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Surface fuel changes after severe disturbances in northern Rocky Mountain ecosystems

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ABSTRACT

It is generally assumed that severe disturbances predispose damaged forests to high fire hazard by creating heavy fuel loading conditions. Of special concern is the perception that surface fuel loadings become high as recently killed trees deposit foliage and woody material on the ground and that these high fuel loadings may cause abnormally severe fires. This study evaluated effects of severe, exogenous disturbance events, namely fire and beetles, on future fuel conditions through biannual field collections. We measured surface fuel deposition and accumulation rates for a number of forest types after severe wildfires, Douglas-fir beetle outbreaks, and mountain pine beetle outbreaks to quantitatively describe fuel dynamics for up to 10 years after the disturbance. Fuel deposition was measured from semi-annual collections of fallen biomass sorted into six fuel components (fallen foliage, twigs, branches, large branches, logs, and all other material) from a network of seven, one meter square litter traps established on 15 sites across the northern Rocky Mountains USA. We also measured fuel loadings of the same six fuel components on each plot every year until the end of the study. Results show that most foliage material fell within the first one to two years after disturbance and surface fuel loadings did not appear to increase substantially at any point during the 10 years of this study. Large woody material greater than 75 mm diameter was found infrequently in the litter traps. Our results suggest that there is little increase in fire hazard during the first 10 years after severe disturbance in the study sites sampled for this study.

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1. Introduction

Conventional wisdom in fire management holds that stands with trees that are rapidly killed by insects, disease, or fire have increased future fire hazard because the dead foliage and fine woody material in the canopy is highly flammable (Axelson et al., 2009; Hicke et al., 2012), and, when this material falls to the ground, it creates heavy fuel loads that could result in faster fire spread and greater fire intensities (Gara et al., 1984; Jenkins et al., 2012). There is little doubt that the dying and dead needles are more flammable than green needles because of lower moistures and higher flammability (Jolly et al., 2012), but these needles only remain in the canopy for a short time (1–5 years). Of greater importance may be the rate at which the dead canopy material accumulates on the forest floor to increase surface fuel loadings and fire hazard. The dead foliage and woody material may fall quickly and create surface fuel conditions that could foster wildfires of high intensity and severity. What is needed is an in-depth analysis that describes the rate of fuel deposition and subsequent accumulation after severe disturbance events.

There are basically two field methods used to quantify fuel accumulation after disturbance: post-disturbance monitoring (Keane, 2008b) and chronosequence sampling (Pickett, 1989; Page and Jenkins, 2007; Jenkins et al., 2008). Monitoring involves continuous measurement of fuel conditions after disturbance on a site and it is the best method to describe temporal fuel changes (Busing et al., 2000). However, it is often difficult and costly to monitor surface fuel dynamics in the field because it requires extensive networks of litterfall traps that must be frequently visited over long time periods (5–10 years or longer) (Keane, 2008b). Chronosequence sampling essentially substitutes space for time by sampling fuels in many disturbed stands that have different time since disturbance (Pickett, 1989; Jeske and Bevins, 1979). Chronosequence sampling is perhaps the more popular but it has a major limitation in that the sampled stands that represent the time gradient often encompass a wide variety of biophysical conditions that result in high across-site variability in fuel loadings that may mask subtle fuel changes over time (Jenkins et al., 2012).

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Wildland fuels change through the complex interaction of four basic ecological processes: vegetation development, deposition, decomposition, and disturbance (Keane, 2015). Plants become established and grow biomass that eventually gets deposited on the ground through mortality or shed plant parts. Decomposition then reduces the deposited biomass (Robertson and Paul, 2000). If deposition rates exceed decomposition rates, fuels accumulate on the ground. Many disturbance agents may increase deposition rates through full or partial plant mortality. Some disturbances, such as fire and grazing, may reduce live and dead accumulated fuel loadings through consumption. To fully understand fuel accumulation dynamics, it is important to quantify rates of all four of these processes, but especially deposition and decomposition. This study describes fuel dynamics by documenting fuel deposition and accumulation on forested sites following disturbance using a fuel monitoring method rather than chronosequence sampling.

Litterfall deposition rates have been monitored for many ecosystems of the world (Bray and Gorham, 1964; Harmon et al., 1986; Facelli and Pickett, 1991; Van Cleve and Powers, 1995) and in some forests of the United States Pacific Northwest (Keane, 2008b). Few studies, however, have quantified litterfall by those fuel components needed for fire management, and fewer still have monitored fuel dynamics after severe disturbance using fuel monitoring (Keane, 2015). Of this limited set of studies, most measured only the rate of foliage or coarse woody debris (CWD; woody fuel particles > 7.6 cm diameter) deposition (Harmon et al., 1986b, Vogt et al., 1986). Fine woody debris (FWD; woody fuel particles <7.6 cm diameter) additions to the forest floor, such as twigs and branches, are rarely reported even though they contribute to fire spread (Rothermel, 1972; Albini, 1976). There are some exceptions, such as Ferrari (1999) who measured twigfall in hardwood-hemlock forests and Meier et al. (2006) who measured fine woody material, along with other canopy litterfall, in an alluvial floodplain hardwood forest. Deposition rates for CWD are usually measured from historical tree mortality and snag fall rates over time, but this assumes tree fall is the only input to CWD buildup. Large branches and tree tops, however, may also contribute to CWD inputs to the forest floor in some ecosystems (Harmon and Hua, 1991). The objectives of this study were to determine if recently disturbed stands have high fire hazard due to increased deposition and accumulation of surface fuels.

2. Methods

In this study, biomass loadings (kg m^{-2}) of the major surface fuel components were monitored over a period of 5–10 years on 15 US northern Rocky Mountain sites that had experienced one of three severe disturbances – wildland fire (Fire), Douglas-fir beetle (DFB), and mountain pine beetle (MPB) – to document changes in fuel loadings over time. We also measured deposition (litterfall) rates of a subset of the same six fuel components to understand fuel accumulation dynamics. Information from this effort may help managers and researchers understand the complex changes in fuelbeds that can happen after severe disturbances by informing potential future fire behavior and effects prediction. This research may lead to new methods of prioritizing fuel treatments after major insect, disease, or fire events. Moreover, it should provide important parameters and values for fuel sampling and fire modeling efforts.

Six surface fuel components are recognized in this study. Freshly fallen leaves and needles from trees, shrubs, and herbaceous plants were considered *foliage* while all other non-woody material, such as fallen cones, bark scales, lichen, and bud scales, are lumped into a category called *other* fuels. These two fuel types composed the *litter* layer measured in this study. The fallen woody material was sorted into four diameter classes using definitions required by the fire behavior and effects models (Fosberg, 1970; Rothermel, 1972; Reinhardt et al., 1997). The smallest size class defines 1 h fuels with diameters less than 3 mm. Branches with diameters between 3–25 mm are 10 h fuels and large branches with diameters ranging from 25–75 mm are 100 h fuels. In this study, we combined all three of these size categories to describe fine woody debris (FWD). The logs (CWD-downed woody fuels greater than 75 mm in diameter) define the 1000 h fuel component; CWD does not include snags or stumps (Hagan and Grove, 1999). We use the term litterfall to describe the process of fuel deposition for all fuel components for simplicity and the devices used to measure fuel deposition are referred to as litter traps. In monitoring fuel loadings, we sampled the litter and duff layer as one fuel component for logistical reasons (it is difficult to distinguish between the two in the field).

