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Models for Predicting Fuel Consumption in Sagebrush-Dominated Ecosystems

Clinton S. Wright

Author is Research Forester, Pacific Wildland Fire Sciences Laboratory, US Forest Service Pacific Northwest Research Station, Seattle, WA 98103, USA.

Abstract

Fuel consumption predictions are necessary to accurately estimate or model fire effects, including pollutant emissions during wildland fires. Fuel and environmental measurements on a series of operational prescribed fires were used to develop empirical models for predicting fuel consumption in big sagebrush (*Artemisia tridentata* Nutt.) ecosystems. Models are proposed for predicting fuel consumption during prescribed fires in the fall and the spring. Total prefire fuel loading ranged from 5.3–23.6 $Mg \cdot ha^{-1}$; between 32% and 92% of the total loading was composed of live and dead big sagebrush. Fuel consumption ranged from 0.8–22.3 $Mg \cdot ha^{-1}$, which equates to 11–99% of prefire loading (mean=59%). Model predictors include prefire shrub loading, proportion of area burned, and season of burn for shrub fuels (R^2=0.91). Models for predicting proportion of area burned for spring and fall fires were also developed (R^2=0.64 and 0.77 for spring and fall fire models, respectively). Proportion of area burned, an indicator of the patchiness of the fire, was best predicted from the coverage of the herbaceous vegetation layer, wind speed, and slope; for spring fires, day-of-burn 10-h woody fuel moisture content was also an important predictor variable. Models predicted independent shrub consumption measurements within 8.1% (fall) and 12.6% (spring) for sagebrush fires.

Key Words: *Artemisia tridentata*, big sagebrush, fire effects, modeling, shrubs

INTRODUCTION

Prescribed fires and wildfires are common and widespread in vegetation types where shrubs are the dominant fuel, including arid rangelands composed of various species of sagebrush (*Artemisia* spp.) and their associates. Recognition of fire as a keystone process in ecosystems generally, and in shrub-dominated types specifically, has led to an increase in the use of prescribed fire for a number of specific purposes, including to preserve or enhance ecosystem properties (Hiers et al. 2007; Keeley et al. 2009), promote specific compositional or structural changes (Beardall and Sylvester 1976; Outcalt and Foltz 2004; Moore et al. 2006; Bates et al. 2009), improve wildlife habitat (Wade and Lunsford 1989), and reduce fuels and potential wildfire behavior to desired levels (Biswell 1989; Brose and Wade 2002; Raymond and Peterson 2005).

Fire effects (e.g., smoke emissions, regional haze, nutrient cycling, plant succession, species composition changes, plant/tree mortality, wildlife habitat restoration and maintenance, erosion, soil heating, and carbon fluxes) are determined in large part by fuel characteristics, fuel conditions, and the energy and other by-products released upon combustion (DeBano et al. 1998; Reinhardt et al. 2001). Quantification of fuel consumption in shrub-dominated vegetation types during prescribed fires and wildfires is therefore critical for modeling fire effects and for meeting management objectives for terrestrial and atmospheric resources.

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Correspondence: Clinton S. Wright, Pacific Wildland Fire Sciences Laboratory, US Forest Service Pacific Northwest Research Station, 400 North 34th Street, Suite 201, Seattle, WA 98103, USA. Email: cwright@fs.fed.us

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Fuel consumption is the quantity of biomass fully combusted and converted to carbon gases, water vapor, other volatile gases, and airborne particulate matter (Hardy et al. 2001), and is typically determined by measuring the difference between the prefire and postfire fuel loading (Beaufait et al. 1977). Emissions of a particular pollutant from a fire are calculated as the product of the area burned, the loading of the fuel consumed per unit area burned, and the ratio of the emissions produced per unit mass of fuel consumed (i.e., the emission factor). Emission factors vary depending upon combustion phase (i.e., flaming vs. smoldering) and fuel type (e.g., woody material vs. leaf litter vs. sagebrush), but are typically treated as constants when calculating pollutant emissions as a function of area burned and fuel consumption (Seiler and Crutzen 1980; French et al. 2011). Fires that occur in locations with high shrub fuel loading or that cover large areas of shrub-dominated vegetation can produce substantial emissions and negatively affect local and regional air quality (Phuleria et al. 2005; Hu et al. 2008). The ability to accurately predict fuel consumption enables fire, air-quality, and natural-resource professionals to plan for and manage smoke from fires, and to mitigate negative impacts associated with air pollution.

Prescribed Fire and Big Sagebrush

Aboveground biomass in big sagebrush (*Artemisia tridentata* Nutt.) types in the western United States varies with site quality, species composition, disturbance history, and successional status, and can exceed 30 $Mg \cdot ha^{-1}$ (Ottmar et al. 2000, 2007). Prescribed fires and wildfires in sagebrush-dominated vegetation types commonly burn over large areas (thousands of ha in prescribed fires and tens of thousands of ha in wildfires; Kuchy 2008). The combination of relatively high biomass and large area burned make fires in sagebrush fuels major sources of greenhouse gases and other pollutant emissions. A variable proportion of shrub biomass is consumed during fires (Hough 1968; Southern Forest Fire Laboratory Staff 1976; Wright and Prichard 2006), however, so accurate methods for assessing fuel consumption are necessary to accurately evaluate emissions and other fire effects.

In planning prescribed fire in big sagebrush ecosystems, land managers must often consider the potential effects on sage grouse (*Centrocercus urophasianus*) habitat and postfire establishment of nonnative grasses, such as cheatgrass (*Bromus tectorum* L.). Applied in select circumstances, prescribed fire can positively affect sage grouse (and other sagebrush-steppe fauna) by favoring important native perennial forb and grass species (Petersen and Best 1987; Crawford et al. 2004). Crawford et al. (2004) noted that fire's role in sagebrush-steppe ecosystems is complex, however, and can have very different impacts on landscape and vegetation structure, recovery, and composition (and thus sage grouse and other wildlife habitat) depending on the floristic and environmental conditions of the vegetation communities in which it occurs.

Prescribed fire is widely used in western North America to limit tree establishment in sagebrush-steppe habitats, create a mosaic of vegetation conditions, and improve and reinvigorate grazed rangelands (Bock and Bock 1988; Severson and Rinne 1988; Holechek et al. 1995; Bates et al. 2009). Fires in sagebrush systems are frequently patchy, creating a mosaic of vegetation ages and structures at subsquare-meter to multiple-hectare scales, which tends to favor avian diversity (Wiens and Rotenberry 1981; Petersen and Best 1987; West 1999). Application of prescribed fire where size, severity, and spread can be controlled to some degree can maintain a patchy landscape structure in sagebrush-steppe habitats that limits potential wildfire size and severity by disrupting fuel continuity (Pellant 1999).

Fuel Consumption Research

Early research to quantify fuel consumption yielded empirical models for predicting consumption of dead and downed woody material, leaf and needle litter (i.e., the O_i horizon), and duff (i.e., the O_e and O_a horizons, composed of fermented and decomposed organic material that develops beneath the O_i horizon). Initial investigations to quantify fuel consumption in the Pacific Northwest sought strategies for minimizing air pollution from prescribed burning for hazard reduction and site preparation following clearcut logging (Sandberg 1980; Sandberg and Ottmar 1983; Ottmar et al. 1985). To improve the accuracy of emissions estimates, additional studies were conducted to determine the proportion of consumption that occurs during the flaming and smoldering phases of combustion under different environmental and fuel conditions (Ottmar 1983; Ferguson and Hardy 1994). These findings were extended to develop models for predicting fuel consumption of dead and downed woody material, litter, and duff in unharvested coniferous forest types (Prichard et al. 2006).

