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Effects of salvage logging and pile-and-burn on fuel loading, potential fire behaviour, fuel consumption and emissions

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Abstract. We used a combination of field measurements and simulation modelling to quantify the effects of salvage logging, and a combination of salvage logging and pile-and-burn fuel surface fuel treatment (treatment combination), on fuel loadings, fire behaviour, fuel consumption and pollutant emissions at three points in time: post-windstorm (before salvage logging), post-salvage logging and post-surface fuel treatment (pile-and-burn). Salvage logging and the treatment combination significantly reduced fuel loadings, fuelbed depth and smoke emissions. Salvage logging and the treatment combination reduced total surface fuel loading (sound plus rotten) by 73 and 77%. All fine woody fuels (<7.6 cm) were significantly reduced by salvage logging and the treatment combination. In contrast, there was significant increase in the 1000-h (7.6–22.9 cm) fuel loading. Salvage logging and the treatment combination reduced mean fuelbed depth by 38 and 65%. Salvage logging reduced $PM_{2.5}$ emissions by 19%, and the treatment combination reduced emissions by 27%. Salvage logging and the treatment combination reduced PM_{10} emissions by 19 and 28%. We observed monotonic changes in flame length, reaction intensity and rate-of-spread after salvage logging and treatment combination. Study results illustrate potential differences between the effects of salvage logging after windstorms and the effects of salvage logging after wildfire.

Additional keywords: blowdown, CONSUME 3.0, FFE–FVS, fuel reduction treatments, fuels, Fuel Characteristic Classification System, windstorms.

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Introduction

Salvage logging, or the removal of dead merchantable timber following disturbances (wildfire, windstorms, insect epidemics), is a controversial management practice on federal and private lands in North America (Beschta *et al.* 1995; Lindenmayer *et al.* 2004; Donato *et al.* 2006; Lang *et al.* 2009; R. Everett, pers. comm., 1995). Some argue that salvage logging impedes forest succession (Donato *et al.* 2006; Lindenmayer and Ough 2006; Greene *et al.* 2006), increases fine and coarse fuel loads and intensifies fire behaviour (Thompson *et al.* 2007), increases soil erosion and stream sedimentation (Helvey 1980; Karr *et al.* 2004) and reduces wildlife habitat (Stone 1993). Others suggest there are benefits of salvage logging: (1) recovery of economic value of timber (Simon *et al.* 1994), (2) reduction of fuel loadings and fuelbed depth (Peterson and Leach 2008; Peterson *et al.* 2009), (3) reduction of fire hazard and fire severity (Shore *et al.* 2003), (4) prevention of insect epidemics (Simon *et al.* 1994) and (5) promotion of forest regeneration and recovery (Simon *et al.* 1994; Sessions *et al.* 2004).

Despite the prevalence of salvage logging in forest management relatively little scientific information exists on its ecological effects (McIver and Starr 2001; Lindenmayer and Noss 2006; Noss and Lindenmayer 2006). Most field studies have examined salvage logging effects following wildfires (McIver and Starr 2001; Beschta *et al.* 2004; Lindenmayer and Noss 2006; Peterson *et al.* 2009) and have focussed on treatment effects on forest succession and tree regeneration (Donato *et al.* 2006), snags and wildlife habitat (Nappi *et al.* 2003), erosion and forest hydrology (Foster *et al.* 1997), soil nutrients (Brais *et al.* 2000) and fuel loads (Donato *et al.* 2006; McIver and Ottmar 2007). Although there has been some recent post-fire logging work on fuel loads and fire behaviour (Donato *et al.* 2006; McIver and Ottmar 2007) few studies have quantified the effects of salvage logging on fuel loads, fire behaviour, fuel consumption and emissions after non-fire disturbances such as windstorms (McIver and Starr 2001; Lang *et al.* 2009).

Frequent disturbances such as wildfires, windstorms and insect epidemics have different effects on fuelbed characteristics including fuel loading, fuelbed depth and fuel accumulation and successional trajectories (Foster *et al.* 1997; Sinton *et al.* 2000). Compared to post-wildfire conditions, stand-replacing windstorms may produce substantially different fuelbed characteristics. For example, loading of fine (<0.64 cm) and coarse (>0.64 cm) woody fuel may increase instantly following a

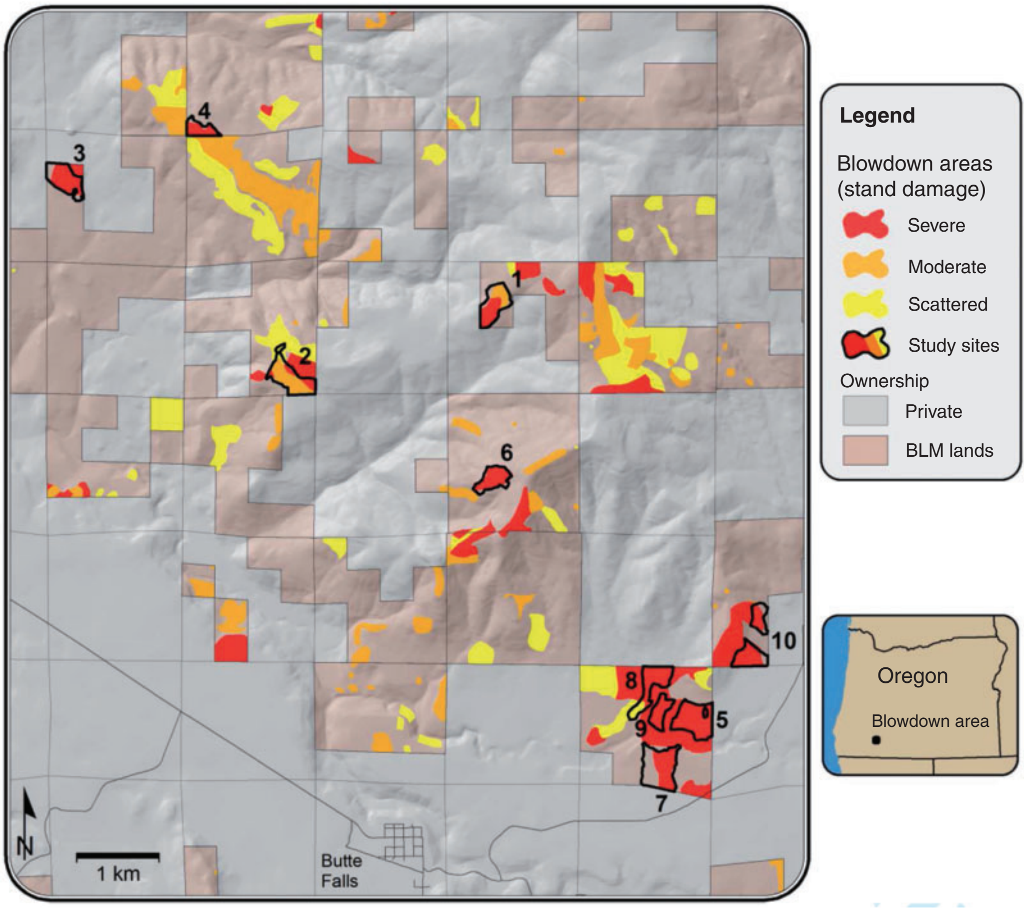

Fig. 1. The Butte Falls blowdown (windstorm) study area in south-western Oregon. Our study was focussed on Bureau of Land Management (BLM) ownership. Areas highlighted in yellow had scattered ($<10\%$ of the canopy) downed trees, areas in orange had moderate levels of downed trees (10–40% of the canopy) and areas in red had severe blowdown effects with $>40\%$ of the canopy downed.

