Biomass Consumption During Prescribed Fires in Big Sagebrush Ecosystems

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***Abstract**—Big sagebrush* (Artemisia tridentata) *ecosystems typically experience stand replacing fires during which some or all of the ignited biomass is consumed. Biomass consumption is directly related to the energy released during a fire, and is an important factor that determines smoke production and the effects of fire on other resources. Consumption of aboveground biomass (fuel) was evaluated for a series of operational prescribed fires in big sagebrush throughout the interior West. Pre-burn fuel characteristics (composition, amount, and structure), fuel conditions (live and dead fuel moisture content), and environmental conditions (weather and topography) affected fire behavior and subsequent fuel consumption. Total aboveground biomass consumption varied from 1.6 to 22.3 Mg ha^{-1} (18 to 99 %) among the 17 experimental areas. Multiple linear regression and generalized linear modeling techniques were used to develop equations for predicting fuel consumption during these prescribed fires. Pre-burn fuel loading, which is influenced by season of burn, site productivity, time-since-last-fire, and grazing is the most important predictor of fuel consumption. Use of fire in big sagebrush is desirable for several reasons, including wildlife habitat improvement, livestock range improvement, fire hazard abatement, and ecosystem restoration.*

***Keywords**: Artemisia tridentata, big sagebrush, fire effects, fuel consumption*

Introduction

Research to quantify and model fuel consumption during wildland fires has been conducted in managed and unmanaged forest types throughout the United States (e.g., Ottmar 1983; Sandberg and Ottmar 1983; Little and others 1986; Brown and others 1991; Hall 1991; Albini and Reinhardt 1997; Reinhardt and others 1997; Myanishi and Johnson 2002), but is generally lacking or of limited scope in shrub-dominated ecosystems (for example, Sapsis and Kauffman 1991). Much of the existing fire research in shrub types has focused on fire behavior prediction in a limited number of shrub types (for example, Lindenmuth and Davis 1973; Green 1981; Brown 1982). Shrub-dominated ecosystems occur on hundreds of millions of hectares of private, state and federal lands in the United States. Sagebrush (*Artemisia* spp.) occurs on at least 38.5 million hectares in the interior West, making it one of the largest biomes in North America (Shiflet 1994). Sagebrush and other shrub-dominated types may be remotely located or they may occur at the wildland-rural/suburban/urban interface throughout their range. Many shrub-dominated ecosystems are home to sensitive, rare, threatened and endangered species, including numerous species of birds, mammals, mollusks, insects,

In: Andrews, Patricia L.; Butler, Bret W., comps. 2006. Fuels Management—How to Measure Success: Conference Proceedings. 28-30 March 2006; Portland, OR. Proceedings RMRS-P-41. Fort Collins, CO: U.S. Department of Agriculture, Forest Service, Rocky Mountain Research Station.

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plants, fish, reptiles and amphibians. In terms of sheer land area, proximity to populated areas, and wildlife habitat, research in shrub-dominated types addresses information needs for a diverse array of natural resource managers.

Increasing public awareness of environmental issues necessitates that resource managers fully evaluate regulatory requirements and potential impacts of land management decisions (in other words, no action, prescribed fire use, wildland fire use, grazing, mechanical treatment, chemical treatment, etc.) using the best available information. Where fire is concerned, quantification of fuel consumption is critical for evaluating fire severity (for example, Keely and others 2005), and for effectively modeling fire effects, including smoke emissions, regional haze, nutrient cycling, plant succession, species composition changes, plant/tree mortality, wildlife habitat restoration and maintenance, erosion, soil heating, and carbon cycling. Fuel consumption is the most critical variable for effectively evaluating and managing the consequences of prescribed and wildland fire as related to land management objectives.

Many sagebrush-dominated ecosystems in the western United States have experienced periodic, naturally occurring fire events (Miller and Rose 1999). Resource managers use prescribed fire as a multi-scale treatment for a number of specific purposes, including fuel and fire hazard reduction, wildlife habitat improvement, and ecosystem restoration. In contrast to forested systems where a large proportion of the fuelbed is composed of dead and down organic matter, in sagebrush-dominated ecosystems, the fuelbed is composed almost entirely of living (and standing dead) vegetation. Prior to the application of fire in forests and shrublands it is desirable to gauge the likelihood of treatment success (in other words, desired change in vegetation or fuel structure) by predicting fuel consumption. Change in the vegetation structure (that is, fuel composition, amount and arrangement) is often the most significant measure of treatment success. If resource managers in the sagebrush biome are to develop effective fire plans and prescriptions designed to meet desired objectives for terrestrial and atmospheric resources, research must quantify both fuel characteristics and fuel consumption during wildland fires.