Other research to quantify fuel consumption during prescribed fires using theoretical and empirical methods has been conducted primarily on dead and downed woody, litter, and duff fuels in forested types in the Pacific Northwest and elsewhere (Sweeney and Biswell 1961; Van Wagner 1972; Beaufait et al. 1977; Brown et al. 1985; Little et al. 1986; Kauffman and Martin 1989; Reinhardt et al. 1989; Ottmar et al. 1990; Brown et al. 1991; Hall 1991; Reinhardt et al. 1991; Albini and Reinhardt 1997; Miyanishi and Johnson 2002). In ecosystems where shrubs are the primary fuel, data and models for predicting fuel consumption (and emissions) from commonly or easily measured fuel and weather variables are scarce (i.e., Hough 1978; Wright and Prichard 2006). Estimates of fuel consumption and emissions from live shrub fuels are based primarily on expert opinion or rules-of-thumb. For lack of more robust models, these simple estimators are encoded in the First Order Fire Effects Model (FOFEM) and CONSUME software tools, which have been developed so that fire practitioners and planners can predict fuel consumption and emissions during fires. For example, 50–90% of shrub fuels are predicted to be consumed in FOFEM v.5.9 (Reinhardt 2003; Keane et al. no date) depending upon ecosystem type and season of burn regardless of fuel characteristics, fuel conditions, or fire weather. Similarly, 70 percent of shrub fuels are predicted to be consumed in CONSUME v2.1 (Ottmar et al. no date), whereas a preliminary model for big sagebrush (Wright and Prichard 2006) is employed universally for all shrub types in CONSUME v3.0 (Ottmar et al. 2009; Prichard et al. no date).

This study addresses a recognized knowledge gap in the ability of the fire science and management communities to predict fuel consumption during fires in shrub-dominated ecosystems in general and big sagebrush ecosystems in particular. The objective of this research was to build on the work of Wright and Prichard (2006) and develop empirical models to predict fuel consumption for big sagebrush rangelands based on field measurements of prefire fuel loading, composition and arrangement; day-of-burn fuel and weather conditions; and fuel consumption. The models reported here will be incorporated into the CONSUME software application and its successors, which will allow for more informed and effective fire planning and fire use in sagebrush-dominated types.

METHODS

Study Areas

Study sites were located in big sagebrush rangelands throughout the intermountain West. New sampling in western Montana was conducted to supplement data from Oregon, Nevada, Wyoming, and California, which were reported in Wright and Prichard (2006). Sites were selected to capture the range in fuel loading, fuel moisture, and environmental conditions typically encountered during operational prescribed burning activities. Selection of sites to represent a wide range of conditions within sagebrush types maximizes the breadth of conditions for which application of the models reported here is appropriate.

Sites with a broad range of coverage and biomass of all three recognized subspecies of big sagebrush were sampled: Wyoming big sagebrush (*Artemesia tridentata* Nutt. subsp. *wyomingensis* [Beetle & Young] S. L. Welsh), mountain big sagebrush (*A. t.* Nutt. subsp. *vaseyana* [Rydb.] B. Boivin), and basin big sagebrush (*A. t.* Nutt. subsp. *tridentata*). Big sagebrush subspecies occur on sites with different ranges of precipitation.

Table 1. Site information for big sagebrush prescribed fires.

Burn unit	Latitude	Longitude	Slope (%)	Aspect	Dominant species[1]	Burn season	State
Flook Lake 1	N42°35.9′	W119°32.6′	0	—	ARTRWY	Fall	Oregon
Flook Lake 2	N42°35.7′	W119°32.5′	0	—	ARTRWY	Fall	Oregon
Flook Lake 3	N42°35.9′	W119°32.0′	0	—	ARTRWY	Fall	Oregon
Stonehouse 1	N42°55.8′	W118°25.9′	15	ENE	ARTRVA	Fall	Oregon
V-Lake A	N42°27.6′	W118°43.8′	5	N	ARTRVA	Fall	Oregon
V-Lake 1	N42°28.8′	W118°43.4′	15	SSW	ARTRVA	Fall	Oregon
V-Lake 2	N42°27.6′	W118°43.9′	3	NNW	ARTRVA	Fall	Oregon
V-Lake 3	N42°27.6′	W118°44.1′	0	—	ARTRVA	Fall	Oregon
V-Lake 4	N42°28.2′	W118°44.3′	10	SW	ARTRVA	Fall	Oregon
Gold Digger 1	N41°45.7′	W121°34.2′	0	—	ARTRVA	Fall	California
Gold Digger 2	N41°45.4′	W121°34.3′	5	NW	ARTRVA	Fall	California
Escarpment 1	N41°52.2′	W119°40.3′	0	—	ARTRWY	Fall	Nevada
Escarpment 2	N41°52.0′	W119°39.9′	5	W	ARTRTR	Fall	Nevada
Heart Mtn	N44°41.1′	W109°09.6′	8	SW	ARTRVA	Fall	Wyoming
Old Tanker	N44°42.1′	W109°07.8′	0	—	ARTRWY	Fall	Wyoming
Sand Coulee	N44°43.1′	W109°08.9′	15	E	ARTRWY	Fall	Wyoming
Sagehen 2	N41°55.4′	W119°14.6′	0	—	ARTRTR	Spring	Nevada
Dyce Creek A	N45°19.1′	W113°01.4′	15	SSE	ARTRVA	Spring	Montana
Dyce Creek B	N45°19.0′	W113°01.4′	17	ESE	ARTRVA	Spring	Montana
Dyce Creek C	N45°18.6′	W113°01.4′	20	ESE	ARTRVA	Spring	Montana
Dyce Creek D	N45°18.5′	W113°01.4′	15	S	ARTRVA	Spring	Montana
N Black Cyn 1a	N44°54.9′	W113°21.1′	16	E	ARTRVA	Spring	Montana
N Black Cyn 1b	N44°55.0′	W113°21.1′	9	E	ARTRVA	Spring	Montana
N Black Cyn 2a	N44°54.6′	W113°21.3′	14	—	ARTRVA	Spring	Montana
N Black Cyn 2b	N44°54.6′	W113°21.3′	14	—	ARTRVA	Spring	Montana
N Black Cyn 2c	N44°54.7′	W113°21.3′	14	—	ARTRVA	Spring	Montana

[1]ARTRWY, *Artemisia tridentata* Nutt. subsp. *wyomingensis* (Beetle & Young) S. L. Welsh; ARTRVA, *A. t.* Nutt subsp. *vaseyana* (Rydb.) B. Boivin; ARTRTR, *A. t.* Nutt. subsp. *tridentata*.

Wyoming big sagebrush occupies the driest sites (18–30 cm annual precipitation), mountain big sagebrush occupies the wettest sites (30–51 cm annual precipitation) and basin big sagebrush is found on intermediate sites (Bunting et al. 1987; Francis 2004).