2.1. Study sites

We selected sites in Montana and Idaho that were on flat ground, within 200 m of a road, and had the potential for high tree mortality (>70%) from a recent disturbance. Red needles had to be present on the recently killed trees. We attempted to target only stands that had 70% or greater mortality from the disturbance, but it was difficult to evaluate future mortality at the inception of an outbreak or burn. As a result, two selected stands had less than 70% mortality; 25% mortality was estimated for Merriwether 1 post-wildfire and Morgan Creek was estimated to have 50% DFB mortality. Efforts to find appropriate sites was challenging due to the specificity of our selection criteria; weeks were spent driving forest roads in search of potential study sites, often without any results. After an exhaustive GIS analysis and numerous reconnaissance trips, we finally established sites in four forest types after major mortality events from three different disturbance agents: Fire, DFB, and MPB (Table 1). We wanted to select sites in just one forest type but that was nearly impossible under our site and disturbance selection criteria and so we sampled across several forest types. Locations of the final 15 sites are shown in Fig. 1.

This study design was based on a previous study that explored the temporal dynamics of fuel deposition and decomposition for undisturbed mature forest stands in the US northern Rocky Mountains (Keane, 2008a, 2008b). In that study, three disturbed lodgepole pine sites near Red River, Idaho were established immediately after an MPB outbreak in 2002. At the close of that study, we found a number of other recently disturbed sites and established plots in those stands during field seasons beginning in 2007 with the last study sites located in 2010. Four forest types are represented in this study: (1) ponderosa pine (*Pinus ponderosa*) at the lower elevations; (2) mixed western larch (*Larix occidentalis*), Douglas-fir (*Pseudotsuga menziesii*), and lodgepole pine (*Pinus contorta*) at the montane elevations; (3) mixed lodgepole, subalpine fir (*Abies lasiocarpa*), and Engelmann spruce (*Picea engalmannii*) at subalpine elevations; and (4) whitebark pine (*Pinus albicaulis*) at the highest, upper subalpine areas. Site elevations ranged from 1429 m to 2828 m (Table 1).

2.2. Plot measurement

A circular, 400 m^2 plot was permanently located within close proximity of roads but with traps hidden from view to prevent vandalism. Traps were placed on slopes that were less than 10 percent to avoid littertrap movement downhill and located inside an area of at least 3 acres (1.2 ha) that represented the disturbed stand. A 1 m long iron rebar about 1 cm thick was driven in the ground for plot center (Keane, 2008b) (Fig. 2), photos and notes of the plot and surrounding area conditions were documented, and the plot coordinates were georeferenced using a GPS (Global Positioning system). We then measured topographic, vegetation,

Table 1
Study sites grouped by disturbance. Three stand-replacement disturbances are represented in this study – wildfire, Douglas-fir beetle, and mountain pine beetle. Sampling period ranged from year established to 2015.

Site name	Project ID	Overstory mortality (%)	Forest cover type	Elevation (m)	Year established
Wildfire (FIRE)					
Jocko Lake	JL1	100	Larch, Douglas-fir, lodgepole pine	1426	2008
Marias Pass	MP1	100	Lodgepole pine	1715	2007
Merriwether 1	MW1	25	Ponderosa pine (thinning unit)	1231	2007
Merriwether 2	MW2	98	Ponderosa pine	1200	2008
Douglas-fir Beetle(DFB)					
Morgan Creek	MC1	50	Douglas-fir	2179	2009
Lost Trail	LT1	90	Douglas-fir	1882	2007
Flesher Pass	FP1	90	Douglas-fir	1839	2009
Mountain Pine Beetle (MPB)					
Galena Summit	GS1	100	Whitebark pine	2737	2007
Bull Run	BR1	98	Ponderosa pine	1429	2010
Red River 5	RR5	100	Lodgepole pine	1653	2003
Red River 6	RR6	100	Lodgepole pine	1670	2003
Red River 7	RR7	100	Lodgepole pine	1328	2003
Homestake Pass	HP1	70	Lodgepole pine	1938	2007
Twin Peaks 1	TP1	80	Whitebark pine	2828	2009
Twin Peaks 2	TP2	70	Whitebark pine	2679	2009