major windstorm (Sinton *et al.* 2000) and these changes may predispose forests to subsequent large-scale disturbances such as wildfires or insect epidemics (Turner *et al.* 1989; Meyers and van Lear 1998). In contrast, stand-replacing wildfires may reduce both surface and crown fuels (Agee 1993; DeBano *et al.* 1998; Sinton *et al.* 2000; Fulé and Laughlin 2007). After wildfire, depending on fire severity and fuel consumption, there is usually an immediate, short-term decrease in the abundance of both coarse and fine woody fuel, potentially reducing subsequent fire intensity and severity in the short-term. However, with time fuels may exceed pre-fire loadings as fire-killed snags fall (Keyser *et al.* 2008).

In early January 2008, a severe windstorm with recorded wind gusts up to 145 km h^{-1} swept across the Bureau of Land Management (BLM) Butte Falls and Ashland Resources Areas in southern Oregon. After the storm, BLM resource managers surveyed more than 11 330 ha, and found blowdown areas scattered across ~2800 ha of mixed-conifer stands (Fig. 1). BLM land managers stratified blowdown areas into three classes according to the percentage of trees that were downed: scattered ($<10\%$), moderate (10–40%) and severe ($\geq 40\%$). Managers were concerned post-windstorm fuel conditions would increase fire hazard, initiate insect epidemics, delay forest succession and generate elevated smoke concentration and emissions (USDI Bureau of Land Management 2008). Several timber sales were proposed to recover the economic value of timber and to reduce potential fire hazard (USDI Bureau of Land Management 2008). In addition to salvage logging, surface fuel treatments (pile-and-burn) were implemented to reduce fuel loads (USDI Bureau of Land Management 2008).

The 2008 windstorm and subsequent salvage logging with pile-and-burn surface fuel treatments presented an opportunity to quantify changes in fuel loading as well as potential changes in fire behaviour, fuel consumption and pollutant emissions from those fuels after the windstorm, and after salvage logging with pile-and-burn surface fuel treatments. We initiated a field study in the blowdown area with the primary objective of evaluating effects of salvage logging and pile-and-burn surface fuel treatment on surface fuel loadings, simulated fire behaviour, and fuel consumption and emissions before and after salvage logging and after pile-and-burn surface fuel treatment. We hypothesised that both fine and coarse woody fuels would increase after salvage logging but that these fuels would decrease after pile-and-burn surface fuel treatments. Likewise,

Table 1. General information for the sampled study sites

Unit	Elevation (m)	Slope (%)	Size (ha)	Aspect (°)	Live density (trees ha^{-1})	Quadratic mean diameter (cm)	Canopy closure (%)	Stand height (m)	Litter depth (cm)	Duff depth (cm)
1	1195	15	13	278	310	28	60	31	3.0	2.0
2	1067	9	15	204	816	30	72	36	2.9	2.1
3	1067	4	13	140	123	45	86	33	1.8	1.0
4	1067	19	6	140	224	48	60	36	2.4	1.4
5	827	9	17	175	588	25	37	36	2.7	2.5
6	1173	15	9	240	684	28	77	31	2.2	2.1
7	832	5	19	250	850	24	59	32	2.6	3.6
8	842	6	13	184	1367	23	64	36	2.9	2.4
9	830	5	7	220	754	21	56	22	2.1	2.6
10	884	18	14	151	985	22	67	34	1.9	3.1

assuming that fire intensity is positively linked to fuel loadings (Schoennagel *et al.* 2004), we hypothesised that simulated fire behaviour, fuel consumption, and pollutant emissions would be higher on sites after salvage logging and lower following the pile-and-burn surface fuel treatment.

Methods

Study sites and treatments

The study sites were scattered across the Butte Falls blowdown salvage project area on the BLM Butte Falls Resource Area in southern Oregon (Fig. 1). Land ownership is diverse and includes a checkerboard pattern of nonindustrial private landowner, federal and city lands (Fig. 1). Climate is characterised by cool, wet winters and warm, dry summers (USDI Bureau of Land Management 2008). Mean annual precipitation is ~90 cm with most precipitation between November and April. Mean minimum temperature in January is 0°C and mean maximum temperature in July is 32°C (USDI Bureau of Land Management 2008). Vegetation is dominated by forests of Douglas-fir (*Pseudotsuga menziesii* (Mirb.) Franco), white fir (*Abies concolor* (Gord. & Glend.) Lindl.), incense cedar (*Calocedrus decurrens* Torr.), ponderosa pine (*Pinus ponderosa* Dougl. ex P. & C. Laws.) and sugar pine (*P. lambertiana* Dougl.) (Franklin and Dyrness 1973). The major plant associations are white-fir–dwarf Oregon grape *(Mahonia repens* (Lindl.) G. Don), white-fir–dwarf Oregon grape –vanilla leaf *(Achyls triphylla* DC.*)* and white fir–Douglas-fir–wood rose *(Rosa gymnocarpa* Nutt.) (Atzet *et al.* 1996). The dominant soil series are Freezner, Geppert, and Dumont–Coyata (Atzet *et al.* 1996) and soils are productive, with an average depth of 51–152 cm. Before the windstorm, most sites had an extensive history of selection thinning treatments followed by surface fuel treatments (J. Bergin, pers. comm. 2008).

Trees removed in the salvage logging operation included dead wind-thrown trees, damaged live trees that were deemed by loggers to be unlikely to survive, insect-killed trees and trees that were hazardous to workers or the public. In post-windstorm conditions loggers focus on all downed trees with green branches. Trees with obvious defects (e.g. cull trees or trees with conks, disease or rot) were probably not extracted, and were removed during the surface fuel treatment operations. All trees were skidded to a central area where the limbs were removed (whole tree harvest). The timber was removed using a variety of helicopter, tractor, shovel and cable yarding systems. For our study we examined only sites that had been logged using tractor yarding systems, because the sample of plots logged using tractor systems was greater than for any other method.

Site preparation or slash disposal activities such as lop and scatter, piling and burning, and underburning were used to treat logging slash and damaged residual conifers. We chose to examine sites where residual slash was tractor piled and burned (USDI Bureau of Land Management 2008), because this was the most common method of slash removal. The slash or surface fuel treatment removed all slash and un-merchantable material. The pile-and-burn surface fuel treatment method was only applied to sites with high-severity windstorm effects and thus our sample was limited to high-severity sites.