In total, fuel characteristics, fuel moisture content, fire weather, and fuel consumption were measured in situ on operational prescribed fires at 26 sites in 11 operational burn units (Table 1). Sampling occurred on moderate slopes on all aspects at elevations ranging from 1 331 to 2 356 m within the perimeter of larger operational units that were burned under a variety of fire weather and fuel moisture conditions during the fall and spring (Table 2). Slope and aspect were measured in the field with a clinometer and compass, respectively.

In several instances, multiple locations were sampled within an individual burn unit. For burn units within which multiple locations were sampled, sites were selected to represent different fuel characteristics and conditions (e.g., vegetation coverage and composition, fuel loading, fuel moisture content) following a reconnaissance of the area designated for burning. In multisite burn units, sites were often widely separated (hundreds to thousands of meters), were ignited at different times or on different days during burning operations, and were often burned under different weather and fuel moisture conditions. Therefore, for modeling purposes, sites were considered independent observations, even though some were nominally part of the same operational prescribed fire.

Data Collection

Fuel Characteristics and Consumption. Fuel mass, or loading, was measured by destructively sampling six to 18 prefire and 18 postfire plots. *Plots* were systematically arranged in an evenly spaced grid pattern that originated from a random origin point at *sites* with relatively uniform vegetation within the boundaries of planned prescribed burn *units* (Fig. 1). Within sites, vegetation uniformity was assessed visually, and sharp changes or discontinuities in composition and structure were avoided. Site fuel-loading and -consumption values were calculated as the mean of all plots sampled within each 0.5 ha to 1.0 ha site within burn units that ranged in size from tens to thousands of hectares.

Fuels were collected before and after each fire from within a square plot frame that ranged from 1.0 m^2 to 4.0 m^2 (see Table S1 for site-specific sampling details; available online at http://dx.doi.org/10.2111/REM-D-12-00027.s1). Only live and standing dead vegetation that was rooted in the plot frame was clipped at ground level and collected for determination of fuel loading. Sampled fuels were separated into different categories in the field. Categories included: grasses, forbs, live and dead shrub material by species and size class (i.e., <2.5 cm and >2.5 cm stem diameter), dead and downed woody fuels by size class (i.e., <0.6 cm, 0.6–2.5 cm, 2.5–7.6 cm, and >7.6 cm diameter), and litter. Samples were either returned to the laboratory in their entirety for drying and weighing, or they were weighed in the field. Samples were

Table 2. Day-of-burn weather and fuel moisture data for big sagebrush prescribed fires.

	Weather				Fuel moisture (%)		
Burn unit	Temp (°C)	RH (%)	Wind speed ($km \cdot hr^{-1}$)	Days since rain[1] (d)	Grass	Sagebrush foliage[2]	Dead 10-h[3]
Flook Lake 1	17.8	21	12.9	2.5	10.2	60.0	9.2
Flook Lake 2	17.2	34	12.1	1.5	9.8	61.8	9.2
Flook Lake 3	17.8	17	12.9	2.5	10.2	60.0	9.2
Stonehouse 1	7.2	40	6.4	7	29.9	78.7	8.4
V-Lake A	22.2	22	3.2	10	19.9	60.6	2.8
V-Lake 1	23.9	24	12.1	10	38.7	70.9	3.4
V-Lake 2	22.2	22	3.2	10	19.9	60.6	2.8
V-Lake 3	21.7	26	4.0	5	22.6	74.9	6.2
V-Lake 4	21.1	28	9.0	5	22.6	74.9	6.2
Gold Digger 1	16.7	26	7.2	30.5	13.7	71.9	7.7
Gold Digger 2	16.7	25	7.2	30.5	13.7	71.9	7.7
Escarpment 1	17.8	35	6.4	3.5	10.6	68.9	6.8
Escarpment 2	17.8	35	6.4	3.5	10.6	68.9	6.8
Heart Mtn	16.1	25	5.6	18	30.3	73.6	5.7
Old Tanker	16.7	28	12.1	18	30.3	73.6	5.7
Sand Coulee	20.6	24	4.0	18	30.3	73.6	5.7
Sagehen 2	17.2	23	16.1	32	14.5	77.1	10.8
Dyce Creek A	15.6	34	8.9	3.5	45.3	106.0	14.4
Dyce Creek B	12.8	28	11.3	2.5	36.7	94.3	11.6
Dyce Creek C	12.8	28	11.3	2.5	12.8	88.7	9.3
Dyce Creek D	12.8	28	7.2	2.5	12.8	88.7	9.3
N Black Cyn 1a	13.9	30	12.1	2.5	54.2	110.1	11.9
N Black Cyn 1b	13.9	30	12.1	2.5	54.2	110.1	11.9
N Black Cyn 2a	13.9	30	13.7	2.5	41.3	107.4	16.9
N Black Cyn 2b	13.9	30	13.7	2.5	41.3	107.4	16.9
N Black Cyn 2c	13.9	30	13.7	2.5	41.3	107.4	16.9

[1]Days since > 2.5 mm of measured rainfall at the nearest Remote Automated Weather Station.
[2]Includes live foliage and fine twigs.
[3]Dead 10-h fuels are woody particles > 6.3 and < 25.4 mm in diameter.

only weighed in the field if they were too large to transport to the laboratory for drying and weighing, as was the case when a plot contained large shrubs. In cases where fuels were weighed in the field, a moisture content subsample was collected in an airtight container at the time the sample was weighed in the field. This subsample was returned to the laboratory, oven-dried, and weighed to allow all fuel loadings

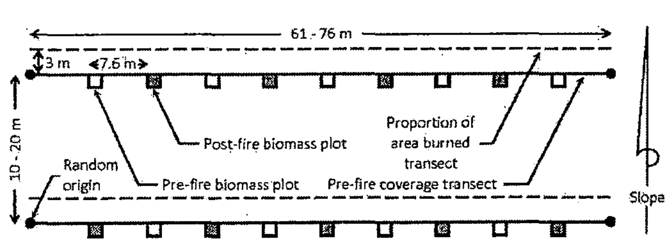

Figure 1. Sampling layout for big sagebrush sites. Plots were established along parallel transects that were oriented perpendicular to the slope (or randomly for flat sites). Big sagebrush, other shrub, grass, forb, litter, and dead and downed woody biomass was measured in small plots. Shrub, forb, and grass coverage and height were quantified on 3–4 prefire transects. The proportion of the area burned was measured on transects that were offset from the prefire transects. Shrub biomass was measured using a different procedure for sites 1 to 4 at the V-Lake unit (see Table S1).

to be expressed on an oven-dry basis by applying the following formula: Oven-dry weight of material in plot = (oven-dry weight of moisture content subsample / wet weight of moisture content subsample) × wet weight of field-weighed material. All material that was returned to the laboratory was oven-dried to a constant weight (100°C for a minimum of 48 h).

Vegetation coverage is one measure of horizontal fuel continuity, and was estimated by lifeform category (grass, forb, and shrub coverage) using the line-intercept method (Canfield 1941) along 205.7, 243.8, or 304.8 m of transect per site (Fig. 1). Proportion of the area burned at each site was measured along transects that were parallel and offset 3 m from the vegetation coverage transects to assess the patchiness of each fire. Grass, forb, and shrub heights were measured at 44, 66, or 68 points located at 3.0-m, 6.0-m, or 7.6-m intervals, respectively, along each vegetation coverage transect.