Objective

The primary objective of our research was to develop models to predict biomass consumption in big sagebrush ecosystems using variables that are relatively easily measured or readily obtained. These fuel consumption models have been incorporated into the software CONSUME 3.0 (Prichard and others, in press). Development of consumption models for sagebrush ecosystems and their application in CONSUME 3.0 promotes more effective and informed use of emission production, fire effects, and wildfire/prescribed fire tradeoff models allowing for better wildland fire emissions and fire effects accounting and planning at a variety of scales.

Methods

Data were collected at 17 locations on a series of operational prescribed fires in big sagebrush (*A. tridentata*) ecosystems in southeastern Oregon, northwestern Nevada, northwestern Wyoming, and northern California (table 1). Sampling for fuel consumption occurred on gentle slopes (0 to 15 percent slope) of all

Table 1—Site information for experimental sagebrush burns.

Site Name	# Sites	Latitude	Longitude	Elevation	Slope	State	Admin. Unit[a]
Flook Lake	3	42° 36’	119° 32’	1539-1542 m	0 %	OR	USFWS1
Stonehouse	1	42° 56’	118° 26’	1937 m	15 %	OR	BLM1
V-Lake	5	42° 28’	118° 44’	2018-2056 m	0-15 %	OR	Private
Gold Digger Pass	2	41° 46’	121° 34’	1331-1346 m	0-5 %	CA	NPS
Escarpment	2	41° 52’	119° 40’	1672-1693 m	0-5 %	NV	USFWS2
Sagehen	1	41° 56’	119° 15’	1717 m	0 %	NV	USFWS2
Heart Mountain	3	44° 42’	109° 09’	1764-1823 m	0-15 %	WY	BLM2

[a]USFWS1 = U.S. Fish and Wildlife Service, Hart Mountain National Antelope Refuge; USFWS2 = U.S. Fish and Wildlife Service, Sheldon National Wildlife Refuge; BLM1= Bureau of Land Management, Burns, OR; BLM2 = Bureau of Land Management, Cody, WY; Private = Roaring Springs Ranch; NPS = Lava Beds National Monument.

aspects at elevations ranging from 1,331 to 2,056 m. Sites were selected to represent a broad range of coverage and biomass of standing big sagebrush of all three recognized subspecies: Wyoming big sagebrush (*A. t.* ssp. *wyomingensis*), mountain big sagebrush (*A. t.* ssp. *vaseyana*), and basin big sagebrush (*A. t.* ssp. *tridentata*). Big sagebrush subspecies occur on sites that follow a gradient of increasing precipitation; Wyoming big sagebrush occupies the driest sites (20 to 32 cm annual precipitation), mountain big sagebrush occupies the wettest sites (31 to 149 cm annual precipitation) and basin big sagebrush is found on intermediate sites (Francis 2004). Experimental areas were embedded within larger operational units, and were burned under a variety of environmental and fuel moisture conditions during the fall of 2001 (September 23 to October 25) and spring of 2002 (March 21; table 2).

Data Collection

Fuel Characterization and Consumption—A regular grid of 2 × 2 m plots (or 1.5 × 1.5 m, if vegetation was particularly large or dense) was used to determine fuel loading and composition in a relatively uniform stand or patch of big sagebrush. A total of 36 plots were numbered sequentially; nine plots each were located every 7.6 m along four 76.2-m long transects that

Table 2—Weather and fuel moisture information for experimental sagebrush burns.