Sampling design

Following extensive field reconnaissance, we selected 10 study sites for intensive sampling (Table 1). These were the only sites that fulfilled our requirements: (1) consistency in combination of logging and surface fuel treatment applied (see above) (in this case tractor yarding system and pile-and-burn); (2) stand age ranging from 160 to 290 years (USDI Bureau of Land Management 2008), in order to avoid variation in fuel levels associated with stand age and management treatments associated with different stand ages and (3) logging occurring on a timescale that accommodated our field crew schedule (little notice was given before logging activities were initiated).

At each study site, we measured fuelbed properties at three points in time: (1) post-windstorm (measured in May 2009), (2) post-salvage logging (measured in September 2009) and (3) post-pile-and-burn surface fuel treatment (measured in May 2010). We installed a series of five permanent sampling plots in each site. Plots were established 60 m from site edge and 60 m apart (from plot centre) along the long axis of each site (because of irregular site shapes). The azimuth for the long axis of a site was determined with a compass on a site map.

At each plot we recorded slope (%), aspect (°), slope position and elevation (m). We took digital photos from plot centre in each of the four cardinal directions. Plots were marked with a permanent centre stake and number metal tag. Pre- and post-disturbance sampling was conducted along the same permanent transect lines. To ensure that we could locate plots after treatments we buried magnets in the ground at plot centre and took GPS coordinates of plot centres and witness trees.

We used a nested sampling design to record live and dead trees in each plot. In a 0.05-ha circular plot we recorded tree species, live or dead status and diameter at breast height (DBH) of trees >10.2-cm DBH. In at least two plots per site we measured the height of three trees in each canopy stratum (used to calibrate heights of unmeasured trees in the Forest Vegetation Simulator (FVS), see methods below). In a 0.004-ha circular plot, we recorded DBH and height of trees <10.2 cm. We also recorded species and average height of two dominant shrubs and herbaceous species. Only two dominant shrub and herbaceous species were recorded in order to build a Fuel Characteristic Classification System (FCCS) fuelbed (see Fire behaviour predictions and fuelbed quantification below). In FCCS the shrub and non-woody contribution to the calculation of fire rate of spread is determined by percent coverage of the two dominant shrubs and herb species; FCCS has built-in allometric equations to calculate shrub and herb loading based on percent cover information (Riccardi *et al.* 2007b). Shrubs and herb species with <10% cover are unlikely to make significant contributions to shrub and herb loading or to significantly affect fire rate-of-spread or reaction intensity. Shrub and non-woody measurements were taken only post-windstorm, and not post-salvage logging and post-surface fuel treatment, because we assumed the dominant species and loading would remain the same after treatment.

On each plot we sampled both fine woody fuel (<7.6 cm) and coarse woody fuel (>7.6 cm), using the planar intersect method outlined by Brown (1974) and described by Maxwell and Ward (1980). Three 20-m transects were originated from plot centre, for a total of 15 transects per site and 300 m of transect per site. We chose to include 15 transects per site according to recommendations by Brown (1974) and Taylor (1997). The azimuth of the first transect was selected randomly and the other two were established at 120° and 240° from the first. We tallied 1-h fuel (<0.64 cm) from 19 to 20 m, 10-h fuel (0.64–2.54 cm) from 18 to 20 m, 100-h fuel (2.5–7.6 cm) from 17 to 20 m, and 1000- and 10 000-h fuel (>20.3 cm) from 0 to 20 m. Woody material <7.6-cm DBH was recorded as sound. Callipers were used to measure the log diameter and decay class of sound and rotten material >7.6-cm DBH. We used a five-class rotten decay system based on Fogel *et al.* (1973) to determine soundness of material. Woody fuel loading was calculated from the algorithms developed by Brown (1974) and Safranyik and Linton (1987).

In addition to measuring down woody fuel along each transect we recorded DBH, height and presence of foliage snags. We estimated tree canopy cover with a spherical densiometer (moosehorn) at 5, 10, 15 and 20 m. Fuelbed depth was measured at 5, 10, 15 and 20 m along each transect by estimating the height from the bottom of the litter layer to the top of the highest fuel particle with a diameter of <7.62 cm.

Fire behaviour predictions and fuelbed quantification

We used the FCCS (version 2.2; Ottmar *et al.* 2007; Riccardi *et al.* 2007*a*, 2007*b*; Sandberg *et al.* 2007*a*, 2007*b*) and the Fire and Fuels Extension to the FVS (FFE–FVS version 2.02; Rebain 2012) to calculate custom fuelbed characteristics based on measured data and to calculate estimates of potential fire rate of spread ($m\,s^{-1}$), reaction intensity ($kW\,m^{-2}$) and flame length (m) for the three treatment scenarios: post-windstorm, post-salvage logging and post-pile-and-burn surface fuel. We chose to focus on surface fire behaviour outputs because the surface fire outputs from FCCS are understandable to fire managers and are the primary metrics they use to make management decisions. In addition, because canopies were thinned and most trees were downed in the study sites (all severe windthrow areas), crown fire potential would likely have been low for all study sites.

The FVS–FCCS process we used allowed us to build fuelbeds using real fuels data for each site for the post-windstorm, post-salvage logging, and post-surface fuel treatment conditions. Our approach to quantifying treatment effects is similar to that of Youngblood *et al.* (2008), who used FCCS fuelbeds to quantify changes in fuelbed characteristics and fire potentials after fuel reduction treatments in the Blue Mountains, Oregon. The custom fuelbed approach used in this and the Youngblood *et al.* (2008) study is an alternative to the common approach of using stylised fuel models (Albini 1976; Scott and Burgan 2005) as fuel data surrogates. However, we performed potential fire behaviour analyses with both custom fuelbeds in FCCS and representative stylised fuel models in FFE–FVS to compare FCCS fire behaviour results with those of more commonly used approaches.

FCCS is a tool that provides a consistent approach to characterise and quantify the structural complexity and variability of wildland fuels found across diverse forest and non-forest ecosystems (Ottmar *et al.* 2007; Riccardi *et al.* 2007*a*, 2007*b*; Sandberg *et al.* 2007*a*, 2007*b*; Prichard *et al.* 2010). The fuelbed is the basic unit of the system. FCCS quantifies fuelbeds based on six horizontal strata that represent unique combustion environments: canopy, shrubs, herbaceous fuels, woody fuels, litter–lichen–moss and ground fuels (Riccardi *et al.* 2007*a*, 2007*b*; Table 2). Fuelbed strata are divided into 18 categories and 20 subcategories with common combustion characteristics (Riccardi *et al.* 2007*a*). To build FCCS fuelbeds, data are required for each stratum (Table 2). FCCS uses both user inputs and inferred variables to calculate fuel characteristics. For some fuel stratum characteristics, such as percent cover, height and depth, FCCS simply summarises the fuelbed inputs. Other characteristics are calculated using algorithms described in detail in Riccardi *et al.* (2007*b*). FCCS fire behaviour predictions are not generated from stylised fuel models; rather these predictions are based on a reformulated Rothermel (1972) rate of spread equation (Sandberg *et al.* 2007*b*), which allows data input for multiple fuelbed strata.