Shrub fuel consumption was calculated as the difference between mean shrub loading of all of the prefire plots and all of the postfire plots at a site. Because virtually all nonshrub fuels were consumed where fire occurred (personal observation), nonshrub fuel consumption was estimated by multiplying the average prefire biomass of this fuel by the proportion of the area burned. Shrub and nonshrub fuel consumption estimates were added for each site to determine total fuel consumption.

Fuel Moisture and Fire Weather. Multiple (n=5–10) samples of different kinds of live and dead fuels and soil, including sagebrush foliage; grass; dead 1-h[1], 10-h, and 100-h sagebrush branchwood; live 100-h sagebrush branchwood; whole live sagebrush branches; and the top 5 cm of the soil layer were collected from within and adjacent to the plot area in airtight containers immediately prior to the fires to quantify fuel moisture content. Fuel moisture sampling was performed to test whether moisture content was an important predictor of fuel consumption, especially among live shrub fuels, which are typically only partially consumed during fires. Moisture samples were weighed shortly after being collected, oven-dried to a constant weight (100°C for a minimum of 48 h), and reweighed after oven drying to determine moisture content as a fraction of dry weight. A single set of moisture samples was sometimes collected and used to represent multiple sites if the sites were reasonably close to one another (i.e., < 500 m) and being burned at the same time.

Temperature, relative humidity, and wind speed were measured immediately prior to, and every 15–30 min during, burning operations with a sling psychrometer, a handheld electronic weather meter, or an automated weather station. Temperature and relative humidity were measured approximately 1.2 m above the ground and wind speed was measured 2 m above the ground. The reported quantities represent 1-min mean values at the time the plot areas ignited. Temperature and relative humidity measurements made with the sling psychrometer and electronic or automated weather stations taken at the same time in the same location often differed slightly. Psychrometer-measured values were used preferentially for consideration in predictive models because this is the device used most commonly to measure temperature and relative humidity by fireline personnel. Fire type (i.e., backing, heading, flanking) and fire behavior (flame length, rate of spread) were estimated visually by using plot markers with known spacing and height for reference where safety allowed.

Ignition. The prescribed fires used for this study were operational in nature, so plots were burned during the course of daily firing activities. Burn units were either ignited by hand with drip torches or by helicopter with incendiary plastic spheres. In most cases plot areas were burned as heading or flanking fires that originated in areas adjacent to the plots from either of the aforementioned ignition sources. Plot areas were not reignited following passage of the main fire front in the event that a plot area was not entirely burned.

Data Analysis

Ordinary least squares regression models were developed from measured fuel and environmental variables to predict fuel consumption; the models reported here build on the preliminary analysis of Wright and Prichard (2006). Pearson product-moment correlation analysis and exploratory plots of response variables against predictors were used to evaluate the nature and strength of the relationships among variables. Transformations (natural log, square root, and arcsine-square root) of the response and predictor variables were examined and used if they helped linearize relationships and homogenize variance. Plots of the standardized residuals, quantiles of the normal distribution, and Cook's distance were examined to assess the data set for outliers and values with potentially high leverage, and to determine whether the data and models met the assumptions of regression analysis (Neter et al. 1990; Gotelli and Ellison 2004). Model development and diagnostic analyses were performed in the R programming environment (R Development Core Team 2010).

Each model was developed by starting with the raw or transformed response and predictor variables that were the most strongly correlated. Additional predictor variables were added one at a time by using a manual forward selection procedure in which the raw or transformed variable with the most significant partial regression coefficient (i.e., the lowest P value less than α_{crit}=0.10) was retained. This procedure continued until no significant predictors could be added. Variables with nonsignificant partial regression coefficients were also retained in some cases if there was a reasonable physical rationale to support their inclusion in the final model. Given the degree of freedom reduction that accompanies the addition of each predictor variable, final models were selected to balance parsimony (three or fewer predictor variables) with variance explanation (maximized R^2). Also, given the modest sample size, we chose to use all data for model development, rather than to reserve a portion of the data set for model testing and validation. Predictive capability was instead evaluated by comparing modeled consumption predictions to independently collected data (Kauffman and Cummings 1989; Sapsis and Kauffman 1991).

RESULTS

Prefire Fuel Characteristics

Total prefire fuel loading for big sagebrush sites ranged from 5.3–23.6 $Mg \cdot ha^{-1}$; on average 76.0% of the total biomass present was shrubs (Table 3). Sites had a variable but substantial percentage of dead shrub material (24.2–64.2% of total fuel loading). Shrub coverage ranged from 14–81% (Table 4), and vegetation stature, as measured by shrub height, averaged 0.3–0.9 m, although many plants were taller than the average height (Table 4). The prefire herbaceous component ranged from 0.1–4.0 $Mg \cdot ha^{-1}$ and 5–80% coverage (Tables 3 and 4). Most sites had little or no litter (0.2–2.7 $Mg \cdot ha^{-1}$), and variable amounts of woody surface fuels <7.6 cm diameter (0.2–3.1 $Mg \cdot ha^{-1}$; Tables 3 and S2; available online at http://dx.doi.org/10.2111/REM-D-12-00027.s1).[2]

Fuel Moisture and Fire Weather

Fuel moisture and fire weather conditions varied among burn sites and between spring and fall fires. For fall (and spring) fires, day-of-burn fuel moisture ranged from 10–39% (13–54%), 60–79% (77–110%), and 3–9% (9–17%) for grass, live sagebrush foliage, and dead 10-h woody material, respectively (Table 2). Temperature, relative humidity, and wind speed during fall (and spring) fires ranged from 7.2–23.9°C (12.8–

[1]1-h, 10-h, and 100-h timelag fuels are defined as woody material <0.64 cm, 0.64–2.54 cm, and 2.54–7.62 cm in diameter, respectively.

[2]Additional site-level results, including site-level standard errors, where appropriate, are reported in Table S2.

Table 3. Prefire fuel loading for big sagebrush sites.

Burn unit	Herbaceous vegetation	Live shrub	Dead shrub	All vegetation	Surface fuels[1]	All fuels
	Mg · ha^{-1}					
Flook Lake 1	0.29	5.52	5.62	11.43	0.87	12.30
Flook Lake 2	0.11	7.14	5.76	13.01	1.52	14.54
Flook Lake 3	0.11	6.15	4.21	10.47	0.71	11.18
Stonehouse 1	0.61	5.20	2.00	7.81	2.21	10.02
V-Lake A	0.16	11.55	5.18	16.89	1.97	18.86
V-Lake 1	0.27	8.15	3.51	11.94	1.97	13.92
V-Lake 2	0.21	9.44	3.79	13.43	1.05	14.48
V-Lake 3	0.16	3.28	1.16	4.60	0.67	5.27
V-Lake 4	0.22	11.37	3.64	15.23	1.12	16.36
Gold Digger 1	0.73[2]	4.52[3]	3.80[3]	9.05	0.34	9.39
Gold Digger 2	0.57[2]	6.35[3]	3.40[3]	10.31	0.51	10.82
Escarpment 1	4.03[2]	3.09	2.65	9.78	2.71	12.49
Escarpment 2	0.28[2]	7.62	6.63	14.53	1.56	16.09
Heart Mtn	0.39	12.71	7.49	20.59	1.99	22.59
Old Tanker	0.41	4.93	2.94	8.28	0.99	9.27
Sand Coulee	0.36	5.53	3.19	9.09	0.97	10.06
Sagehen 2	0.11[2]	6.08	10.92	17.11	2.23	19.34
Dyce Creek A	0.66	6.02	4.81	11.48	5.96	17.45
Dyce Creek B	0.86	9.83	6.46	17.16	6.48	23.64
Dyce Creek C	0.98	7.60	5.92	14.50	7.85	22.35
Dyce Creek D	0.75	6.32	6.12	13.19	8.29	21.48
N Black Cyn 1a	0.59	7.10	4.81	12.49	6.08	18.58
N Black Cyn 1b	1.83	7.31	4.81	13.96	4.73	18.69
N Black Cyn 2a	0.81	1.59	0.79	3.19	4.15	7.34
N Black Cyn 2b	1.32	4.65	2.59	8.57	3.30	11.87
N Black Cyn 2c	1.29	5.73	3.97	10.99	5.33	16.31

