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ARTICLE

Surface fuel loads following a coastal–transitional fire of unprecedented severity: Boulder Creek fire case study

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Abstract: British Columbia experienced three years with notably large and severe wildfires since 2015. Multiple stand-replacing wildfires occurred in coastal–transitional forests, where large fires are typically rare, and thus, information on post-fire carbon is lacking. Because of their carbon storage potential, coastal–transitional forests are important in the global carbon cycle. We examined differences in surface fuel carbon among fire severity classes in 2016, one year after the Boulder Creek fire, which burned 6 735 ha of coastal–transitional forests in 2015. Using remotely sensed indices (dNBR), we partitioned the fire area into unburned (control), low-, moderate-, and high-severity classes. Field plots were randomly located in each class. At each plot, surface fuel carbon was quantified by type, namely coarse, small, and fine woody material, duff, and litter, and carbon mass by fuel type was compared among severity classes. Total surface fuel carbon did not differ significantly between burned and unburned plots; however, there was significantly less duff and litter carbon in burned plots. Remotely sensed severity classes did not properly capture wildfire impacts on surface fuels, especially at lower severities. Pre-fire stand characteristics are also important drivers of surface fuel loads. This case study provides baseline data for examining post-fire fuel carbon dynamics in coastal–transitional British Columbia.

Key words: wildfire, forest carbon, fire severity, forest floor, surface fuels.

Résumé : Depuis 2015 la Colombie-Britannique a connu trois années durant lesquelles sont survenus des feux de forêts particulièrement vastes et sévères. De multiples feux de forêt qui entraînent le renouvellement des peuplements sont survenus dans les forêts transitionnelles côtières où de tels feux sont typiquement rares et où l'information sur le carbone après feu est par conséquent inexistante. Étant donné leur capacité à emmagasiner le carbone, les forêts transitionnelles côtières sont importantes dans le cycle global du carbone. Nous avons étudié les différences dans la quantité de carbone contenu dans les combustibles de surface parmi les classes de sévérité du feu en 2016, un an après le feu de Boulder Creek qui a brûlé 6735 ha de forêt transitionnelle côtière en 2015. À l'aide d'indices déterminés par télédétection (réflectance des zones brûlées), nous avons découpé la région touchée par le feu en fonction de la classe de sévérité du feu : nulle (témoin non brûlé), faible, modérée, élevée. Des places échantillons ont été localisées au hasard sur le terrain dans les zones correspondant à chacune des classes de sévérité. Dans chaque place échantillon, le carbone des combustibles de surface a été quantifié par type : matériel ligneux grossier, petit et fin, humus et litière. La masse de carbone par type de combustibles a été comparée parmi les classes de sévérité. La quantité totale de carbone dans les combustibles de surface n'était pas significativement différente que les places échantillons aient été brûlées ou non. Cependant il y avait significativement moins de carbone dans l'humus et la litière dans les places échantillons brûlées. Les classes de sévérité déterminée par télédétection ne reflétaient pas adéquatement les impacts des feux de forêt sur les combustibles de surface, particulièrement dans le cas des feux de faible sévérité. Les caractéristiques du peuplement avant feu sont également d'importants déterminants des charges de combustibles de surface. Cette étude de cas fournit les données de base pour étudier la dynamique du carbone après feu dans la zone transitionnelle côtière en Colombie-Britannique. [Traduit par la Rédaction]

Mots-clés : feu de forêt, carbone forestier, sévérité du feu, couverture morte, combustibles de surface.

Introduction

Wildfire is a common disturbance in many forest ecosystems, with historical fire regimes ranging from frequent surface fires that cause minimal overstory tree mortality to infrequent but intense stand-replacing crown fires (Schoennagel et al. 2004). Forest wildfire characteristics are shifting with climate change, and increasing temperatures may cause future increases in the total area burned, fire activity, and the severity of the impacts (Westerling et al. 2006; Wotton et al. 2017). Projected changes in climatic conditions toward longer, warmer, and drier summers have important implications for future fire regimes (Daniels et al. 2017) and wildfire impacts on forest carbon.

In western North America, mixed-severity fire regimes are most common. They are well-documented in the interior conifer forests growing in dry climates of the Pacific Northwest region, where fire return intervals range from years to decades (Marcoux et al. 2015). Before extensive forest management began in British Columbia (BC), mixed-severity fires likely burned in the coastal tem-

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perate rainforests of the region as well, albeit with long fire return intervals (Daniels and Gray 2006). The transitional forests between the coastal and interior ecosystems are likely exposed to a combination of both of these regimes with highly variable return intervals and fire severities.

In southwestern BC, coastal maritime rainforests transition to interior continental forests over a linear distance of 200 km. These forests lie on the boundary between the Pacific Maritime and Montane Cordillera ecozones of Canada (Government of Canada 2017). Temperate forests across this gradient are important in the global carbon balance, as they sequester and store large amounts of carbon (Smithwick et al. 2002; Nave et al. 2011). Decaying surface fuels consist of several distinct types: forest floor (duff, litter, fine woody material (FWM)), small woody material (SWM), and coarse woody material (CWM) (McRae et al. 1979). Combined, these fuels can account for almost one-quarter of total ecosystem carbon in some Pacific Northwest forests, with carbon mass ranging from 30 Mg ha^{-1} in drier regions to over 100 Mg ha^{-1} in moist coastal areas (Smithwick et al. 2002). Forest surface fuels benefit ecosystems in many different ways such as storing nutrients and protecting soils from erosion (Chojnacky et al. 2009). These fuels are also important in fire risk and behaviour, because they affect surface fire intensity and spread (Agee and Huff 1987).