FFE–FVS is a semi-distance-independent growth and yield model (Dixon 2013) that also calculates fire behaviour (Rebain 2012). Tree inventory data and geographic specific growth equations (variants) simulates tree growth and mortality, fuel decomposition, tree regeneration, insect and disease effects, silvicultural treatments, forest succession and potential fire behaviour (Rebain 2012; Dixon 2013). To predict fire behaviour, the model uses Rothermel's (1972) fire behaviour model as implemented by Albini (1976) in FIREMOD and subsequently by Andrews (1986) in BEHAVE. The Rothermel's (1972) fire behaviour model uses stylised fuel models (Albini 1976; Anderson 1982; Scott and Burgan 2005) as surrogates for measured fuel

Table 2. Variables used for the development of fuelbeds in the Fuel Characteristic Classification System (FCCS)
Adapted from Prichard *et al.* (2010). These values are based on field data and were calculated using the FCCS

Stratum	Category	Subcategory	Variable
Canopy	Total canopy		Percentage cover (%)
	Trees	Overstorey	Percentage cover (%)
		Midstorey	Height (m)
		Understorey	Height to live crown (m)
			Density (number of stems ha^{-1})
			Diameter at breast height (cm)
			Species and relative cover (%)
	Snags	Class 1 with foliage	Density (number of stems ha^{-1})
		Class 1 without foliage	Diameter (cm)
		Class 2	Height (m)
		Class 3	Species and relative cover (%)
	Ladder fuels	Arboreal lichens and moss	Minimum height (m)
		Climbing ferns and other epiphytes	Maximum height (m)
		Dead branches	Is there vertical continuity sufficient to carry fire between the canopy and lower strata? (yes or no)
		Leaning snags	
		Stringy or fuzzy bark	
		Tree regeneration	
		Vines – liana	
Shrub	Primary layer		Percentage cover (%)
	Secondary layer		Height (m)
			Percentage live (%)
			Species and relative cover (%)
	Needle drape		Is needle drape on shrubs sufficient to affect fire behaviour? (yes or no)
Non-woody fuels	Primary layer		Percentage cover (%)
	Secondary layer		Height (m)
			Percentage live (%)
			Loading ($Mg\,ha^{-1}$)
			Species and relative cover (%)
Woody fuels	All woody		Total percentage cover (%)
			Depth (m)
	Sound wood	All sound wood	For >3-in sound wood
		Size classes –	Species and relative cover (%)
		0 to 0.25 in, >0.25 to 1 in, >1 to 3 in, >3 to 9 in, >9 to 20 in, >20 in	For size classes
			Loading ($Mg\,ha^{-1}$)
	Rotten wood	All rotten wood	For all rotten wood
		Size classes	Species and relative cover (%)
		>3 to 9 in, >9 to 20 in, >20 in	For size classes
			Loading ($Mg\,ha^{-1}$)
	Stumps	Sound	Density (number of stumps ha^{-1})
		Rotten	Diameter (cm)
		Lightered-pitchy	Height (m)
			Species and relative cover (%)
	Woody fuel accumulation	Piles	Width (m)
		Jackpots	Length (m)
		Windrows	Height (m)
			Density (number of accumulations ha^{-1})
Litter-lichen-moss	Litter	Arrangement	For overall litter
		Fluffy, normal, perched	Depth (cm)
		Type	Percentage cover (%)
		Short needle pine, long needle pine, other conifer, broadleaf deciduous, broadleaf evergreen, palm frond, grass	For each litter type
			Relative cover (%)
	Lichen	None	Depth (cm)
			Percentage cover (%)
	Moss	Type	Depth (cm)
		Spaghnum, other moss	Percentage cover (%)

(*Continued*)

Table 2. (Continued)

Stratum	Category	Subcategory	Variable
Ground fuels	Duff	Percentage rotten wood	For percentage rotten wood
		Upper layer	Percentage cover (%)
		Partially decomposed dead moss and litter, partially decomposed sphagnum moss and sedge	For duff layers
		Lower layer	Depth (cm)
		Fully decomposed dead moss and litter, fully decomposed sphagnum moss and sedge	Percentage cover (%)
	Squirrel middens	None	Depth (cm) Radius (m) Density (number of middens ha^{-1})
	Basal accumulations	Type	Depth (cm)
		Bark slough, branches, broadleaf deciduous, broadleaf evergreen, grass, needle litter, palm fronds	Radius (m)
			Percentage of trees affected (%)

data. Each fuel model represents a range of fuel conditions in which fire behaviour may be expected to respond similarly to changes in fuel moisture, wind and slope (Rothermel 1972). We estimated fire behaviour variables (rate of spread, flame length, reaction intensity) from both FCCS and FFE–FVS for comparison purposes. Crown fire initiation is predicted using approaches developed by Van Wagner (1977) and Scott and Reinhardt (2001). Tree mortality, fuel consumption and smoke production estimates are derived from FOFEM (Reinhardt *et al.* 1997).

FFE–FVS has numerous algorithms to generate fire behaviour predictions from Anderson's (1982) 13 fuel models or Scott and Burgan's (2005) 40 fuel models. FFE–FVS uses stand data and other stand characteristics to select stylised fuel models that best represent the fuel conditions (Rebain 2012). Fuel model selection rules vary among the geographic variants. FFE–FVS has two fuel model selection options: a static option that calculates fire behaviour from a single fuel model and a dynamic option that calculates fire behaviour from a weighted average of two or more fuel models (Rebain 2012). We estimated fire behaviour with four FFE–FVS modelling options (subscript numbers indicate the set of fuel models used to estimate fire behaviour): FVS $static_{13}$, FVS $dynamic_{13}$, FVS $static_{53}$ and FVS $dynamic_{53.}$ FVS $static_{13}$ and FVS $dynamic_{13}$ fire behaviour estimates are derived from Anderson's (1982) fuel models and FVS $static_{53}$, and FVS $dynamic_{53}$ fire behaviour estimates are derived from both Anderson's (1982) and Scott and Burgan's (2005) models.

We developed an FVS portfolio with 30 stands to represent our 10 sites after the windstorm, 10 sites after salvage logging and 10 sites after pile-and-burn surface fuel treatment. We developed an algorithm to transform FVS–simulated data into FCCS input format. We then built 30 customised FCCS fuelbeds. We calculated FCCS and FFE–FVS surface fire behaviour estimates under the following weather scenarios: 1-h fuel moisture content (FMC) = 3%, 10-h FMC = 4%, 100-h FMC = 5%, 1000-h FMC = 8%, non-woody FMC = 30%, shrub FMC = 60%, crown FMC = 60%, duff FMC = 25%, slope = 0% and mid-flame windspeed = 8 and 16 km h^{-1}. Our weather parameters were similar to the 90th percentile values recorded at Evans remote automated weather station (RAWS), which are values based on historical weather data for a 100-day fire season and used by local BLM managers to determine extreme fire weather (USDI Bureau of Land Management 2008). The 90th percentile is a common threshold used by the fire management and fire science communities to determine extreme fire weather conditions (e.g. Stephens and Moghaddas 2005; Finney *et al.* 2007; Stephens *et al.* 2009).