[1]Includes litter and dead and downed woody fuels.
[2]Includes rabbitbrush (*Chrysothamnus* spp.).
[3]Includes antelope bitterbrush (*Purshia tridentata* [Pursh] DC.).

17.2°C), 17–40% (23–34%), and 3.2–12.9 km·hr^{-1} (7.2–16.1 km·hr^{-1}), respectively.

Fuel Consumption

Both the absolute amount and the proportion of the prefire fuel loading that was consumed varied. Shrub consumption ranged from 0.2–19.9 Mg·ha^{-1}, and total biomass consumption ranged from 0.8–22.3 Mg·ha^{-1} (Table 5). Prescribed fires were often patchy with 11–100% of the area burned; area burned exceeded 85% on only seven of 26 sagebrush sites. Season of burning did influence consumption of the shrub fuels, with greater consumption occurring on fall fires. Virtually all dead fuels and fine live fuels (i.e., grasses and forbs) were consumed in those portions of the sites that actually burned (i.e., the burned areas within the burned/unburned mosaic), although whether, and the mechanism by which, these fuels contributed to the consumption of the adjacent and overtopping live shrub component was not documented.

Model Variables

A number of variables were evaluated for their strength as predictors of shrub and total fuel consumption, as well as their correlation with each other. Correlation analysis indicated that some of the considered variables were weakly correlated (Table S4; available online at http://dx.doi.org/10.2111/REM-D-12-00027.s1), including measures of fuel loading (L_s and L_a) with proportion of area burned (B; $r=0.38$–0.46) and measures of herbaceous fuel coverage (P_h) with windspeed × slope ($W \times S$; $r=0.65$–0.66). Given the objective of accurately predicting the overall responses without the need to examine the contribution of individual predictor variables to variance explanation, however, mild multicollinearity was deemed acceptable (Graham 2003). Multiple linear regression models for estimating shrub and total fuel consumption are reported in Table 6 and illustrated in Figure 2. Patchiness of the fire and the amount of prefire shrub loading were important for estimating shrub consumption. The proportion of the area burned was best modeled as a function of the season of burn, coverage of fine live fuels, wind speed, and slope; in addition, day-of-burn 10-h woody fuel moisture content was important for spring fires (Fig. 3). Including season of burn significantly improved shrub consumption models.

Most nonshrub biomass is consumed when burned. Because postfire nonshrub biomass (i.e., herbaceous vegetation, litter, and dead and downed woody fuel) was not measured with destructive sampling methods, but rather derived from prefire loading and proportion of the area burned; however, proportion of area burned was not independent of nonshrub biomass

Table 4. Prefire coverage, proportion of area burned, and vegetation height for big sagebrush sites.

Burn unit	Prefire coverage and area burned (%)				Height (m)	
	Herbaceous vegetation	Shrub vegetation	All vegetation	Area burned	Grass	Shrub
Flook Lake 1	10.8	36.0	46.8	32.7	0.12	0.39
Flook Lake 2	20.1	38.1	58.1	38.6	0.17	0.50
Flook Lake 3	4.6	29.2	33.8	36.9	0.15	0.39
Stonehouse 1	20.0	42.6	62.5	39.8	0.24	0.55
V-Lake A	20.0	55.8	75.8	50.6	0.11	0.50
V-Lake 1	12.3	53.2	65.4	74.6	0.36	0.70
V-Lake 2	14.8	46.9	61.7	53.8	0.16	0.48
V-Lake 3	15.1	36.0	51.2	23.9	0.15	0.37
V-Lake 4	23.0	62.6	85.6	96.9	0.22	0.48
Gold Digger 1	25.7[1]	27.3[2]	53.0	36.4	0.22	0.40
Gold Digger 2	25.0[1]	31.6[2]	56.6	60.4	0.23	0.49
Escarpment 1	32.8[1]	13.5	46.3	75.9	0.17	0.64
Escarpment 2	22.5[1]	35.1	57.6	78.2	0.41	0.69
Heart Mtn	37.6	66.8	98.3	98.4	0.16	0.51
Old Tanker	34.3	32.4	66.7	94.8	0.14	0.32
Sand Coulee	31.5	42.1	73.6	99.8	0.12	0.29
Sagehen 2	10.9[1]	43.3	54.2	14.5	0.22	0.92
Dyce Creek A	59.0	64.9	92.2	56.7	0.11	0.56
Dyce Creek B	66.1	81.3	97.7	85.2	0.16	0.70
Dyce Creek C	77.8	66.0	94.4	96.0	0.15	0.69
Dyce Creek D	79.9	65.7	98.7	100.0	0.13	0.58
N Black Cyn 1a	47.6	52.9	93.6	80.0	0.14	0.53
N Black Cyn 1b	48.3	55.9	84.2	41.9	0.14	0.50
N Black Cyn 2a	46.8	52.2	99.0	11.3	0.08	0.46
N Black Cyn 2b	43.5	63.8	92.6	23.7	0.14	0.46
N Black Cyn 2c	49.0	51.5	87.7	57.0	0.16	0.52

[1]Includes rabbitbrush (*Chrysothamnus* spp.).
[2]Includes antelope bitterbrush (*Purshia tridentata* [Pursh] DC.).

consumption, so these data were not appropriate for development of a model to predict nonshrub fuel consumption.

Model Performance

Given the modest sample size ($n = 26$), rather than splitting the data into separate sets for model development and model validation (Quinn and Keough 2002), all data were used to develop the models. Model performance was evaluated by comparing model predictions to measured values for two independently gathered data sets (Kauffman and Cummings 1989; Sapsis and Kauffman 1991). Agreement between measurements and modeled estimates of fuel consumption overall was quite good (Fig. 4). Modeled consumption was within 8.1% and 12.6% (root mean squared error) of measured values on average for fall and spring big sagebrush fires, respectively (Table S3; available online at http://dx.doi.org/10.2111/REM-D-12-00027.s1).

DISCUSSION

Postfire fuel loading and fuel consumption are a function of the amounts of three fuel states in a given area: 1) unburned, 2) burned and fully combusted, and 3) burned but only partially combusted. Accounting for the proportion of the area that burns and the proportion of the prefire loading that is consumed in the areas that burn are therefore important for generating an accurate estimate of overall unit-wide fuel consumption. Models were developed that predict shrub and total fuel consumption, and proportion of the area that is expected to burn under a variety of fuel and environmental conditions.