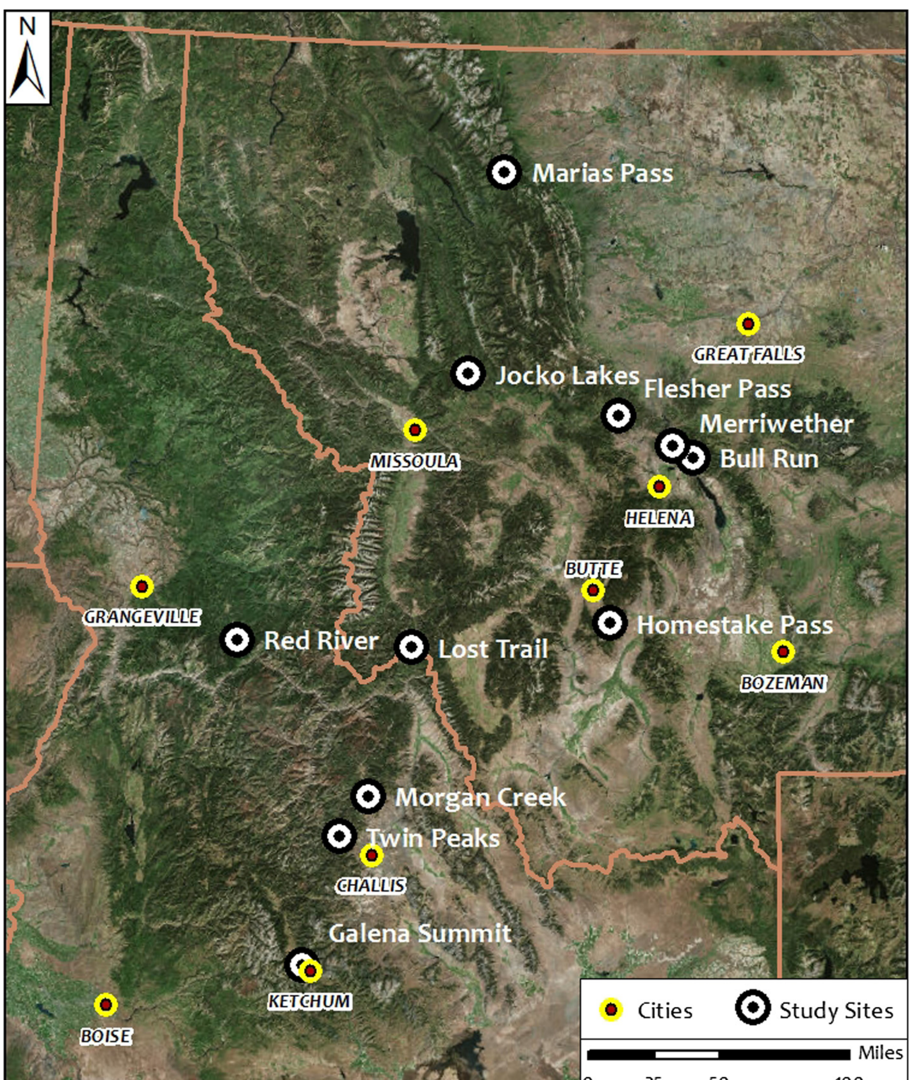


Fig. 1. Geographic locations of the 15 littertrap collection sites in the US northern Rocky Mountains. Study sites are marked using the black and white symbol and labeled by name. Locations with more than one plot in close proximity are indicated by one symbol only. Closest towns or cities are labeled by name using the yellow and red symbol (ESRI Basemap Imagery layer).

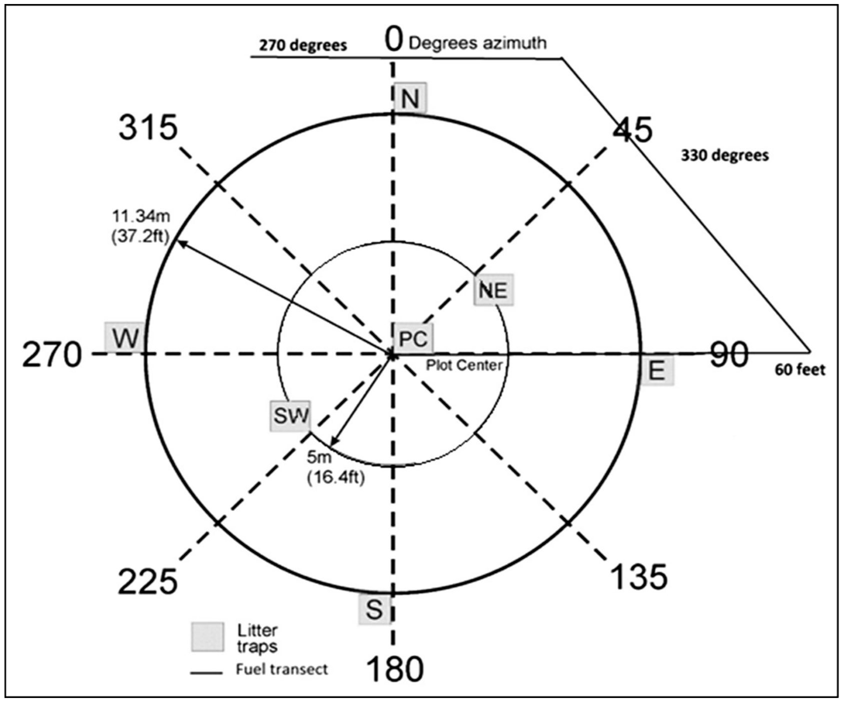


Fig. 2. Plot layout showing littertrap locations (grey boxes labeled by direction from plot center – N-North, S-South, E-East, W-West) and the 60 ft (18.3 m) fuel transects at 90°, 270°, and 30° azimuth originating at plot center. Large numbers are azimuth degrees from plot center.

and ecological characteristics using the FIREMON sampling methodology (Lutes et al., 2006). Study site information was collected the year plots were established including tree densities, basal area, and quadratic mean diameter in order to characterize overstory conditions (Table 2). Understory species composition was recorded for all shrub, forb, and graminoid percent cover was estimated for the circular plot; all plants were keyed to species if possible, then to genera. Table 3 displays understory vegetation ordered from highest estimated percent cover and listed in descending order to lower percent cover. Fuel accumulation (amount of fuel on the ground in the disturbed sites) was documented from annual fuel loading measurements taken at each site while fuel deposition was measured from litter that fell into wooden traps and were collected twice a year.

2.3. Fuel accumulation

Fuel loading was measured annually in each plot in the late summer or early fall. Downed woody fuel components (1 h, 10 h, and 100 h fuels collectively referred to as FWD) were measured using the FIREMON Fuel Loading method (Lutes et al., 2006) where woody fuel particle intersects were counted along three, 18.3 m (60 foot) transects with the first running at 90° azimuth from plot center. The second transect begins at the end of transect one, on an azimuth of 330° and, likewise, the third transect continues at 270° (Fig. 2). Each transect was permanently marked using 25 cm spikes at the beginning and end of each transect that were pounded into the ground and flagged for visual identification. We tallied 1 h and 10 h fuels between the 3 m (10 foot) and 4.9 m (16 foot) marks along the transect, the 100 h fuels between the 3 and 6 m (20 foot) marks, and 1000 h fuels from the 3–18.3 m (10–60 feet) marks along the transect length. Litter plus duff (LD) depths were measured at the 9.1 m (30 foot) and 18.3 m points along each transect and were entered as a single fuel component in this study. Data were entered in the FIREMON database and loadings were computed using the FIREMON (Lutes et al., 2006) algorithms.

2.4. Fuel deposition

At each plot, we installed seven litter traps within the circular plot boundary using the pattern shown in Fig. 2. Litter traps were constructed by creating a 1 × 1 m wooden frame (inside dimen-

Table 2
General description of study sites and plots included in this study calculated from data collected post-disturbance the year of site establishment. MPB-Mountain pine beetle; DFB-Douglas-fir beetle, and Fire-Wildfire. The site acronyms are defined in Table 1.

	MPB sites								DFB sites			Fire sites			
	BR1	GS1	HP1	RR5	RR6	RR7	TP1	TP2	FP1	LT1	MC1	JL1	MP1	MW1	MW2
[a]Tree Density (live trees ha^{-1})	470.0	741.3	1556.7	49.4	197.7	173	667	568.3	371	296.5	371	840.1	1409	766	667.2
Basal Area (m^2 ha^{-1})	31.5	53.9	37.1	1.0	6.3	9.4	18.8	20.9	18	20.3	56.7	30.1	32.3	35.2	28.2
Live Tree QMD (cm)	29.2	30.4	17.4	16.1	20.1	26.3	18.9	21.6	24.8	29.5	44.1	21.4	17.1	24.2	23.2
Sapling Density (trees ha^{-1})	222.0	1062.1	345.8	913.9	1977.0	939	1013	963	99	0	0	1630	0	0	0
Seedling Density (live trees ha^{-1})	1976	8401	4446	5187	7410	3211	1482	9386	247	0	2223	6175	6669	247	0
Dead Trees (dead trees ha^{-1})	49.4	24.7	197.7	420.1	642.5	345.9	222	98.8	74.1	24.7	49.4	49.4	197.7	98.8	49.4

[a] Note: Live stems include trees coded according to FIREMON protocols (Lutes et al., 2006) as healthy (H), unhealthy (U) or sick (S). Trees coded H have little biotic or abiotic damage of note. Trees are coded U when some biotic or abiotic damage is observed and the damage is surmised to reduce growth. The tree is not expected to immediately die from the damage. Trees coded S are severely damaged and will ultimately die within the next 5–10 years. Trees were predominantly coded U and/or S on all sites in this study.