Fuel consumption and emissions

We used CONSUME 3.0 (Prichard *et al.* 2005) to estimate potential fuel consumption and emissions for our study sites (using the same FCCS fuelbeds as described above) under the fuel moisture and weather conditions described above, which are typical of a south-western Oregon wildfire. CONSUME 3.0 is used throughout the United States to predict woody fuel consumption and pollutant emissions. CONSUME has two fuel consumption models, which represent activity fuels (logging slash) and natural fuels (Prichard *et al.* 2005). CONSUME uses individual algorithms to predict consumption of defined fuelbed layers including grasses, shrubs, five woody fuel size classes (0.64–2.54 cm, 2.54–7.62 cm, 7.62–22.86 cm, 22.86–50.8 cm, >50.8 cm), litter and duff. CONSUME calculates the emissions of the following pollutants: non-methane hydrocarbon (NMHC), carbon dioxide (CO_2), carbon monoxide (CO), particulate matter $<10\,\mu m$ in mean diameter (PM_{10}), methane (CH_4), particulate matter $<2.5\,\mu m$ in mean diameter ($PM_{2.5}$) and particulate matter (PM). Of these pollutants, $PM_{2.5}$ concentrations is one of the most important because a majority of the smoke particles are $\leq 2.5\,\mu m$ in mean diameter and can affect human health and air quality; 90% of smoke particles emitted from fires are PM_{10} and ~90% of PM_{10} is $PM_{2.5}$ (Ward and Hardy 1991; Ottmar *et al.* 2009).

Table 3. Mean, range (in parentheses) and percentage change in fuelbed depth and fuel loading in 10 sampled sites after a windstorm but before salvage logging, after salvage logging, and after a pile-and-burn surface fuel treatment

For each variable, means with the same lowercase superscript letter are not significantly different ($P < 0.05$)

Fuelbed characteristics	Woody fuel size class	Mean response following treatment			Percentage change (%)	
		Windstorm (pre-treatment)	Windstorm + salvage logging	Windstorm + salvage logging + surface fuel treatment	(a–b)	(a–c)
Fuelbed depth (m)		0.40^{a} (0.28–0.65)	0.25^{b} (0.21–0.30)	0.14^{c} (0.10–0.23)	38	65
Fine woody loading (Mg ha^{-1})	1-h (< 0.64 cm)	1.6^{a} (0.88–2.6)	1.2^{b} (0.94–1.8)	0.97^{c} (0.60–1.5)	25	39
	10-h (0.64–2.54 cm)	6.0^{a} (4.2–7.0)	4.6^{b} (3.2–6.8)	3.9^{b} (2.7–4.8)	23	35
	100-h (2.54–7.6 cm)	9.6^{a} (6.7–11.8)	8.5^{b} (6.7–9.8)	7.10^{c} (4.0–9.3)	11	26
Coarse woody loading (Mg ha^{-1})	1000-h (7.6–22.9 cm)	9.0^{a} (0.86–17.8)	11.7^{b} (2.5–22.8)	7.9^{a} (3.0–15.7)	−30	12
	Large sound 1 (22.9–50.8 cm)	43.9^{a} (9.2–98.8)	20.8^{b} (8.8–40)	18.7^{b} (8.8–29)	53	57
	Large sound 2 (50.8–251.5 cm)	45.9^{a} (5.0–117.3)	22.8^{b} (0–48.3)	16.3^{b} (0–38.9)	50	64
	Rotten					
	1000-h (7.6–22.9 cm)	7.1^{a} (1.00–13.0)	6.6^{ab} (3.2–16.7)	5.2^{b} (1.9–12.1)	7	27
	Large rotten 1 (22.86–50.8 cm)	21.7^{a} (8.36–38.3)	17.3^{a} (6.11–33.6)	13.3^{a} (0.77–27.6)	20	39
	Large rotten 2 (50.8–251.5 cm)	23.3^{a} (3.9–52.4)	16.4^{a} (0–37.7)	15.5^{a} (0–60)	20	39

We directly imported the FCCS fuelbeds described above into CONSUME and used the activity fuel consumption module within CONSUME to calculate consumption and emissions for study sites at three points in time: (1) post-windstorm, (2) post-salvage logging and (3) post-surface fuel treatments. We assume that calculations of fuel consumption and emissions in the post-surface-fuel treatment sites are from residual slash left in each site, minus the logging slash that was piled and burned. We ran CONSUME using the following conditions: (1) 10-h fuel moisture (FM) = 4%, (2) 1000-h FM = 8%, (3) duff FM = 20%, (4) windspeed = 8 km h^{-1}, (5) length of ignition = 60 min and (6) days since rain = 20.

Statistical analysis

We used repeated-measures analysis of variance (ANOVA) to compare mean levels of fuelbed depth, fuel loading (1-, 10-, 100-, 1000-, and 10 000-h), simulated fire behaviour variables, fuel consumption and pollutant emissions at the 10 sites (replicates) under the three conditions: (1) post-windstorm, (2) post-salvage logging and (3) post-surface fuel treatment. We used repeated-measures ANOVA because we measured the same variables on the same experimental units (sites) under different conditions (post-windstorm, post-salvage logging and post-surface fuel treatment) and we were investigating differences in means of those variables under those different conditions. We used PROC MIXED in SAS v9.2 (SAS Institute, Cary, NC, USA) to fit a mixed effects model to the data with site as a repeatedly measured unit. We identified the most appropriate covariance structure by choosing the structure that provided the model with the lowest AIC value. We checked assumptions of normality and constant variance before interpreting results of the analysis. We used log transformations when necessary to improve constant variance for a given variable and used LSMEANS with a Bonferroni adjustment (SAS v9.2) for multiple comparisons of means.

Results

Treatment effects on fuel loadings

Salvage logging and a combination of salvage logging and pile-and-burn fuel surface fuel treatment (hereafter referred to as the treatment combination) both significantly reduced mean fuelbed depths (Table 3). Salvage logging reduced mean fuelbed depth by 38% from 0.40 m (post-windstorm) to 0.25 m and the treatment combination reduced mean fuelbed depth by 65% to 0.14 m (Table 3).

Salvage logging and the treatment combination also reduced total surface fuel loading. Post-windstorm total (sound plus rotten) surface fuel loading averaged 151 Mg ha^{-1} (range 36–226; Table 3). After salvage logging mean loading was reduced to 41 Mg ha^{-1} (range 16–56) and after the treatment combination mean loading was 35 Mg ha^{-1} (range 19–56).