Proportion of Area Burned

Prescribed fires (and wildfires) can create a mosaic of burned and unburned patches in some ecosystems or burn the entire area in others. Whether a fire is patchy or continuous appears to be related to the horizontal continuity of fine surface fuels. Patchy prescribed fires are common (and even are objectives of fire and resource management and burning operations) in sagebrush ecosystems. Thus, determining how much of an area is likely to burn is key for estimating smoke emissions and other fire effects. Models for predicting proportion of area burned during spring fires and fall fires were similar to the model proposed by Wright and Prichard (2006), and include variables that are readily available to resource managers (Table 6): season of burn; coverage of herbaceous vegetation; wind speed; and slope; and for spring fires, 10-h fuel moisture content.

Fine herbaceous fuels provide a vector for fire spread (Britton et al. 1981; Bunting et al. 1987), and might be particularly

Table 5. Fuel consumption for big sagebrush sites.

Burn unit	Herbaceous vegetation	Shrub	All vegetation	Surface fuels[1]	All fuels
	Mg · ha^{-1}				
Flook Lake 1	0.10	3.13	3.23	0.29	3.52
Flook Lake 2	0.04	4.02	4.06	0.59	4.65
Flook Lake 3	0.04	5.02	5.06	0.27	5.33
Stonehouse 1	0.25	2.22	2.47	0.88	3.35
V-Lake A	0.08	9.98	10.07	1.05	11.11
V-Lake 1	0.21	7.75	7.95	1.49	9.44
V-Lake 2	0.13	9.60	9.73	0.66	10.38
V-Lake 3	0.05	1.33	1.38	0.21	1.60
V-Lake 4	0.22	13.95	14.17	1.09	15.26
Gold Digger 1	0.27[2]	4.66[3]	4.93	0.13	5.06
Gold Digger 2	0.35[2]	5.66[3]	6.00	0.31	6.31
Escarpment 1	3.15[2]	3.12	6.26	2.11	8.38
Escarpment 2	0.22[2]	12.66	12.88	1.23	14.11
Heart Mtn	0.39	19.92	20.31	1.98	22.28
Old Tanker	0.41	7.75	8.16	0.99	9.15
Sand Coulee	0.36	8.53	8.89	0.97	9.86
Sagehen 2	0.02[2]	2.74	2.76	0.76	3.52
Dyce Creek A	0.37	4.29	4.66	3.38	8.04
Dyce Creek B	0.74	10.49	11.23	5.52	16.75
Dyce Creek C	0.94	11.59	12.53	7.53	20.06
Dyce Creek D	0.75	9.76	10.50	7.93	18.43
N Black Cyn 1a	0.47	8.04	8.51	4.87	13.38
N Black Cyn 1b	0.77	2.16	2.92	1.98	4.91
N Black Cyn 2a	0.09	0.22	0.31	0.47	0.78
N Black Cyn 2b	0.31	1.90	2.21	0.78	3.00
N Black Cyn 2c	0.74	4.89	5.63	3.04	8.67

[1]Includes litter and dead and downed woody fuels.
[2]Includes rabbitbrush (*Chrysothamnus* spp.).
[3]Includes antelope bitterbrush (*Purshia tridentata* [Pursh] DC.).

important where the distance between big sagebrush plants is too far, or the heat transfer and flame contact effect of wind speed and slope is insufficient to sustain fire spread from plant to plant. Wind speed and slope are important drivers of fire spread (Rothermel 1972; Albini 1976); when in alignment, wind amplifies the effect of slope in rate of spread models (Curry and Fons 1938; Fons 1946; Weise and Biging 1997; Nelson 2002). The wind speed × slope (or slope category) variable in the models to predict proportion of area burned is meant to reflect this complementary effect of aligned wind and slope on successful fire spread; it is included as a combination variable rather than as a statistical interaction. The slope category multiplier incorporated into the equation for spring fires is comparable to the values suggested by Brown (1982) for rate of spread.

These models will allow fire planners to develop site-specific prescriptions that are likely to meet their management objectives with respect to fire coverage or patchiness (and subsequent fuel consumption and emissions production) across a range of conditions in big sagebrush ecosystems. For

Table 6. Equations for predicting shrub and all aboveground biomass consumption, and proportion of area burned for big sagebrush fires.

Equations[1]	*n*	*F* ratio[2]	RSE[3]	Adj. R^2
$\sqrt{C_s} = 0.1102 + 0.1139(L_s) + 1.9647(B) - 0.3296(Season)$	26	87.11	0.27	0.91
$\sqrt{C_a} = 0.0929 + 0.1036(L_a) + 2.2451(B) - 0.2985(Season)$	26	146.50	0.23	0.95
If *Season* = fall,				
$B = -0.1584 + 0.0188(P_h) + 0.1101\{\ln[(W + 1) \times (S + 1)]\}$	16	14.48	0.16	0.64
If *Season* = spring,				
$B = 0.3597 + 0.0102(P_h) - 0.0456(F_{10}) + 0.0098(W \times S_C)$	10	10.82	0.16	0.77

[1]Symbols: *B* indicates area burned, proportion of total area; C_a, consumption of all aboveground biomass, Mg · ha^{-1}; C_s, consumption of shrubs, Mg · ha^{-1}; F_{10}, day-of-burn 10-h fuel moisture, % by dry weight; L_a, prefire loading of all aboveground biomass, Mg · ha^{-1}; L_s, prefire loading of shrubs, Mg · ha^{-1}; P_h, prefire coverage of herbaceous vegetation, %; *S*, slope, %; S_c, slope category, 0–5% = 1, 5–15% = 2, 16–25% = 3, 26–35% = 4, > 35% = 5; *Season*, season of burn, spring burn = 1, all else = 0; *W*, day-of-burn wind speed, km · hr^{-1}.
[2]*P* values < 0.01 for all models.
[3]Residual standard error from regression; in units of the dependent variable.