Table 3
Understory species and percent cover recorded post-disturbance at time of site establishment. List includes only the top ten species with highest percent cover unless fewer than 10 understory species were recorded on the site. Site acronyms are defined in Table 1 under ProjectID.

MPB sites

Site	Species	Type	Cover (%)
BR1	Arctostaphylos uva-ursi	Shrub	40
	Juniperus communis	Shrub	20
	Symphoricarpos albus	Shrub	20
	Lonicera utahensis	Shrub	10
	Rhus trilobata	Shrub	10
	Shepherdia canadensis	Shrub	3
	Ribes	Shrub	3
	Antennaria microphylla	Forb/Herb	0.5
	Aster	Forb/Herb	0.5
	Hieracium albiflorum	Forb/Herb	0.5
GS1	Calamovilfa longifolia	Forb/Herb	30
	Carex geyeri	Graminoid	30
	Ribes lacustre	Shrub	20
	Valeriana sitchensis	Forb/Herb	10
	Lupinus argenteus	Forb/Herb	10
	Achillea millefolium	Forb/Herb	3
	Aquilegia coerulea	Forb/Herb	3
	Silene acaulis	Forb/Herb	0.5
	Carex concinnoides	Graminoid	0.5
	Penstemon	Forb/Herb	0.5
HP1	Juniperus communis	Shrub	10
	Calamagrostis rubescens	Graminoid	10
	Antennaria racemosa	Forb/Herb	3
	Arctostaphylos uva-ursi	Shrub	3
	Ribes	Shrub	3
	Juniperus scopulorum	Shrub	3
	Hieracium albiflorum	Forb/Herb	0.5
	Fragaria virginiana	Forb/Herb	0.5
	Antennaria rosea	Forb/Herb	0.5
	Spiraea betulifolia	Shrub	0.5

MPB sites

Site	Species	Type	Cover%
RR5	Linnaea borealis	Forb/Herb	40
	Vaccinium globulare	Shrub	40
	Vaccinium scoparium	Shrub	20
	Xerophyllum tenax	Forb/Herb	20
	Alnus viridis	Shrub	10
	Chimaphila umbellata	Shrub	3
	Viola orbiculata	Forb/Herb	3
	Solidago canadensis	Forb/Herb	3
	Spiraea betulifolia	Shrub	3
	Lonicera utahensis	Shrub	3
RR6	Vaccinium globulare	Shrub	70
	Arnica latifolia	Forb/Herb	30
	Cornus canadensis	Forb/Herb	10
	Thalictrum occidentale	Forb/Herb	10
	Chimaphila umbellata	Shrub	10
	Spiraea betulifolia	Shrub	10
	Linnaea borealis	Forb/Herb	3
	Symphoricarpos albus	Shrub	3
	Menziesia ferruginea	Shrub	3
	Mitella stenopetala	Forb/Herb	0.5
RR7	Vaccinium scoparium	Shrub	40
	Xerophyllum tenax	Forb/Herb	30
	Linnaea borealis	Forb/Herb	20
	Arctostaphylos uva-ursi	Shrub	10
	Vaccinium globulare	Shrub	10
	Trifolium	Forb/Herb	10
	Viola orbiculata	Forb/Herb	3
	Chimaphila umbellata	Shrub	3
	Carex geyeri	Graminoid	3
	Berberis repens	Shrub	3

MPB sites

Site	Species	Type	Cover (%)
TP1	Carex	Graminoid	10
	Phlox	Forb/Herb	3
	Stipa	Graminoid	0.5
	Castilleja miniata	Forb/Herb	0.5
	Poa	Graminoid	0.5
	Festuca idahoensis	Graminoid	0.5
	Carex geyeri	Graminoid	0.5
TP2	Vaccinium scoparium	Shrub	40
	Carex geyeri	Graminoid	3
	Poa	Graminoid	0.5
	Agropyron	Graminoid	0.5

DFB Sites

Site	Species	Type	Cover (%)
FP1	Calamagrostis rubescens	Graminoid	70
	Arnica latifolia	Forb/Herb	30
	Spiraea betulifolia	Shrub	10
	Achillea millefolium	Forb/Herb	3
	Antennaria racemosa	Forb/Herb	3
	Berberis repens	Shrub	3
	Carex	Graminoid	3
	Ligusticum canbyi	Forb/Herb	0.5
	Erythronium grandiflorum	Forb/Herb	0.5
	Collinsia parviflora	Forb/Herb	0.5
LT1	Carex geyeri	Graminoid	20
	Calamagrostis rubescens	Graminoid	20
	Symphoricarpos albus	Shrub	20
	Arnica latifolia	Forb/Herb	10
	Fragaria virginiana	Forb/Herb	10
	Hieracium albiflorum	Forb/Herb	10
	Ligusticum canbyi	Forb/Herb	10
	Erythronium grandiflorum	Forb/Herb	3
	Chimaphila umbellata	Shrub	3
	Berberis repens	Shrub	3
MC1	Calamagrostis rubescens	Graminoid	40
	Arnica latifolia	Forb/Herb	10
	Antennaria racemosa	Forb/Herb	3
	Carex	Graminoid	3
	Balsamorhiza sagittata	Forb/Herb	3
	Lupinus argenteus	Forb/Herb	3
	Poa	Graminoid	3
	Symphoricarpos albus	Shrub	3
	Fragaria virginiana	Forb/Herb	0.5
	Collinsia parviflora	Forb/Herb	0.5