In BC, three of the past four fire seasons included uncharacteristically large and severe wildfires that burned during droughts and extreme fire weather. In the summer of 2015, an area of 24 789 ha of coastal and transitional forest burned in the Coastal Fire Zone (BC Wildfire Service 2017). Fires in these coastal–transitional ecosystems can have long return intervals, up to several centuries (Daniels et al. 2017), suggesting a fire regime that is characterized by relatively rare fires. Due to these long fire return intervals, little information is available about post-fire conditions and dynamics of surface fuels. Yet, this information is going to become more important, as climatic changes are likely to alter existing fire regimes (Daniels et al. 2017), suggesting a need to understand how these altered fire regimes can affect forest stand conditions. Understanding the impact of contemporary wildfires on forest composition, structure, and post-fire recovery is essential to project future carbon storage dynamics in the region (Dymond et al. 2016). Post-fire fuel loads play an important role in the risk and severity of reburns, which can substantially impair post-fire recovery (Agee and Huff 1987; Prichard et al. 2017).

The purpose of this case study was to examine surface fuel loads after the Boulder Creek fire, a relatively large, high-severity wildfire that burned second-growth coastal – interior transitional forests in the Coastal Fire Zone of BC in 2015 (BC Wildfire Service 2018). To understand how surface fuel loads differ among remotely sensed forest severities in these forests, we quantified differences in surface fuels remaining in plots that burned at different severities and tested for differences in fuel loads between burned and unburned plots. This case study provides baseline fuel loads one year after the Boulder Creek fire. The study established permanent sample plots to be revisited in the future to document post-fire surface fuel dynamics.

Materials and methods

Study area

This study was conducted in the Boulder Creek fire (50.626°N, 123.401°W) located along the upper Lillooet River valley, 60 km northwest of the village of Pemberton in southwestern BC (Fig. 1). The Boulder Creek fire, ignited by lightning on 14 June 2015, was one of seven 2015 fires that were notable due to their size, severity, and the risk they posed to communities. It burned 6 735 ha of forest, largely at high severity (BC Wildfire Service 2017). This study area is in the Coastal Western Hemlock moist submaritime subzone (CWHms1) and Mountain Hemlock moist maritime subzone biogeoclimatic zones; consisting of a transition between moist submaritime ecosystems and drier interior ecoregions (Fairbarns 2011). This transition is strongly influenced by complex physiography and steep climatic gradients (Daniels et al. 2017).

Within the study area, tree species also vary with elevation, which ranges from 400 to 2 000 m above sea level, with steep slopes and river valleys (Fairbarns 2011). In the lower elevation CWHms1 variant, the dominant tree species include western redcedar (*Thuja plicata* Donn ex D. Don), western hemlock (*Tsuga heterophylla* (Raf.) Sarg.), and Douglas-fir (*Pseudotsuga menziesii* (Mirb.) Franco) with minor components of amabilis fir (*Abies amabilis* Douglas ex. J. Forbes) (Hamann et al. 2005). On valley-bottom floodplains, red alder (*Alnus rubra* Bong.), black cottonwood (*Populus trichocarpa* Torr. & A. Gray ex. Hook.), and bigleaf maple (*Acer macrophyllum* Pursh) dominate. Red alder is also common on steep slopes (Hamann et al. 2005).

The region surrounding the study area is prone to coarse-scale disturbances including seismic activity, landslides, avalanches, and floods (Green et al. 1988). However, wildfires are relatively rare, depending on the dominant vegetation of the area. Forests in the CWHms1 variant are classified as Natural Disturbance Type 2, with infrequent mixed severity or stand-replacing fires at mean intervals of 200 years (BCMOF and BCMOE 1995; Daniels and Gray 2006). At high elevations in the region, the forests are classified as Natural Disturbance Type 1, with mean fire return intervals of 350 years (BCMOF and BCMOE 1995). Wildfires above 3 000 ha are rare in the coastal fire zone of BC. When large fires (>200 ha; Stocks et al. 2002) occur in the coastal region, they are commonly 300–800 ha in size (BC Wildfire Service 2018). The Boulder Creek fire is only the third wildfire that has burned more than 5 000 ha of coastal–transitional forest between 1950 and 2015. Consistent with representations of a stand-replacing fire regime, clear-cut harvesting and even-aged silvicultural systems have been applied throughout much of the valley since 1977. Following harvesting, tree planting supplemented natural regeneration to ensure adequate stocking of the economically desirable species Douglas-fir and western redcedar.