Despite relatively low initial loadings, all categories of fine woody fuels, (1-h, 10-h, 100-h) were significantly reduced by both salvage logging and the treatment combination (Table 3).

With the exception of the 1000-h (7.6–22.9 cm) fuels salvage logging and the treatment combination also significantly reduced all categories of sound and rotten coarse woody fuel (Table 3).

Treatment effects on predicted fire behaviour

We summarise the FCCS and FFE–FVS estimates of flame length (m), reaction intensity (kW m^{-2}) and rate of spread (m s^{-2}). Because treatment significance was identical for our two windspeed scenarios (8 and 16 km h^{-1}) we summarise the results for the 8-km h^{-1} windspeed scenario.

Salvage logging and pile-and-burn treatment effects on simulated flame length varied among models. The FCCS and FVS $dynamic_{53}$ projected no significant difference in mean flame length between treatments (Table 4). In contrast, FVS $static_{13}$ and FVS $dynamic_{13}$ projected a significant difference after salvage logging and the treatment combination treatment (Table 4). FVS $static_{53}$ projected a significant difference in flame length only after the treatment combination (Table 4).

For reaction intensity, FCCS projected no significant difference after treatments (Table 3). In contrast, FVS $static_{13}$, FVS $static_{53}$ and FVS $dynamic_{53}$ projected a significant difference in reaction intensity following the combination treatment only (Table 4). FVS $dynamic_{13}$ projected a significant reduction in reaction intensity after salvage logging and the treatment combination (Table 4).

Salvage logging and pile-and-burn treatment effects on simulated rate-of-spread also varied among models (Table 4). FCCS projected a significant difference in rate-of-spread after the treatment combination only. In contrast, FVS $static_{13}$, FVS $dynamic_{13}$, FVS $static_{53}$ and FVS $dynamic_{53}$ projected no significant difference in rate-of-spread (Table 4).

Treatment effects on fuel consumption and pollutant emissions

Salvage logging and the treatment combination significantly reduced total fuel consumption and pollutant emissions as predicted by CONSUME, assuming typical wildfire conditions (Table 5). Average pre-treatment total fuel consumption was predicted to be 97 Mg ha^{-1} (range 53–128; Table 5). Salvage logging reduced total consumption by 21% to 77 Mg ha^{-1} (range 54–95 Mg), and the treatment combination reduced total consumption by 33% to 65 Mg ha^{-1} (range 56–80).

Pre-treatment total emissions (sum of all emissions) were 17 072 Mg ha^{-1} (Table 5). CO_2 emissions comprised more than 90% of total emissions (Table 5). Salvage logging reduced total emissions by 21% and the treatment combination reduced emissions by 33% (Table 5). Emissions of all pollutants except CO and CH_4 were significantly different following treatments. For CO and CH_4, there was no significant difference between post-salvage logging and the treatment combination. Of the emissions projections, $PM_{2.5}$ and PM_{10} emissions are of particular concern to fire and resource managers. Average pre-treatment emission of $PM_{2.5}$ particulate was 91 Mg ha^{-1} (range 48–113). Salvage logging reduced $PM_{2.5}$ emissions by 19% and the treatment combination reduced emissions by 27%. Average pre-treatment emission of PM_{10} was 99 Mg ha^{-1} (range 53–124). Salvage logging reduced PM_{10} emissions by 19% and the treatment combination reduced emissions by 28% to 71 Mg ha^{-1} (range 57–90).

Discussion

Our results for post-windstorm salvage logging differ from results for post-wildfire salvage logging (e.g. Brown 1980; Donato et al. 2006; McIver and Ottmar 2007; Monsanto and Agee 2008) in that we did not find salvage logging increased fine woody fuels ($\leq$7.28 cm). In our study both salvage logging and the treatment combination (salvage logging plus pile-and-burn surface fuel treatment) significantly reduced the loading of fuels (total loading and most fuel size categories), which controls wildfire ignition and fire behaviour (Anderson 1982; Rothermel 1983; DeBano et al. 1998; Graham et al. 2004). These fuel loading reductions did not support our hypothesis that woody fuels would increase after salvage logging.

Intuitively, salvage logging should increase surface fuels by transferring un-merchantable biomass such as tree branches and limbs to the ground (Thompson et al. 2007). However, in our study fine and coarse woody fuels did not increase, possibly because salvage logging was implemented using whole-tree harvesting. With whole-tree harvesting, trees are dragged to a central landing where most branch materials are removed from the tree bole (Jacobson et al. 2000). Removing tree branches on site would likely have created a significant increase in both fine and coarse surface fuel loadings and fuelbed depth. Thus, it seems that post-salvage logging fuel levels could be tied to the operational aspects of tree removal (Peterson et al. 2009). However, whole-tree harvesting was also used in the post-wildfire salvage logging study by McIver and Ottmar (2007) and the authors observed significant increases in fine fuels after salvage logging. Another potential reason why activity fuel loads might differ between post-fire and post-windstorm salvage logging operations is that, whereas most of the harvested trees in a post-fire logging operation are standing at the time of logging, in post-windstorm logging many trees are already on the ground. If most activity fuels are moved to the ground through the felling process (and post-fire felling would be relatively more common than post-windstorm felling) then one would expect more activity fuels after post-wildfire logging than after post-windstorm logging, because relatively minor amounts of slash fuels are left due to yarding in post-windstorm logging.

Our results are consistent with post-wildfire studies showing an increase in coarse woody fuels following salvage logging (Donato et al. 2006; McIver and Ottmar 2007). We suggest that the increase in coarse woody fuels resulted from branch breakage from trees removed from site and from material being moved onto our transect lines. Although fire managers have less concern about coarse woody fuel because these fuels do not influence fire rate-of-spread and flame length (Rothermel 1972), elevated loading of coarse woody fuel may increase soil heating and flame duration (Monsanto and Agee 2008). On the other hand, coarse woody fuel can provide wildlife habitat and other ecological benefits.