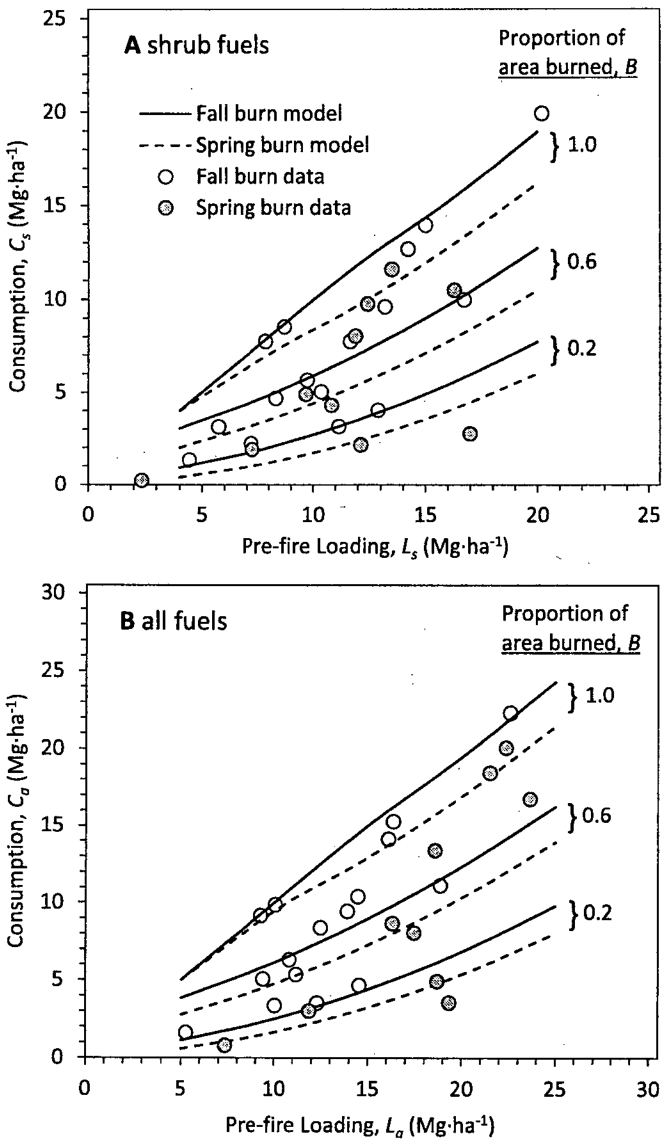

Figure 2. Multiple linear regression models for big sagebrush fuel types showing: **A**, shrub consumption as a function of prefire shrub biomass and season of burn for a range of values of proportion of area burned, and **B**, total aboveground biomass consumption as a function of prefire biomass and season of burn for a range of values of proportion of area burned.

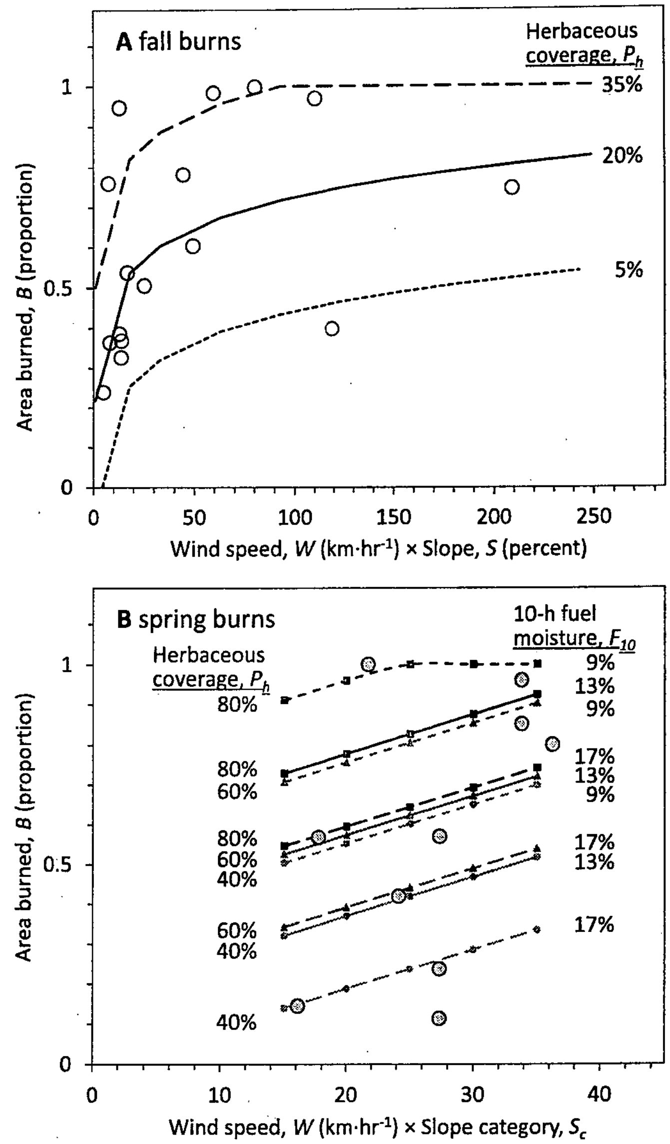

Figure 3. Multiple linear regression models showing proportion of area burned in big sagebrush fuel types for: **A**, fall burns as a function of wind speed and slope for a range of values for herbaceous species coverage, and **B**, spring burns as a function of wind speed and slope category for a range of values of herbaceous species coverage and 10-h fuel moisture. See footnote in Table 6 for definition of slope categories.

example, where and when fire is an appropriate landscape treatment, prescriptions can be developed for specific projects and for coordinated groups of projects to preserve a desired level of shrub coverage for sage grouse or other sensitive wildlife species at a variety of spatial and temporal scales (Crawford et al. 2004). At the same time, these models can be used to assess potential air quality, site hydrology, erosion, and range-quality impacts associated with prescribed burning, which causes an immediate fire-induced loss of vegetative biomass, and a subsequent shift from dominance by shrubs to dominance by herbaceous vegetation following fire that can persist for several decades (Paysen et al. 2000; Bates et al. 2009).

Fuel Consumption Models

Prefire biomass was consistently the most important variable for predicting fuel consumption for all fuelbed components. Prefire biomass can be determined directly from field measurements using allometric (e.g., Brown 1982; Frandsen 1983) or destructive methods, or it can be estimated using published guides (Ottmar et al. 2000, 2007) or expert knowledge. Fuel amount was the strongest predictor variable, but variation in fuel condition (i.e., dead fuel moisture content) and environment (i.e., season, wind speed, slope) increased or decreased the proportion of the area burned, which affected subsequent fuel consumption, probably because of their effects on the energetics of the combustion process (Byram 1973). That is,

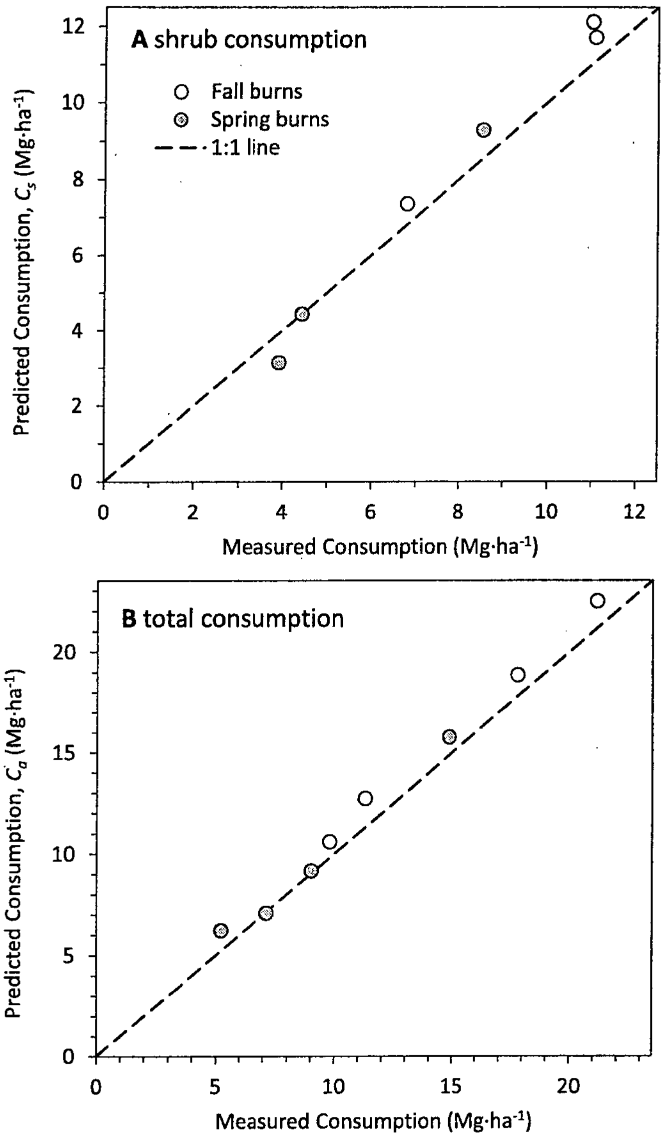

Figure 4. Assessment of model performance. Comparison of independently measured values and model predictions for: **A**, shrub consumption, and **B**, all fuel consumption for big sagebrush fuel types. Independently measured data are from: Kauffman and Cummings (1989) and Sapsis and Kauffman (1991).