Fire Sites

Site	Species	Type	Cover %
JL1	Epilobium angustifolium	Forb/Herb	30
	Xerophyllum tenax	Forb/Herb	10
	Calamagrostis rubescens	Graminoid	3
	Poa	Graminoid	3
	Spiraea betulifolia	Shrub	0.5
	Berberis repens	Shrub	0.5
	Aster conspicuus	Forb/Herb	0.5
	Arctostaphylos uva-ursi	Shrub	0.5
	Vaccinium globulare	Shrub	0.5
	Amelanchier alnifolia	Shrub	0.5
MP1	Xerophyllum tenax	Forb/Herb	10
	Aster conspicuus	Forb/Herb	3
	Carex concinnoides	Graminoid	3
	Bromus	Graminoid	3
	Veratrum viride	Forb/Herb	3
	Viola orbiculata	Forb/Herb	0.5
	Vaccinium globulare	Shrub	0.5
	Lonicera utahensis	Shrub	0.5
	Clintonia uniflora	Forb/Herb	0.5
	Arnica latifolia	Forb/Herb	0.5
MW1	Agropyron spicatum	Graminoid	20
	Taraxacum officinale	Forb/Herb	10
	Achillea millefolium	Forb/Herb	10
	Lactuca canadensis	Forb/Herb	3
	Penstemon	Forb/Herb	3
	Medicago arabica	Forb/Herb	3
	Lomatium dissectum	Forb/Herb	3
	Phacelia	Forb/Herb	0.5
	Antennaria rosea	Forb/Herb	0.5
	Vicia	Forb/Herb	0.5

Fire Sites

Site	Species	Type	Cover (%)
MW2	Taraxacum officinale	Forb/Herb	20
	Phacelia	Forb/Herb	3
	Vicia	Forb/Herb	3
	Verbascum thapsus	Forb/Herb	3
	Cirsium vulgare	Forb/Herb	3
	Sisymbrium altissimum	Forb/Herb	3
	Achillea millefolium	Forb/Herb	0.5
	Allium cernuum	Forb/Herb	0.5
	Agropyron spicatum	Graminoid	0.5
	Oxyria	Forb/Herb	0.5

sions) with 2 × 9 cm boards and then tacking a coarse grid hardware cloth on the bottom of the frame to allow water drainage and minimize losses from accumulated material due to decomposition and wind. We also tacked a plastic screen (mesh size 0.7 mm) on top of the hardware cloth to prevent fine material from falling through the hardware grid and also to facilitate litter collection. Each site was visited twice a year, generally during the spring and fall depending on snowpack. During each visit, all material in each trap was transferred to heavy paper bags that were labeled for identification. Woody fuel particles that lay partially out of the trap were cut directly at the trap border as defined by the inside dimension of the trap boards. It was impossible to collect the large woody fuels so the dimensions of the logs were measured on the site and recorded directly on a sample bag to compute loadings later.

Collected materials were then transported to the laboratory and the labeled bags placed in ovens set at 90 °C for 3 days. The dried litter was placed in cake tins and sorted by hand into the six fuel components (foliage, other, 1, 10, 100, and 1000 h). The weight of each fuel component was recorded to the nearest 0.01 g along with the date, site, plot, and trap information written on the collection bag; all data were entered into spreadsheets for later analysis.

2.5. Data analysis

We calculated the annual surface fuel loadings using FIREMON and exported to statistical packages for further analysis. We grouped the 1 h, 10 h, and 100 h woody fuel loadings into the FWD category; the CWD category was composed of only 1000 h fuels with loadings that were either measured directly or calculated from the intersects; LD was measured as an individual component of fuel loading. Bar charts display annual fuel loadings (kg m^{-2}) for all plots and then for loadings pooled by each of the disturbance types (Fire, DFB, and MPB) considered in this study.

Annual litterfall deposition rates (kg m^{-2} y^{-1}) were computed by dividing the total amount of accumulated material in each trap on a plot for the entire time period by the number of days in that time period, and then we multiplied this daily rate by 365 to obtain an annual rate. We again grouped the three fine woody components to create a FWD category. To estimate CWD loadings, we computed volume from the dimensions recorded in the field and then multiplied the volume by the dry wood density value of that species used in FIREMON. Annual litterfall time series were evaluated using box and whisker plots (Sokal and Rohlf, 1981) to summarize temporal changes by the FWD, CWD, foliage, and other fuel classes; data were then pooled to create a time series by disturbance agent. We kept a CWD group even though we rarely found logs in the litter traps. Average fuel deposition was summarized across all plots and by individual disturbance.

Generalized linear mixed models (GLMM's) were used to analyze differences in litterfall and fuel loadings by year. Because minimum values of zero were often observed in the responses, the natural log transformation described in Stahel (2002) was used. For both the annual litterfall and loading analysis, main effects of fuel component, year, disturbance and forest type were included along with all second-order interactions that were complete across treatment combinations. Random effects for plot and year within plot were also included. A Kenward-Roger adjustment was used to properly compute the error degrees of freedom for both models (Kenward and Roger, 2009). All *post hoc* comparisons were adjusted by the Tukey-Kramer method (Kramer, 1956). Parameter estimates and 95% confidence intervals were back-transformed to median estimates. All statistical analyses were done using SAS 9.4, PROC GLIMMIX (Copyright © 2016 SAS Institute Inc.).

3. Results

3.1. Fuel accumulation

Average annual fuel loadings for FWD, CWD, and LD across all study plots are shown in Fig. 3a and annual fuel loadings grouped by disturbance type (Fig. 3b–d). The average annual fuel loadings of CWD and LD components were both higher and more variable than FWD which changed little from year to year. Average CWD loadings ranged from a minimum value of 1.26 kg m^{-2} to a maximum of 2.37 kg m^{-2} with high variability (SE $\geq$ 1) seen in all years. Average annual LD loadings were also highly variable and ranged from 1.48 to 3.18 kg m^{-2} while FWD loadings were much less variable and ranged from 0.50 to 1.15 kg m^{-2}. Analysis of variance (ANOVA) on the natural log transformed annual fuel loadings yielded no significant difference ($F_{16,\ 202} = 0.43$, $p > 0.97$) among the CWD, FWD, and LD fuel components and no significant difference ($F_{16,\ 74} = 0.74$, $p > 0.74$) when fuel components were grouped by disturbance.

3.2. Fuel deposition

Dry weight of all fuel components collected from littertraps varied both within and across individual fuel components across all study sites (Fig. 4a). Rates of foliage deposition appeared to be consistently highest in the first 1–2 years with a mean of 0.15 and 0.11 kg m^{-2} y^{-1} respectively, most other years were half that amount. Annual dry weight of FWD and Other varied around an average of 0.07 and 0.04 kg m^{-2} y^{-1}, respectively. Dry weight of Foliage collected on MPB sites was also the highest in years 1 and 2, whereas highest deposition for FWD and Other fuel was found in the 9th year of collection (Fig. 4b). Foliage dry weight on DFB sites was greatest in the first year following disturbance; FWD and Other fuel components were also highest (0.04 kg m^{-2} y^{-1}) the first year of collection although average dry weight was similar across all years (Fig. 4c). Foliage litterfall measured on the Fire sites was highest (0.20 kg m^{-2} y^{-1}) in the first year following disturbance while FWD and Other dry weights were quite similar for all years (Fig. 4d). CWD was found very infrequently in litter traps on the MPB and Fire sites and no logs were found on DFB sites.