Sample plots

Landsat 8 delta normalized burn ratio (dNBR) derived fire severity classes (BC MFLNRO 2016) were used in this study. These are calculated by comparing pre-fire normalized burn ratio values with imagery captured shortly after the fire was declared "out". Normalized burn ratios record infrared reflectance from plant materials and the water content of vegetation and soils (Soverel et al. 2010). The dNBR values are then used to calculate Burned Area Reflectance Classifications values, which are divided into four fire severity classes (BC Ministry of Forest, Lands, and Natural Resource Operations, personal communication, 2016). These dNBR-derived severity classes, as well as biogeoclimatic zones (BCMOF and BCMOE 1995), were used in a geographic information system to stratify the study area by fire severity — unburned, low, moderate, and high — within biogeoclimatic variants. We generated a grid of 200 m × 200 m squares across the fire area and randomly selected plots from the centre point of the grid cells. Much of this area had been harvested and replanted prior to the year 2000 and was covered by second-growth CWHms1 forests less than 50 years old. Therefore, we sampled 37 plots in the second-growth forests in the CWHms1 zone across the four severity classes (Fig. 1): 10 unburned plots, and 10, 8, and 9 plots that burned at low-, moderate-, and high-severity, respectively.

Field sampling

Eight to 10 plots (n = 37) were sampled in 2016, 1 year after the fire, in each of the unburned, low-, moderate-, and high-severity classes. Following the protocol for the Canadian National Forest Inventory (CFIC 2008), plot centers were permanently staked and random azimuths were chosen to establish a 30 m fuels transect with the plot center bisecting the transect (Fig. 2). A second fuel

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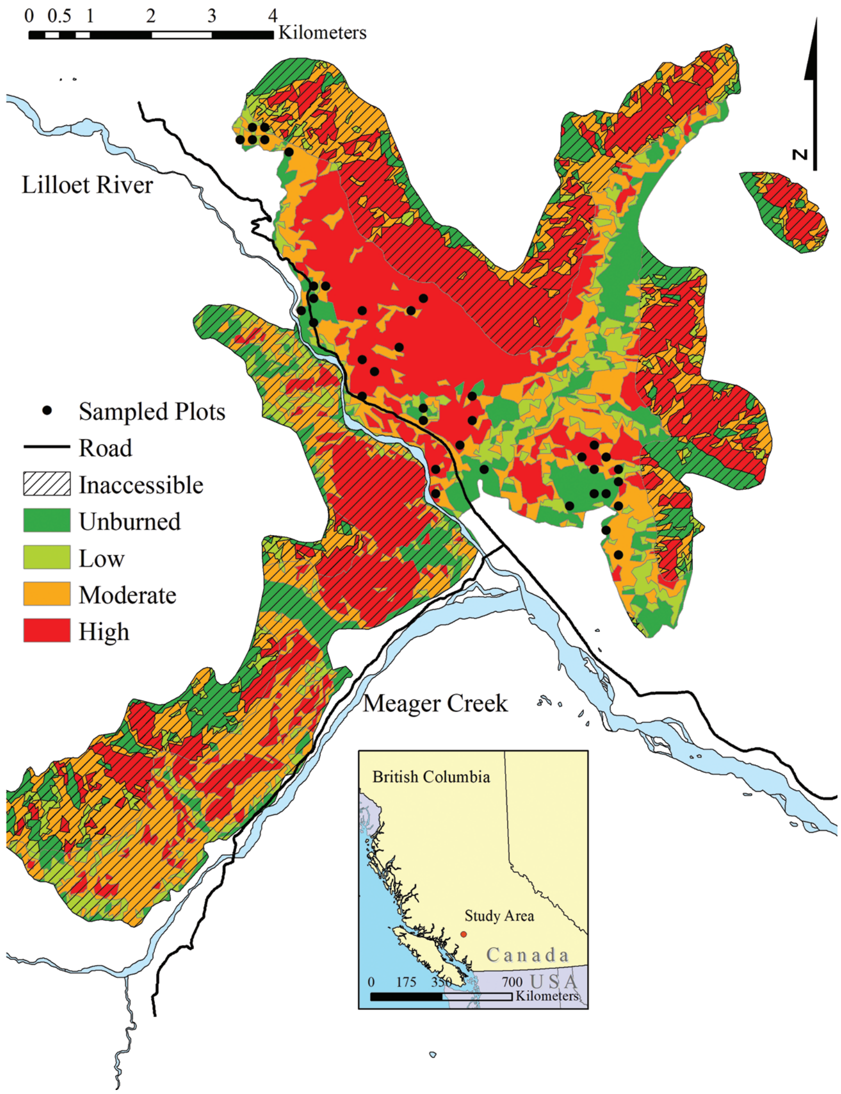
Fig. 1. Fire severity map of the 2015 Boulder Creek fire. Political boundary data provided by U.S. Geological Survey. Fire severity data from BC MFLNRORD 2016.



transect was established at a 90 degree angle from the first transect. Using the line intercept method (Thompson 2012), large CWM (>30 cm in diameter) was measured along the entire transect, and medium CWM (7.5–30 cm in diameter) was measured on a total distance of 20 m, from 0–10 m and 20–30 m. For both large and medium CWM fuels, we recorded diameter at the point of intersection (cm), the angle at which the piece was tilted (degrees), and the distances along the transect (m). For each piece of wood, we recorded the species, if discernable, and assigned a decay class (1–5) (Maser et al. 1979). We did not assess the scale to which each piece was burned. For all analyses, we combined the large and medium CWM data, referred to as CWM. Along 10 m of the transect (from 0–5 m and 25–30 m), SWM was tallied into one of three intersection diameter size classes (1.1–3.0 cm, 3.1–5.0 cm, and 5.1–7.5 cm).