In our study area, it is likely that past active forest management influenced post-disturbance fuel conditions and effects on salvage logging and surface fuel treatments. Post-windstorm woody fuel loading and fuelbed depth were unusually low (Table 3); for sites that experienced a stand-replacing disturbance we expected to measure higher loading of fine and coarse woody fuel. Harvest records indicate that timber harvest had

Table 4. Mean (top number) and range (in parentheses) simulated fire behaviour for 10 sites after a windstorm before salvage logging, after salvage logging and after a pile-and-burn surface fuel treatment

Fire behaviour variables were calculated with the Fuel Characteristics Classification System and the Fire and Fuels Extension to the Forest Vegetation Simulator. For each variable, means with the same lowercase superscript letter are not significantly different ($P < 0.05$)

Modelling projection	Simulated windspeed	Simulated mean response following treatment								
		Flame length (m)			Reaction intensity surface ($\mathrm{kW\,m^{-2}}$)			Rate of spread ($\mathrm{m\,s^{-1}}$)		
		Windstorm (pre-treatment)	Windstorm + salvage logging	Windstorm + salvage logging + pile and burn	Windstorm (pre-treatment)	Windstorm + salvage logging	Windstorm + salvage logging + pile and burn	Windstorm (pre-treatment)	Windstorm + salvage logging	Windstorm + salvage logging + pile and burn
FCCS[A]	8 km h^{-1}	1.6^{a} (1.0–2.0)	1.5^{a} (1.1–2.0)	1.4^{a} (1.0–1.8)	401^{a} (262–544)	395^{a} (312–457)	425^{a} (310–560)	0.09^{a} (0.05–0.11)	0.08^{a} (0.05–0.11)	0.06^{b} (0.04–0.08)
	16 km h^{-1}	2.6^{a} (1.5–3.1)	2.4^{a} (1.8–3.2)	2.2^{a} (1.6–2.8)				0.23^{a} (0.13–0.29)	0.21^{a} (0.13–0.30)	0.15^{b} (0.10–0.21)
FVS static_{13}^{B}	8 km h^{-1}	1.3^{a} (0.9–2.0)	1.0^{b} (0.8–1.7)	0.9^{b} (0.9–1.0)	1413^{a} (639–2222)	1278^{a} (639–1486)	985^{b} (639–1331)	0.02^{a} (0.01–0.03)	0.02^{a} (0.01–0.03)	0.02^{a} (0.01–0.03)
	16 km h^{-1}	1.6^{a} (1.1–2.6)	1.3^{b} (1.0–2.2)	1.2^{b} (1.1–1.4)				0.03^{a} (0.02–0.05)	0.03^{a} (0.02–0.05)	0.04^{a} (0.02–0.05)
FVS $\mathrm{dynamic}_{13}^{C}$	8 km h^{-1}	1.4^{a} (0.9–1.9)	1.0^{b} (0.9–1.4)	1.0^{b} (0.9–1.1)	1461^{a} (749–1974)	1229^{b} (856–1413)	1106^{c} (829–1355)	0.02^{a} (0.01–0.03)	0.02^{a} (0.01–0.03)	0.02^{a} (0.01–0.03)
	16 km h^{-1}	1.7^{a} (1.1–2.4)	1.4^{b} (1.0–1.9)	1.2^{b} (1.1–1.5)				0.03^{a} (0.02–0.05)	0.03^{a} (0.02–0.04)	0.03^{a} (0.02–0.04)
FVS $\mathrm{dynamic}_{53}^{D}$	8 km h^{-1}	0.8^{a} (0.4–1.2)	0.9^{a} (0.4–1.6)	0.6^{a} (0.6–1.5)	887^{a} (315–1337)	810^{a} (315–1347)	665^{b} (313–1255)	0.01^{a} (0.01–0.02)	0.02^{a} (0.01–0.05)	0.02^{a} (0.01–0.04)
	16 km h^{-1}	1.1^{a} (0.5–1.6)	1.2^{a} (0.5–2.1)	1.1^{a} (0.7–2.0)				0.03^{a} (0.01–0.05)	0.04^{a} (0.01–0.10)	0.04^{a} (0.01–0.09)
FVS static_{53}^{E}	8 km h^{-1}	0.8^{ab} (0.3–1.4)	0.9^{a} (0.2–1.7)	0.6^{b} (0.2–1.7)	912^{a} (187–1554)	856^{a} (187–1331)	590^{b} (187–1331)	0.01^{a} (0.01–0.03)	0.02^{a} (0.0–0.05)	0.01^{a} (0.0–0.05)
	16 km h^{-1}	1.0^{ab} (0.4–1.9)	1.1^{a} (0.3–2.3)	0.80^{b} (0.3–2.3)				0.02^{a} (0.01–0.06)	0.04^{a} (0.01–0.11)	0.02^{a} (0.01–0.11)

[A] Projections using the Fuel Characteristic Classification System.

[B] FVS projections using a single Anderson (1982) 13 fuel model.

[C] FVS projections using a combination of Anderson (1982) 13 fuel models.

[D] Projections using a combination of Anderson (1982) 13 fuel models and Scott and Burgan (2005) 40 fuel models.

[E] Projections using a single Anderson (1982) 13 fuel models or Scott and Burgan (2005) 40 fuel model. FVS selects fuel models based on habitat type, fuel loading and management history.

Table 5. Mean (top number), range (in parentheses), and percentage change of CONSUME 3.0 projections for 10 sites post-windstorm, post-salvage logging and post-pile-and-burn surface fuel treatment

For each variable, means with the same letter are not significantly different ($P < 0.05$). Total particulate matter (PM), 10-µm particulate matter (PM_{10}), 2.5-µm particulate matter ($PM_{2.5}$), carbon monoxide (CO), carbon dioxide (CO_2), methane (CH_4), non-methane hydrocarbon (NMHC)

CONSUME output		Mean response following treatment				
		Windstorm (pre-treatment)	Windstorm + salvage logging	Windstorm + salvage logging + surface fuel treatment	Percentage reduction (pre-treatment – salvage logging)	Percentage reduction (salvage logging – pile and burn)
Total consumption (Mg ha^{-1})		97^{a} (53–128)	77^{b} (54–95)	65^{c} (56–80)	21	33
Total emissions (Mg ha^{-1})		17 072^{a} (9347–22 665)	13 483^{b} (9477–16 720)	11 426^{c} (9771–14 111)	21	33
Emission (Mg ha^{-1})	PM	137^{a} (74–174)	110^{b} (76–132)	96^{c} (80–119)	20	30
	PM_{10}	99^{a} (53–124)	80^{b} (55–95)	71^{c} (57–90)	19	28
	$PM_{2.5}$	91^{a} (48–113)	74^{b} (51–88)	66^{c} (53–84)	19	27
	CO	1233^{a} (634–1548)	1019^{b} (687–1259)	955^{b} (704–1303)	17	23
	CO_2	15 444^{a} (8503–20 753)	12 145^{b} (8570–15 199)	10 187^{c} (8729–12 764)	21	34
	CH_4	40^{a} (21–50)	33^{b} (22–41)	31^{b} (23–43)	18	23
	NMHC	27^{a} (14–34)	22^{b} (15–27)	20^{c} (16–26)	19	26

occurred on many of our study sites (USDI Bureau of Land Management 2008) and most had been commercially thinned within the preceding 10 years (J. Bergin, pers. comm., 2008). We suggest that previous timber harvest and thinning combined with subsequent surface fuel treatments has influenced both canopy and surface fuel loading on our sites. Thinning prescriptions likely created single-canopy stands composed of residual trees with low crown biomass (Oliver and Larson 1980). Slash generated from thinning treatments was piled and burned and in some instances harvest units were prescribe burned. It is possible that the residual stand conditions increased windthrow susceptibility. In addition, post-windstorm fuel loadings and fuelbed depths may have been higher had sites not been actively managed and more salvage logging slash in the form of fine and woody fuels may have been created if residual trees had greater crown biomass.