Statistical analysis supported the observed trends indicated by the box-whisker plots of Fig. 4. An ANOVA on the natural log transformed fuel dry weight of Foliage, FWD, Other, and CWD fuel components supported significant variation ($F_{36,\ 3357} = 4.50$, $p < 0.0001$) among dry weight scores for all disturbances; ANOVA also supported significance ($F_{6,\ 3357} = 19.78$, $p < 0.0001$) for dry weight scores grouped by Fire, DFB, and MPB disturbance types. A *post hoc* Tukey-Kramer transformation of the fuel components showed that in the first 1–2 years following severe disturbance, Foliage differed significantly (alpha = 0.05) from all subsequent years whether disturbance was grouped or ungrouped. However, the Tukey-Kramer test showed no difference (alpha = 0.05) among the FWD, Other, or CWD fuel components across all years of this study regardless of disturbance, grouped or ungrouped. Significantly different years are highlighted in Fig. 4a–d.

4. Discussion

We found little annual change in FWD fuel loadings on all forest types included in this study, following severe beetle and wildfire disturbances; there were no clear changes in surface fuel loadings in the 10 years of this study regardless of forest or disturbance type over the study period. However, some substantial changes were found in foliage that was deposited during the first 1–2 years of monitoring after disturbance. FWD and other non-woody fuel components displayed little change in deposition from canopy to litter trap during the years after disturbance and CWD was only rarely collected from the litter traps during the entirety of this study.

Jenkins et al. (2012) showed that the time required for substantial needle loss following beetle outbreak tends to take place 1–3 years following disturbance. In addition, a period of 20 or more years must pass before substantial amounts of dead trees begin to fall to the ground (Jenkins et al., 2008). In this study we found that the greatest level of canopy foliage fell during the 1–2 years following disturbance. Larger branches and logs were not found to increase at greater levels during the entirety of the study. In another study located in the northern Rocky Mountains, Keane

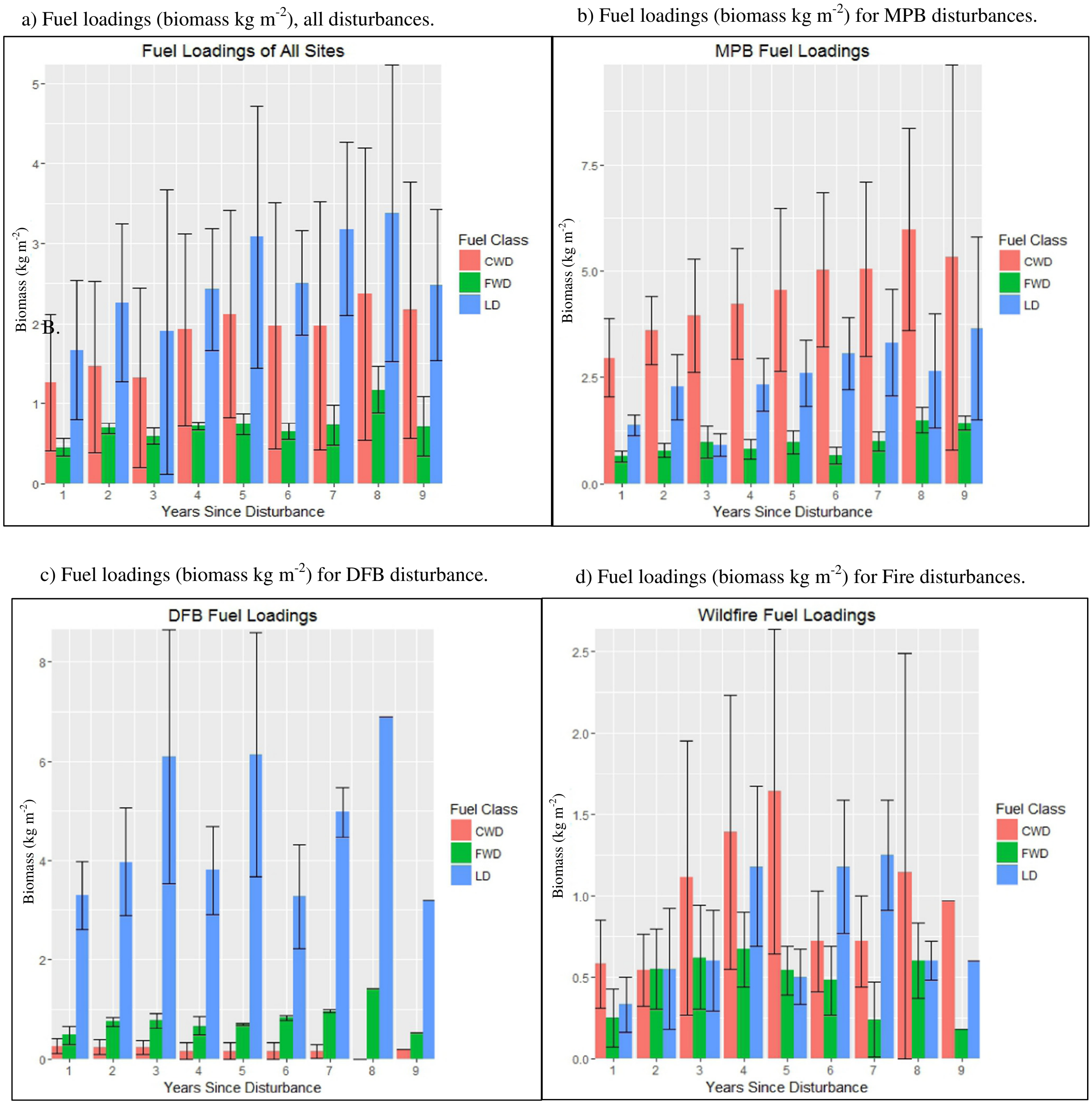


Fig. 3. Annual fuel loadings (biomass kg m^{-2}) across 9 years of record for the FWD (fine woody debris), CWD (coarse woody debris), and LD (litter and duff) fuel classes. Fuel loadings are shown for: (a) all disturbance sites (15 sites), (b) MPB (mountain pine beetle) disturbance sites only (8 sites), (c) DFB (Douglas-fir beetle) disturbance sites only (3 sites), and (d) wildfire disturbance sites only (4 sites). Standard error is represented by the black whisker line. Annual fuel loadings by fuel class were not significantly different for all sites ($F_{16,\ 202}$ = 0.43, p > 0.97) or sites grouped by disturbance ($F_{16,\ 74}$ = 0.74, p > 0.74).

(2008a) found that littertraps effectively and consistently detected fine fuels, whereas, large branches and logs were detected much less frequently and with high variance on forest types similar to those sampled in this study.

4.1. Study limitations

There are some aspects of this study that should be considered when interpreting results. First, the planar intersect technique used to collect down woody fuels data for the first years of this study has a high level of uncertainty and it has limited repeatability (Keane et al., 2012); we probably should have included additional transects to obtain a more accurate estimate of FWD and CWD variability. There are many years where the FWD and CWD loadings actually decreased (Table 2) and this could be a result of the non-repeatability of planar intersect sampling, the low number of transects, and actual decomposition. Other methods for quantifying fuel loadings may be considered in future efforts.