In each plot, we collected FWM fuels (<1.0 cm in diameter) in 30 cm × 30 cm quadrats, established at the beginning and end of both transects. Using a sampling frame, all FWM pieces were collected and clippers were used to cut any pieces that straddled the frame border. Roots and stems still attached to the ground were not collected. The samples were then dried at 70 °C until they reached constant mass, and dry weight biomass (g) was recorded.

For the purposes of this study, we defined litter as all non-woody plant material such as foliage and cones (Keane 2015) that are not decayed or not decayed past the point of recognition. Although litter is often expanded to include the smallest woody materials (Chojnacky et al. 2009; Jain and Fried 2010), we chose to exclude those from litter measurements because we collected and measured them separately as FWM. Duff was considered to be decayed and unrecognizable plant materials (Keane 2015). The depths of the duff and litter layers above the mineral soil were measured to the nearest millimetre at 10 and 20 m along both transects in each plot and in each FWM quadrat (Brown 1974; CFIC 2008). If there was no apparent duff or litter or if the measurement point intersected rock or fallen logs, the depths were recorded as zero. To estimate duff and litter bulk density, a 10 cm × 10 cm sample of the duff and litter was taken from each plot, where possible, and the depth of the sample was measured. To record dry weight biomass (g), each duff or litter sample was dried at 70 °C until it reached constant mass.

Biomass and carbon calculations

For CWM, fuel biomass was calculated using equations from the United States Forest Inventory and Analysis program (Woodall

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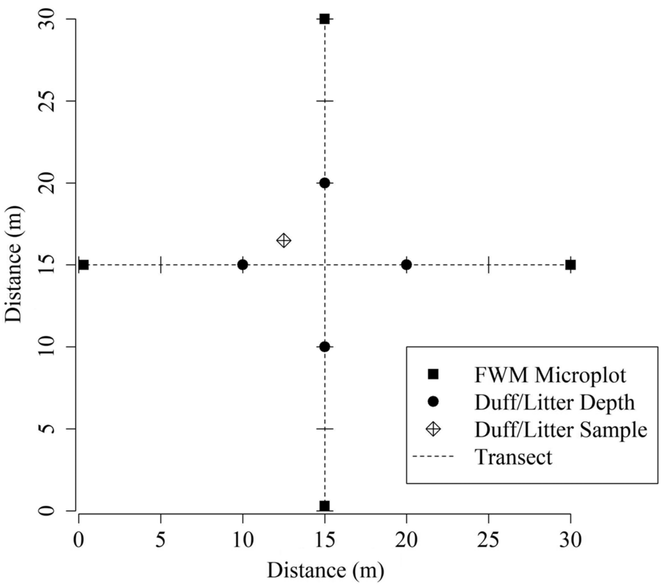
Fig. 2. Ground plot layout, adapted from protocols used in the Canadian National Forest Inventory program (CFIC 2008).



and Monleon 2008, p. 19, eq. 4) with species- and region-specific bulk density and decay reduction factors (Natural Resources Canada, personal communication, 2016). For SWM, we used the midpoints of each SWM diameter class in the analysis. The midpoint was 2.05 cm in class 1 (range = 1.1–3.0 cm), 4.05 cm in class 2 (range = 3.1–5.0 cm), and 6.3 cm in class 3 (range = 5.1 – 7.5 cm). The volume of SWM in each class was calculated from the midpoint diameter and number of pieces of wood using the volume formula by Woodall and Monleon (2008). We converted volume to biomass using bulk density averages reported by Fasth et al. (2010).

Duff and litter fuel carbon mass were calculated from the measured depth and estimated mean density values. To estimate the mean density value, the volume of each sample collected in the microplot was calculated and divided by the dry weight. The volume of the duff and litter layer was calculated for an area of 1 ha with the average duff and litter depths used as height. To obtain biomass per hectare, this volume was multiplied by the density.

To obtain carbon mass for woody fuels, the biomass values in megagrams per hectare (Mg ha^{-1}) were multiplied by 0.5, a standard conversion factor for woody fuels (Campbell et al. 2007). The same conversion constant was used for litter, as the proportion of carbon in fresh Douglas-fir and western redcedar litter has been found to be approximate 50% (Moore et al. 2006). Decayed fuels such as duff typically contain a smaller proportion of carbon — approximately 39% for Douglas-fir and 45% for western redcedar forests (Moore et al. 2006). As Douglas-fir was one of the most common species in the sample plots, we applied a biomass to carbon conversion constant of 0.4 for duff.

Statistical analysis

Poisson pseudo-maximum likelihood models (Santos Silva and Tenreyro 2006) were fit with the PROC GLIMMIX procedure in SAS 9.4 to test for differences in mean fuel carbon mass between remotely sensed fire severity classes. This modelling approach was chosen because our data were strictly positive and had many zero values. We applied these methods for carbon mass in the following surface fuels: woody material (SWM, CWM), forest floor (duff, litter, FWM), and all of the examined fuel types combined, which will be referred to as total surface. The one fixed factor used in our analysis was severity with four levels: unburned, low, moderate, and high. If severity levels were not significantly different from each other, a burn indicator variable with two levels — unburned, burned — was used in place of severity. The response variable was fuel carbon mass (Mg ha^{-1}) by fuel type.