Treatment effects on simulated fire behaviour

In addition to reducing fine and coarse woody fuel loadings, another common justification for salvage logging is to reduce fire intensity and severity of a subsequent wildfire (Shore *et al.* 2003; Peterson *et al.* 2009). There is considerable debate and controversy over whether salvage logging reduces wildfire behaviour (Donato *et al.* 2006). In our study we hypothesised that fire behaviour would increase after salvage logging and decrease after the treatment combination. Because field experiments to test our hypothesis are not possible we used fire simulation models to generate estimates of fire behaviour after treatments. Irrespective of the model used, in most cases we observed monotonic decreases in flame length, reaction intensity and rate of spread after salvage logging and after pile-and-burn surface fuel treatments (Table 4). However, the statistical significance of these changes varied among models. For example, flame length – a fire behaviour metric firefighters use to determine suppression tactics (Andrews and Rothermel 1982) – was not significantly different between treatments with the FCCS and FVS dynamic$_{53}$ models but was significantly lower after salvage logging and the treatment combination with the FVS static$_{13}$ and FVS dynamic$_{13}$ model (Table 4). FFE–FVS Albini 13 fuel models and FCCS flame length predictions were consistently high (Table 4). In contrast, FFE–FVS flame length prediction with the combination of the 13 and 40 fuel models were considerable lower (Table 4). Compared to FFE–FVS FCCS produced the lowest reaction intensities and the highest rate-of-spread (Table 4). We suggest the disagreement between FCCS and FFE–FVS is a consequence of the different modelling methodologies. FFE–FVS fire behaviour predictions do not use actual fuels. Instead, FFE–FVS predicts fire behaviour from stylised fuel models and the Rothermel's (1972) rate-of-spread equation (Rebain 2012). Stylised fuel models (Albini 1976, Scott and Burgan 2005) were developed to generate reasonable fire behaviour predictions (Sandberg *et al.* 2007*a*). In contrast FCCS predicts fire behaviour from measured fuels and a reformulated Rothermel (1972) spread model (Sandberg *et al.* 2007a). The main difference between the original Rothermel (1972) spread equation and Sandberg *et al.* (2007*b*) reformulation is that the latter allows for heterogeneous surface fuel inputs. As a result the reformulated model does not use stylised fire behaviour fuel models and can more realistically represent actual surface fuel characteristics (Sandberg *et al.* 2007*a*). The FCCS reformulated fire spread equation offers an alternative approach for calculating fire behaviour with actual fuel data.

Fire and natural resource managers use estimates of flame length and rate of spread to make management decisions. Rate of spread is a standard metric to estimate potential fire behaviour (Rothermel 1972) and is the basic calculation in current fire behaviour models (Sandberg *et al.* 2007*a*). However, for most fire managers rate of spread is not the most important metric of fire behaviour; flame length estimates are more commonly used to select fire suppression tactics (Andrews and Rothermel 1982). For some fire and forest managers our statistically significant reductions in rate of spread after surface fuel treatment may justify surface fuel treatments following salvage logging. However, some managers may decide the diminutive reductions in flame length and rate of spread fire would not justify the cost to implement surface fuel treatments. It is likely that simulated flame lengths and reaction intensity were not (statistically) significantly lowered by logging and surface fuel treatments because fuels levels, and thus these simulated fire behaviour metrics, were low to begin with as discussed above. Thus, it is possible that the treatments included in this study would have a more significant effect on potential fire behaviour on sites with higher initial fuel loadings.

Treatment effects on fuel consumption and emissions

As would be expected fuel, consumption and pollutant emissions were highest on sites with the highest average fuel loadings (mainly pre-treatment sites) and lowest in sites where fuel loadings were reduced by treatments (i.e. on sites where both salvage logging and surface fuel treatments had been conducted) (Table 2). This is similar to the trend observed between fuel loading and predicted fire behaviour (Table 4). However, even after the treatment combination fuel consumption and pollutant emissions seem elevated. Pile-and-burn is recognised as an effective surface fuel treatment for reducing both fine (<7.6 cm) and coarse (>7.6 cm) woody fuel loadings, and is widely implemented on millions of hectares of forest lands throughout the United States. However, in most cases surface fuel loadings following a pile-and-burn treatment are lower than our average post-pile-and-burn loadings (35 Mg ha^{-1}). The specification of the pile-and-burn prescription may account for these conditions. To accomplish coarse woody fuel objectives, fire managers retained at least 37 linear metres of coarse woody debris in stands, which is equivalent to approximately eight logs with an average diameter of 41 cm and length of 4.9 m (USDI Bureau of Land Management 2008). Large fuels (>7.6 cm) burn for greater duration and produce more emissions (Ottmar 2001).

Overall, CONSUME results show changes in fuel consumption and pollutant emissions and would be useful to include in *National Environmental Protection Act* 1969 documents or other reports intended to show the tradeoffs of alternative management strategies. Resource managers can use CONSUME results to evaluate the potential effect of emissions on air quality and human health, and CONSUME results can be used as input to initiate other decision support tools. For example, CONSUME could be used in combination with smoke dispersion models, which are used to estimate smoke and emissions concentrations along the trajectory of a smoke plume (Larkin *et al.* 2009).

Conclusions

We draw two main conclusions from our field measurements and modelling results on effects of salvage logging and surface fuel treatment after windthrow. First, salvage logging and the pile-and-burn surface fuel treatment clearly reduced fuel loadings, fuelbed depth and simulated smoke emissions, but our results did not produce unequivocal evidence that salvage logging and surface fuel treatment significantly decreased potential wildfire behaviour.

Second, our results illustrate potential differences between the effects of salvage logging after windstorms and the effects of salvage logging after wildfire. Post-windstorm stands have most of the logging material already on the ground whereas post-wildfire stands consist mostly of stems and branch material still standing. Thus, it is potentially the felling process that increases slash fuels in post-wildfire logging and, because post-wildfire stands require more felling, it is possible that this produces the comparatively higher levels of fine fuels after logging.

We have focussed here on the effects of salvage logging on fuels and potential fire behaviour. However, there are many other factors that must be considered by resource managers in making decisions about salvage logging and surface fuel treatments. For example, although salvage logging and surface fuel treatments may reduce fire hazard, salvage logging may decrease biological legacies, including large living and dead overstorey trees (Gibbons and Lindenmayer 2002), logs (Harmon *et al.* 1986) and patches of undisturbed or partially disturbed forest (DeLong and Kessler 2000). It is important to weigh the benefits of potentially reducing future fire behaviour and emissions through salvage logging and surface fuel treatments with benefits associated with other resource management factors such as carbon storage. Timber sales also have social and economic impacts in rural communities. For example, gross timber sale receipts are a major funding source for local fire departments and public school systems in south-western Oregon (USDI Bureau of Land Management 2008). Thus, effects of salvage logging on fuels and potential fire behaviour are just one of many factors needed to make informed resource management decisions on salvage logging.

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