CWD deposition rates were measured differently than FWD rates. CWD rates were measured using the littertraps in the first part of the study, but in 2010 we switched to measuring logs on the entire plot because we were getting little CWD material in

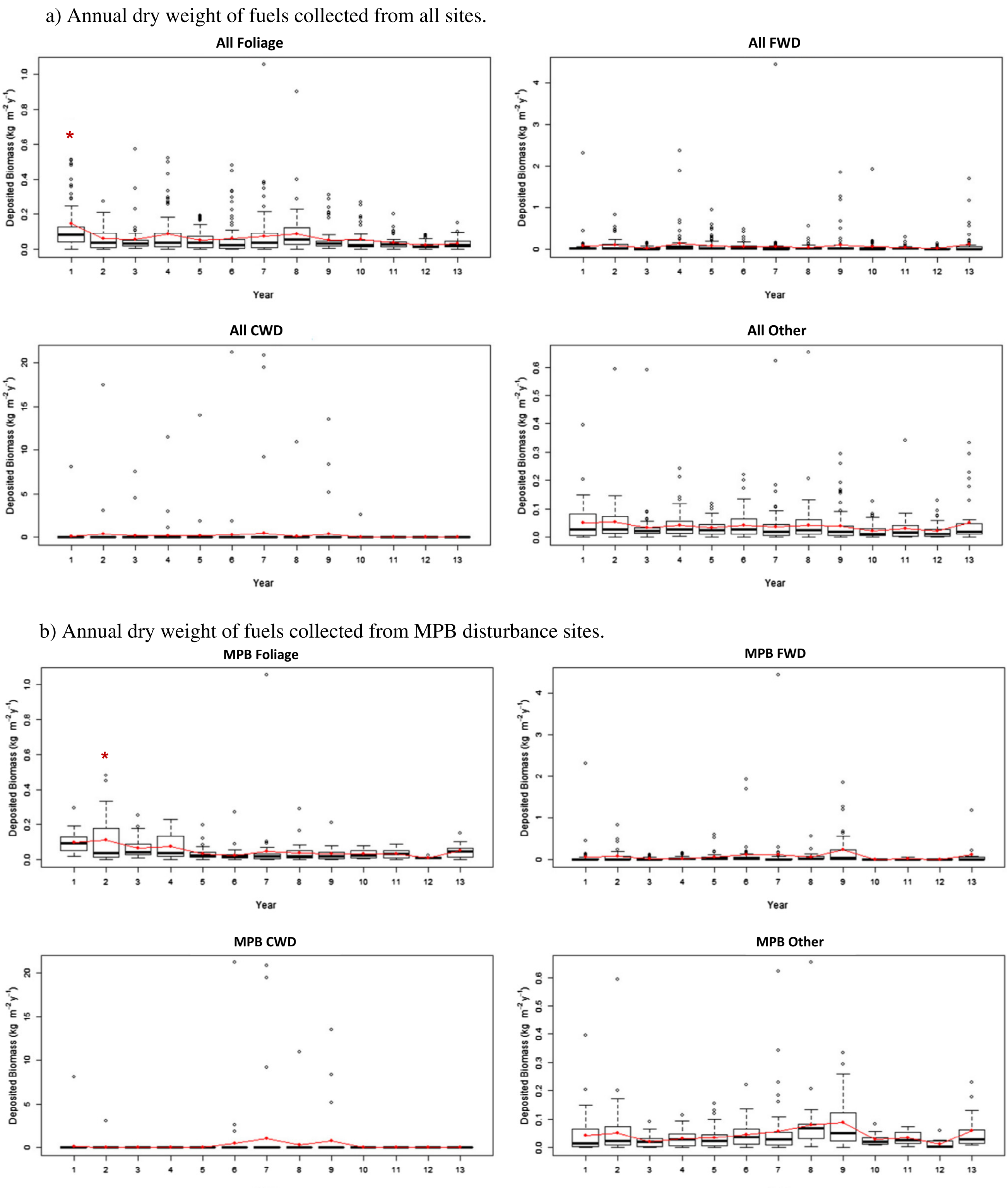
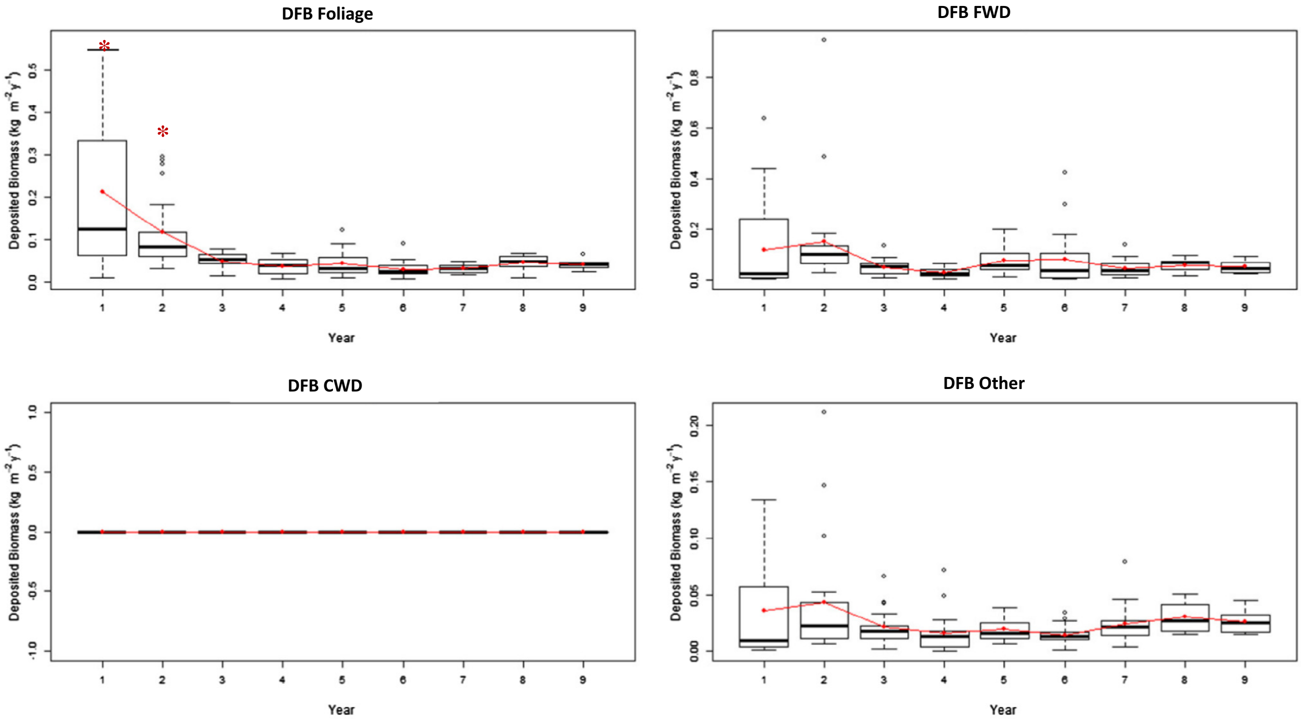