Table 1. Plot characteristics by fire severity.

		Elevation (m)			Slope (%)		
Severity	n	Mean	SD	Range	Mean	SD	Range
Unburned	10	713	194.8	493–1065	25.0	22.7	0–60
Low	10	857	246.6	475–1058	32.9	20.6	0–68
Moderate	8	811	173.4	486–965	48.1	22.2	21–80
High	9	722	211.7	432–1059	36.0	27.4	0–65

Note: SD, standard deviation.

Results

The most common overstory species was Douglas-fir, followed by western hemlock and western redcedar, with scattered stands of black cottonwood and amabilis fir in the unburned areas. Plot elevation ranged from 432 to 1 065 m, with a minimum slope of 0% and a maximum slope of 80% (Table 1). With a mean elevation of 857 m, plots that burned at low severity had the highest elevation (Table 1). Moderate-severity plots had the steepest slopes overall, with mean of 48% (Table 1). Low- and moderate-severity plots were typically found on southwestern slopes, whereas most unburned plots and high-severity plots were on south-facing slopes. High and moderate severities were classified as 39% and 32% of the fire area, respectively. Low-severity and unburned classes covered 10% and 19% of the fire, respectively (BC MFLNRO 2016). In moderate- and high-severity plots, most of the overstory trees were killed, leaving minimal living plant material. In moderate-severity plots, dead foliage was often still present on branches, whereas most foliage and fine twigs were consumed in high-severity plots. The impact of fire on low-severity plots was more variable, with minimal, patchy overstory mortality.

Seven out of 37 plots had been clearcut within 7 years prior to the Boulder Creek fire, and all burned at low (n = 5) or moderate (n = 2) severities. We initially performed the analyses with and without the logged plots and compared the results that only showed minor differences (Peterson 2018). Therefore, all 37 second-growth plots measured were included in all presented analyses.

The Boulder Creek fire burned large areas of managed second-growth forests that have experienced several logging operations, as well as a run-of-the-river hydroelectric project (V. Woodruff, personal communication, 2016), with few scattered old-growth management areas. One moderate-severity plot was found to be old-growth, with several large Douglas-fir trees that were approximately 1 m in diameter at breast height (DBH, 1.3 m) in size. Because the rest of the plots were second-growth stands, we excluded the old-growth plot from further analyses, as it was not representative of second-growth forests, our population of interest. During field sampling, we found that the remote sensing information misclassified one plot as unburned when there was clear evidence of a low-severity fire. This plot was treated as low severity in the analyses.

Total surface carbon

Overall, there was no significant statistical difference in total surface carbon between burned and unburned plots ($p \geq 0.1456$) (Table 2). For total surface carbon, the only difference among severity classes was between low and moderate severities ($p = 0.0365$), where plots that burned at moderate severity had significantly less total surface carbon compared with plots that burned at low severity. CWM was separated from the analysis to ensure that any differences in the total fine fuels (duff, litter, FWM, SWM) were not obscured by the relatively large amount of carbon mass found in CWM. No significant differences in total fine fuel carbon were found between burned and unburned plots ($p = 0.0924$) (Table 2). Although the differences were not significant, there were de-

Table 2. Carbon mass (Mg ha⁻¹ per fuel type) by fire severity, with standard deviation in parentheses.

Severity	*n*	Duff	Litter	FWM	SWM	CWM	Total fine fuels	Total surface fuels
Unburned	10	0.42 (0.39)	0.16 (0.09)	0.63 (0.40)	2.31 (2.45)	17.5 (25.02)	3.53 (2.89)	21.03 (24.75)
Low	10	0.12 (0.15)	0.08 (0.13)	0.59 (0.49)	1.54 (1.30)	18.31 (10.58)	2.34 (1.49)	20.65 (10.28)
Moderate	8	0.03 (0.04)	0.05 (0.07)	0.55 (0.37)	1.71 (1.73)	8.78 (7.67)	2.34 (1.69)	11.12 (8.12)
High	9	0.01 (0.01)	0.005 (0.008)	0.37 (0.33)	1.51 (1.28)	21.22 (24.89)	1.89 (1.38)	23.11 (25.53)

Note: Total fine fuels are the sum of duff, litter, FWM, and SWM. The total surface column represents the sum of all surface fuel types examined (duff, litter, FWM, SWM, and CWM).

creases in carbon mass in several of the examined fuel types, leading to an apparent decrease in total fine fuel carbon mass between burned and unburned plots, with minimal differences between low, moderate, and high severities (Fig. 3; Table 2).

