha$^{-1}$). In a southeastern Australia eucalypt forest (Aponte *et al.* 2014), sites that were prescribed burned on a three-year return interval had significantly more black C on CWD (330 kg ha$^{-1}$) than sites that were prescribed burned on a 10-year return interval (220 kg ha$^{-1}$). High-frequency fire may initially increase CWD black C stocks relative to less-frequent fire (Aponte *et al.* 2014) but, eventually, CWD recruitment, and charcoal production and consumption, should reach equilibrium under high-frequency fire (DeLuca an Aplet 2008).

We suggest that pre-fire CWD load is the primary control of charcoal production in wildfires (including reburns), given sufficiently active fire behavior to initiate CWD combustion. After an initial high-severity fire (Donato *et al.* 2009), CWD biomass increases over time as fire-killed trees fall, creating a fuel bed susceptible to charring during a repeat burn. Other factors such as fuel moisture, fire behavior, and fire weather may influence charcoal production as well. But, the consistent increase of black C on CWD in compound disturbance sequences in which the initial disturbance increases CWD biomass (Table 1; Donato *et al.* 2009, Buma *et al.* 2014) suggests that pre-fire CWD biomass is the primary driver. This idea should be tested with experimental burns of sites with different CWD loads. Measurements of charred CWD fragmentation and mineralization rates are needed to determine and model fates of black C produced on CWD (Wiechmann *et al.* 2014).

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