Fig. 4. Dry weight (kg m^{-2} y^{-1}) of surface fuel components deposited annually for the foliage, fine woody debris (FWD), coarse woody debris (CWD), and other fuel components (buds, bark, etc.) for: (a) all disturbance sites combined, (b) MPB (Mountain pine beetle), (c) DFB (Douglas-fir beetle), and (d) Fire (wildfire). The lower boundary of each box is the first quartile (25th percentile), the upper boundary is the third quartile (75th percentile), and the line within the boundary box represents the median of the distribution. The upper and lower error bars are the 10th and 90th percentile and the circles above the error bars represent outlying values. A red line represents the average of the distribution. X-axis reflects years since disturbance. Red asterisks highlight statistical significance (Tukey-Kramer, $\alpha = 0.05$). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

the littertraps. As we continue to monitor fuel loadings, we will analyze age data from the logs to determine when each log fell and then tag each log to record deposition dates.

There are only a few and unbalanced number of sites to represent each disturbance type in this study (Fire = 4, DF beetle = 3, and MPB = 8) making statistical analysis difficult and interpretation

c) Annual dry weight of fuels collected from DFB disturbance sites.



d) Annual dry weight of fuels collected from Fire disturbance sites.

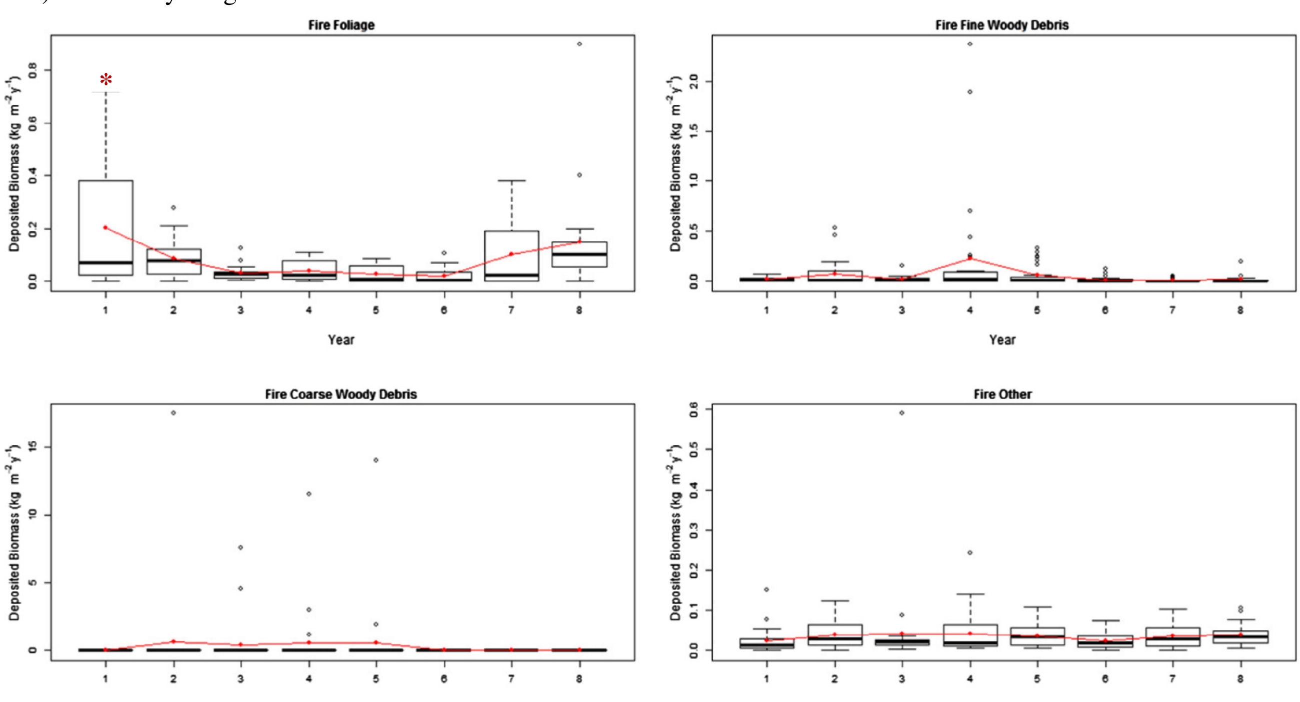


Fig. 4 (*continued*)

confusing. However, this problem is mainly because of the lack of suitable study sites and the high cost of semi-annual sampling across such a large study area. While results from this study are lacking sampling and statistical rigor, we feel that the results are still informative for fire management.

The forest cover types monitored in this study included ponderosa, lodgepole, and whitebark pine as well as Douglas-fir and Douglas-fir mixed with larch-lodgepole. This study was limited to sites in the northern Rocky Mountains in western Montana and eastern Idaho, results are applicable to pine and Douglas-fir types similar to those monitored.

5. Conclusions

The objectives of this study were to document changes in fuel loading and deposition over a period of 5–10 years on sites altered by severe disturbance by insects and wildfire. Generally, fuel loadings remained relatively constant from year to year. We found that foliage deposition was greatest during the first two years following severe fire and beetle disturbances. Across all 15 study locations encompassing elevations ranging from low, mid-, to high elevations, the foliage fuel components were substantially higher in the first 1–2 years following disturbance than in all other years of this study. Unlike the foliage component, FWD and non-woody canopy fuels fell irregularly with no apparent pattern over time; fuels were deposited at essentially the same rate from one year to the next. CWD was an inconsequential component of deposition in this study, only rarely did anything larger than FWD fall into the litter traps.

Surface fuel loadings for all fuel classes and fuel class groupings did not increase substantially at any point of this study. Since no other disturbances were noted after the plots were installed, we can assume that surface fuel accumulations did not exceed the rate of decomposition on these sites over time. Our findings indicate that fire hazard on forested stands following insects or wildfire may introduce considerably less risk than conventional wisdom might imply. While the dead foliage is highly flammable 1–2 years after severe disturbance it does not stay in the canopy for long; once the canopy material is deposited to the ground, accumulation does not exceed the rate at which fuels are processed on a yearly basis. Our findings indicate that canopy foliage and fine woody material are supported in the canopy for a relatively brief period of time and surface fuel loadings do not accumulate at an increased rate over a decade. Thus, stand-replacing disturbance caused by insects or wildfire may increase fire spread and intensity for 1–2 years after disturbance because of fuels remaining in the canopy. However, fuel loadings did not change substantially over the 10 years in this study indicating that heavy surface fuel loads do not immediately accumulate as a consequence of severe disturbance.

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