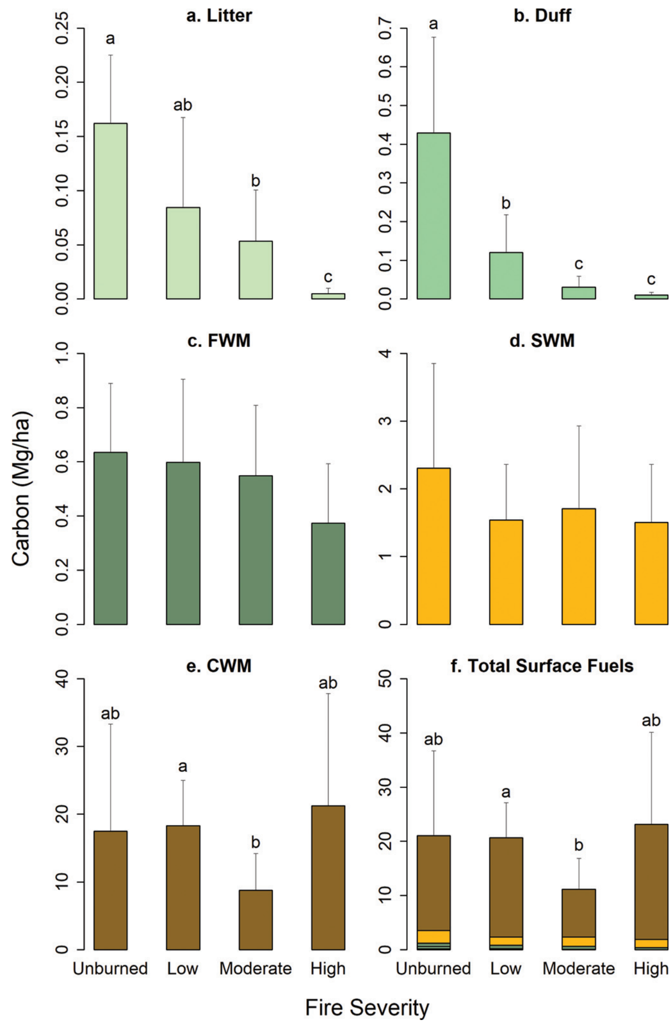
Woody fuels

Although not statistically significant, CWM carbon mass was higher in low- and high-severity plots compared with unburned plots (Table 2). Moderate-severity plots had significantly less CWM carbon mass than low-severity plots ($p = 0.0365$; Fig. 3*e*). Both SWM and FWM did not differ significantly among any severity classes ($p \geq 0.77$ and 0.21, respectively). There was also no significant difference between burned and unburned plots in these fuel types (SWM, $p = 0.296$: FWM, $p = 0.3674$). However, FWM carbon mass decreased as fire severity increased (Fig. 3*c*). Like CWM, SWM fuel carbon mass at moderate severity differed from low and high severity, albeit in the opposite way, with more carbon mass at moderate-severity plots compared with low- and high-severity plots. These differences were not statistically significant.

Non-woody fuels

For both duff and litter, there were significant differences in carbon between burned and unburned plots ($p < 0.0196$), as well as among fire severity classes ($p < 0.0257$) (Table 2). Litter decreased as fire severity increased, with significantly less litter carbon mass on moderate- and high-severity plots compared with unburned plots ($p < 0.0196$; Fig. 3*a*). High-severity plots also had less litter carbon than low-severity plots ($p = 0.0002$). However, there were no significant differences in litter carbon mass between unburned and low-severity plots ($p = 0.2025$) and between low- and moderate-severity plots ($p = 0.469$). Similar to litter, duff carbon decreased with increasing fire severity (Fig. 3*b*). Unburned plots had significantly more duff carbon than plots that burned at any severity ($p < 0.011$). Duff carbon mass in low-severity plots was significantly higher than in both moderate- ($p = 0.0257$) and high-severity ($p < 0.0001$) plots. However, the difference between duff carbon mass at moderate and high severities was suggestive but inconclusive ($p = 0.06$).

Fig. 3. Carbon mass (Mg ha⁻¹) in 2016, one year after the fire, by fuel type. Carbon masses for each fuel type without a lowercase letter or with the same lowercase letter in each panel are not significantly different from each other.



Discussion

Implications of remotely sensed fire severity classifications

The results of this study clearly indicate the limitations of using remotely sensed fire severity classification for surface fuels. Fire severity is defined as the immediate impact of fire on fuels (Keeley 2009); however, in several fuel types, we found no differences among carbon mass in different fire severity classes. We used Landsat dNBR derived fire severity classes for our study, which were not validated in the field prior to sampling. These remotely sensed fire severity classes rely on changes in forest canopy to determine severity levels (Eidenshink et al. 2007). Stand-replacing disturbances such as high-severity fires are easy to discern using Landsat imagery, but disturbances that do not result in stand replacement can be more difficult to distinguish from normal variations in spectral indices (Cohen et al. 2018). Due to this uncertainty, along with the lack of ground-truthing, it is possible that some of our plots were assigned to an incorrect fire severity class, especially in the areas where mixed-severity fire caused uneven tree mortality and carbon consumption. In particular, moderate-severity areas can be a major source of errors as they often occur in thin bands surrounding high-severity patches, making them difficult to discern on a larger scale (Miller et al. 2009). It is also likely that the crown fire severity was accurately assessed by the dNBR metrics; however, the impact of wildfires on tree crowns may not be equivalent to the impacts of wildfire on the forest floor. Because Landsat-derived fire severity classes are based on changes in tree crowns, changes in the forest floor and surface fuels may not be fully captured (Alonzo et al. 2017), potentially leading to the observed lack of significant differences in fuel carbon mass across fire severity classes. Evidently, ground-based fire severity measures would be optimal for future studies of post-fire surface fuels and the relationships between crown fire severity and surface fire severity.