burning drier fuels under windier conditions on steeper slopes during the fall enhanced fire spread and increased fuel consumption.

Live fuel moisture affects flammability and fire behavior, but it was generally not correlated with fuel consumption for big sagebrush, as one might expect based on the importance of moisture content as a predictor for consumption of dead fuels (e.g., Sandberg 1980; Sandberg and Ottmar 1983; Little et al. 1986; Harrington 1987; Brown et al. 1991). In this regard, the findings of this study agree with other studies in shrub-dominated ecosystems that also failed to observe a relationship between live fuel moisture and live fuel consumption (Hough 1978; Bilgili and Saglam 2003; Wright and Prichard 2006).

Season of burn and weather have been shown to affect fire behavior, fire effects, and vegetation response following fire (Bragg 1982; Brown 1982; Sparks et al. 2002; Outcalt and Foltz 2004), which suggests that they also might have an effect on fuel consumption. In fact, Ottmar et al. (1990) were better able to predict consumption of large woody fuels (> 7.6 cm diameter) upon discovering that they responded differently under spring vs. summer fuel moisture and burning conditions. Season of burn was an important predictor of proportion of area burned and of consumption of shrub fuels in big sagebrush types. Day-of-burn weather observations were not useful for predicting fuel consumption, although wind speed was an important variable in the equations for predicting how much of an area was likely to burn. The inclusion of season in the consumption prediction models might have effectively captured the long- and short-term fluctuations in weather and fire environment that instantaneous point measurements of day-of-burn weather and fuel moisture did not. Seasonal differences can represent a threshold effect on fuel consumption in a manner that different continuous observations of fire weather (e.g., temperature, relative humidity, days since rain) and fuel condition (live and dead fuel moisture content) cannot. Addition of spring-prescribed-fire data and inclusion of season as a categorical predictor for big sagebrush systems expanded the range for which the model is applicable and improved upon the model performance reported by Wright and Prichard (2006) as measured against the same independent data sets.

Fire type (i.e., heading vs. backing vs. flanking) has a pronounced effect on fire behavior and can also influence fuel consumption (Sackett 1975; Brown 1982). The sites sampled for this study were burned during operational prescribed fires, however, and I had no control over how burn sites were ignited or the type of fire used in their burning. Given this limitation, the study was not able to investigate whether fire type, lighting method, or firing pattern affected fuel consumption. Further data collection, designed in such a way as to control fuel characteristics, fuel conditions, and fire weather, would be necessary to better understand the effects of fire type and application method on fuel consumption.

Limitations

The models presented here are based on correlations between field-measured variables; they do not prove cause and effect. Such models are considered phenomenological in that the response (i.e., fuel consumption and proportion of area burned) is statistically related to physically sensible explanatory variables using observational data, but the mechanisms are not measured or modeled directly (e.g., Higgins et al. 2008). Variables were considered for inclusion in the final models only if there was a reasonable physical explanation for the modeled correlation. For example, wind speed and slope are included in models for predicting proportion of area burned because they influence convective and radiant heat transfer and flame contact to adjacent unburned fuels affecting the spread of fire (Byram 1973; Weise and Biging 1997).

Because the models presented here are empirical, they should only be applied when fuel characteristics and environmental conditions fall within the range of the sample data. Not all possible combinations of fuel loading and proportion of area burned are included in the data set from which the models were developed. Furthermore, some combinations of fuel loading and proportion of area burned might be unrealistic. For example, sites with very low biomass are unlikely to achieve complete burn coverage, although in this case, the proposed models estimate fuel consumption will be in excess of prefire fuel loading, which is clearly impossible. Under these circumstances, use of the proposed models is not appropriate and the user should employ other methods for estimating fuel consumption and emissions. Within the constraints of the preceding caveat, the models presented here should be applicable for wildfires (and wildland fire use fires) in which the fuel and environmental variables fall within the range of the data used to develop the models, even though no wildfires were sampled for this project (see Tables 2, 3, and 4).

This paper represents a refinement of the work by Wright and Prichard (2006) that was made possible with the collection of additional data under previously unsampled fuel and environmental conditions. Owing to the difficulty and expense involved with measuring fuel consumption in situ, however, they are still based on a sample of limited size and data range. Further fuel consumption experiments should be performed to test, and, if necessary, revise the reported models, with data collection efforts focused on sampling at the lower and upper extremes of fuel loading, fuel moisture, and fire weather likely to be encountered during both prescribed fires and wildfires in big sagebrush ecosystems. Such data will allow scientists and managers to both assess the robustness of the existing models and potentially provide the measurements necessary for the development of new models with broader application.

MANAGEMENT IMPLICATIONS

Land managers utilize prescribed fire to achieve a variety of objectives. Regardless of the objective, and whether they are prescribed or wild, fires consume biomass and produce smoke. Consumption of dead and living biomass during wildland fires has the potential to alter ecosystem structure, composition, and function in a variety of ways, and the resulting emissions have the potential to impact air quality, visibility, and human health and safety.

This study documented the physical conditions that influence fuel consumption in a fuel type dominated by live shrubs, and yielded models that will improve fuel consumption predictions during prescribed fires in big sagebrush ecosystems. Fire managers will be able to develop data-based estimates of fuel consumption based on quantitative information rather than relying on expert opinion and the "rules-of-thumb" that are currently used. More accurate estimates of consumption will contribute to better estimates of emissions during prescribed fires in big sagebrush, a widespread and commonly burned shrub-dominated type. Empirically based fuel consumption estimates will: 1) allow fire practitioners to employ smoke management techniques (see Hardy et al. 2001 for a discussion of smoke management) that utilize an understanding of the effects of varying fuel and environmental conditions on fuel consumption, such as burning in the spring, and burning under moister conditions to minimize the proportion of the treatment area that is burned and the amount of fuel that is consumed; 2) improve emissions and air quality inventories and models that are based on inadequate fuel consumption models; and 3) develop fire management prescriptions to meet ecological and resource management objectives. The ability to predict the consumption of fuels of varying type, amount, arrangement, and moisture content under different burning conditions will allow fire, land, and air quality managers in jurisdictions with big sagebrush fuel types to better plan for and, if necessary, mitigate the effects of prescribed fires and anticipate the effects of wildfires.

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