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Pre-fire drivers of fire severity

Topography is a possible driver of fire severity, as steeper slopes could be more likely to burn at low or moderate severity (Bigler et al. 2005), partly consistent with our findings that moderate-severity plots were the steepest on average. Topography also plays an important role in stand structure and species composition (Harris and Taylor 2015), suggesting that our moderate-severity plots may have differed from plots in the other remotely sensed fire severity classes or the control group, even before the fire occurred. However, without pre-fire data, this is impossible to determine. Overall, the possible impacts of topography and forest type on fire severity demonstrate the need for pre-fire data. The permanent sample plots established in this study will provide pre-fire data for any future reburns that may occur within the Boulder Creek fire boundary.

All measurements for this study were taken after the fire, and pre-burn data were unavailable. Due to this, it is impossible to know whether control plots and plots across the three fire severities were comparable with regards to pre-fire fuel carbon. Our unburned plots had more deciduous trees than plots that burned at any severity, suggesting that there are differences in species composition that could have led to differences in fire behaviour, as different forest stands have different degrees of flammability (Alexander et al. 2012). Mixed-conifer forests often burn at high severity due to their tendency of growing densely with several canopy layers (Prichard and Kennedy 2014). In contrast, deciduous forests can often be less flammable than conifers (Chapin et al. 2008). It is possible that our plots burned at different severities, or did not burn at all, due to pre-fire differences in stand characteristics, making post-fire comparisons difficult. This illustrates the need for permanent monitoring plots across the landscape, which can provide pre-fire information for future fire impact studies. If pre-fire data are unavailable, it may be useful to include a larger number of unburned control plots to better gauge pre-fire conditions.

Post-fire surface fuel carbon

CWM can be abundant in hemlock and Douglas-fir stands after large-scale disturbances (Agee and Huff 1987). In the Boulder Creek fire, CWM carbon mass did not significantly differ between unburned and burned plots at any severity, which confirms similar findings of Maestrini et al. (2017). It also aligns with results from Eskelson et al. (2016), where pre- and post-fire CWM carbon mass did not differ significantly for wildfires in California. Mitchell et al. (2009) also found that pre- and post-fire carbon stored in larger downed woody fuels do not differ substantially, even after high-severity fires, possibly due to input during fire. However, we did find that there was less CWM carbon in moderate-severity plots than in high-severity plots, though this difference was not significant. One possible reason for this could be that pre-existing CWM was consumed at both severities but that the moderate-severity fire may not have weakened the standing trees enough to become immediate input into the CWM fuels, whereas the high-severity fire likely did. This is further confirmed by the fact that the high-severity plots had less standing tree carbon (Peterson 2018) than any other severity class, suggesting that most standing trees transitioned into CWM either during or after the fire. In this study, we found lower amounts of CWM carbon and higher amounts of SWM carbon in the moderate-severity plots. One reason for this could be that moderate-severity plots had much steeper slopes than any other severity class. As previously predicted by Bassett et al. (2015), sloped areas that burn at higher severities may have less CWM and more SWM volume when compared with low-lying, less sloped areas, possibly due to pre-fire differences in snag fall rates and differences in mortality rates between slopes and low-lying areas.

Much of the Boulder Creek region is covered by second-growth forest that had been logged in the late 1900s. Logging can alter the amount of surface fuels (Tinker and Knight 2000), increasing the amount of fine and coarse woody fuels, leading to changes in the fire risk and flammability of the stand (Donato et al. 2006; Lindenmayer et al. 2009). Changes in surface fuels can also increase the short-term risk of burning in the adjacent, less flammable stands (Lindenmayer et al. 2009). For future research, it would be beneficial to incorporate forest management practices into fire area stratification for plot selection, in addition to severity and forest type, for a better understanding of the interacting disturbances across the landscape.

Post-fire carbon accumulation

In this study, duff carbon was significantly lower in low-severity plots compared with unburned plots; however, the same was not the case for litter carbon. This was unexpected as litter is typically consumed at a higher rate than duff (Campbell et al. 2007). The similarities in litter fuel carbon mass between unburned and low-severity plots could be explained by post-fire accumulation. Litter carbon in low-severity plots would have accumulated in the year after the Boulder Creek fire prior to measurement. Litter from scorched and dead trees, as well as herbaceous understory growth, can accumulate quickly after a fire (Agee and Huff 1987; Dunn and Bailey 2015), but duff accumulation may not begin to occur for 5–10 years after a fire (Dunn and Bailey 2015; Eskelson and Monleon 2018). A low- or moderate-severity fire may have consumed all of the duff and litter but may not have climbed to the crowns (Campbell et al. 2007). Therefore, the fire may have killed the trees but not consumed the foliage, which would remain to become litter input in the year after the fire.

Yocom-Kent et al. (2015) found that the differences in post-fire carbon between severity classes widen over time. Thus, we hypothesize that post-fire carbon will decrease the most in stands that burned at high severity as we monitor change in surface fuel carbon at the Boulder Creek fire. The Boulder Creek fire left large high-severity patches with very few living overstory trees, which has important implications for post-fire fuel carbon dynamics, where it could take decades for carbon mass to return to pre-fire levels (Ryan et al. 2010).

Regional significance of the Boulder Creek fire

The Boulder Creek fire burned mostly at moderate and high severity, leaving very few living trees, which will likely have long-term impacts on the forest carbon trajectories of the region. Prior to widespread logging, the region surrounding the Boulder Creek fire most likely experienced mixed-severity fires on long return intervals (Daniels and Gray 2006). The atypically severe Boulder Creek fire aligns with predictions of increased fire severity across Canada due to climate change (Wotton et al. 2017). It is important to understand how these extreme events might affect forest stand conditions. In southwestern Oregon, high-severity patches in the 1987 Silver fire appeared to play a role in the severity when it burned again in the large 2002 Biscuit fire (Thompson et al. 2007). This suggests that the Boulder Creek region could be vulnerable to reburns, especially considering the large patches that burned at high severity, as initial fire severity can indicate the subsequent reburn severity (Thompson et al. 2007).

Conclusions and future work

The Boulder Creek fire was atypically large and severe for the coastal–transitional region, which does not frequently experience large forest wildfires. We found that the total amount of surface fuel carbon did not differ between burned and unburned plots one year after the fire. However, there was significantly less carbon mass in the finest fuels — duff and litter — in burned plots compared with unburned plots. Impacts of the Boulder Creek fire on surface fuels may have been obscured by post-fire accumulation and also by issues associated with using crown-based fire severity classifications to assess surface fire severity. We found that remotely sensed fire severity classes did not capture the severity of impacts of the Boulder Creek fire on several forest surface fuel types, which illustrates the limitations of using remotely sensed fire severity classifications for post-fire forest floor studies. Measures of ground-based fire severity would allow for a more correct picture of post-fire differences among severity classes. This case study provides baseline post-fire surface fuel data for the Boulder Creek fire, which can be used as a starting point for longitudinal studies of post-fire fuel and carbon dynamics. Understanding the impacts of forest fires on surface fuels will also allow for the development of post-fire forest management plans. The established permanent plots provide a valuable opportunity for analyzing post-fire forest carbon dynamics in coastal–transitional forests of BC. Information on disturbances in these transitional zones is currently lacking due, in part, to the historically long fire return intervals and relatively few fires in the documentary records. Fire behaviour, severity, size, and frequency are expected to shift with climate change, which leads to a need to study individual fires as they occur. As the current fire regimes change, we must continually study new fires, especially in areas that may not have burned frequently in the past.

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Appendix A. Biomass calculations

To obtain post-fire carbon mass per hectare for each fuel type, it was necessary to first obtain biomass per hectare for each fuel type. This appendix details the equations used to calculate the biomass present in each fuel type.

A.1. Coarse woody materials

Per-plot coarse woody material (CWM) biomass was calculated using a modified version of a biomass equation from Woodall and Monleon (2008):

$$y_i = \left(\frac{\pi^2}{8}\frac{\left(\sum_{j=1}^{n}\mathrm{BD}_{ij}\mathrm{DI}_{ij}^{\ 2}\right)}{L_i}\right)\Big|1000$$

where y_i is the biomass in megagrams per hectare (Mg ha^{-1}) in the ith plot, BD_{ij} is the species- and decay-specific bulk density in kilograms per cubic metre (kg m^{-3}) for CWM piece j in plot i, DI_{ij} is the piece diameter (cm) at the point of intersection for CWM piece j in plot i, and L_i is the slope-corrected total traversed transect length (m) in the ith plot. Biomass values were converted to carbon by multiplying with a conversion factor of 0.5.

A.2. Small woody materials

Small woody material (SWM) biomass (Mg ha^{-1}) in each plot was calculated using the following equation (Woodall and Monleon 2008) for all three SWM size classes j, where j = 1, 2, 3:

$$y_i = \left(\frac{\pi^2}{8}\frac{\left(\sum_{j=1}^{n}n_{ij}d_{\mathrm{mid}j}^{\ 2}\right)}{L_i}\mathrm{BD}\right)\Big|1000$$

where y_i is SWM biomass in the ith plot, n_i is the number of SWM pieces in size class j in plot i, $d_{\mathrm{mid}j}$ = is the midpoint diameter of size class j (cm), L_i is the total SWM transect length (m) measured in plot i, and BD is the mean density value of SWM from Fasth et al. (2010), equal to 430 kg m^{-3}. Biomass values were converted to carbon by multiplying with a conversion factor of 0.5.

A.3. Fine woody materials

Mean fine woody material biomass (Mg ha^{-1}) in each plot was calculated by converting the dry weight in grams of the collected samples in each 900 cm^2 microplot into Mg ha^{-1} values, which were then converted to carbon by multiplying by a conversion factor of 0.5.

A.4. Duff and litter

To obtain duff and litter fuel carbon mass (Mg ha^{-1}), density was calculated using the following formula:

$$\mathrm{dens}_i = \frac{h_i l_i w_i}{m_i}$$

where dens_i is the density (kg m^{-3}), h_i, l_i, w_i = height, length, and width of the duff and litter sample in plot i, respectively, and m_i is the dry weight of the sample (kg). Once density was calculated, duff and litter biomass (Mg ha^{-1}) was calculated using the volume of a 1 ha area with height equal to the average depth measurement of duff and litter. This volume was multiplied by the mean density value converted to Mg ha^{-1} to obtain plot biomass in Mg ha^{-1}. For litter, carbon was considered to be 0.5 of biomass. For duff, biomass was converted to carbon by multiplying by 0.4, as carbon content of duff tends to approximate 40% in Douglas-fir forests (Moore et al. 2006).

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