		Weather			Fuel moisture		
Site name	Subspp.[a]	Temp.	RH	Windspeed	Grass	Live sage foliage	Dead sage 10hr[b]
		°C	*percent*	*km hr^{-1}*	*percent*		
Flook Lake	W	17.2-17.8	17-34	12.1-12.9	9.8-10.2	59.9-61.8	9.2
Stonehouse	M	7.2	40	6.4	29.9	78.7	8.4
V-Lake	M	21.1-23.9	22-28	3.2-12.1	19.9-38.7	60.6-74.9	2.8-6.2
Gold Digger Pass	M	16.7	25-26	7.2	13.7	71.9	7.7
Escarpment	W-B	17.8	35	6.4	10.6	68.9	6.8
Sagehen	B	17.2	23	16.1	14.5	77.1	10.8
Heart Mountain	M-W	16.1-20.6	24-28	4.0-12.1	30.3	73.6	5.7

[a]W = Wyoming (*A. wyomingensis*); M = Mountain (*A. vaseyana*); B = Basin (*A. tridentata*).
[b]10hr fuel particles are 0.64 – 2.54 cm in diameter.

were spaced 10 to 20 m apart (no plots were placed at transect endpoints). Odd- or even-numbered plots were randomly selected to be destructively sampled before the fire; remaining plots were destructively sampled after the fire. Fuels were characterized by clipping at ground level or collecting, drying and weighing all standing biomass or surface fuels rooted or located inside the plot frame. Biomass was separated into the following categories in the field: grasses, forbs, live sagebrush, dead sagebrush, shrubs other than sagebrush (hereafter referred to as 'other shrubs'), dead and down woody fuels by size class (1hr, 10hr, 100hr, and 1000hr[1]), and litter. Dead branches and twigs on living sagebrush plants were removed and included in the dead sagebrush category. Grasses, forbs, other shrubs, dead and down woody fuels, and litter were collected, returned to the laboratory, dried for a minimum of 48 hours at 100 °C, and weighed to determine ovendry fuel loading by category on an area basis. Sagebrush was harvested, separated into live and dead biomass, and weighed in the field. One or two complete branches from each field sample were collected in heavy-gauge plastic bags with airtight seals. These subsamples were weighed shortly after collection, returned to the laboratory, dried for a minimum of 48 hours at 100 °C, and weighed to determine live and dead sagebrush moisture content per plot. The following formula was used to adjust sagebrush field weight to ovendry weight:

$$\frac{\text{moisture subsample dry weight}}{\text{moisture subsample wet weight}} \times \text{undried field weight} = \text{ovendry weight} \qquad (1)$$

Pre-fire coverage by category (grass, forbs, sagebrush, other shrubs, litter) was measured using the line intercept method (Canfield 1941) along the full length of all four 76.2-m long layout transects. Grass, forb, sagebrush, and other shrub heights were measured at points every 7.6 m along the full length of all four transects. As most fires were patchy, coverage of the area burned during the fire was measured along parallel transects that were offset 3 m from the original layout to avoid sampling in areas that had been destructively sampled before the fire.

Fuel consumption was calculated by subtracting average post-burn biomass from average pre-burn biomass for sagebrush, and by multiplying average pre-burn biomass by the percentage of the area burned for the other fuel categories. Based on post-fire field observations, we assumed that all non-sagebrush biomass was consumed in areas that were burned.

Day of Burn Fuel Moisture and Weather—Five to 10 grab samples of grass, sagebrush foliage, and standing dead sagebrush in 1hr, 10hr, and 100hr size classes were collected in the interplot area prior to the burning of each experimental area. A single set of fuel moisture samples was collected to represent multiple sites if they were relatively close to one another, and being burned at or around the same time. Samples of approximately 50 to 400 g each were collected in heavy gauge, plastic bags with airtight seals, weighed immediately after collection, returned to the laboratory, ovendried for a minimum of 48 hours at 100 °C, and weighed to determine fuel moisture content on a dry weight basis. Weather conditions during the burning period were measured every 15 to 30 minutes using a sling psychrometer (temperature and relative humidity) and an electronic pocket weather meter (temperature, relative humidity, windspeed 2 m aboveground). Weather conditions were

[1] 1hr, 10hr, 100hr, and 1000hr timelag fuels are defined as woody material ≤0.64 cm, 0.64-2.54 cm, 2.55-7.62 cm, and >7.62 cm in diameter, respectively.

also measured with a portable weather station (temperature, relative humidity, windspeed 2 m aboveground) logging 15-minute average values at several of the experimental locations. Temperature and relative humidity measurements taken using the sling psychrometer and windspeed measurements taken using the pocket weather meter were used preferentially, as these are the tools available to practitioners on the fireline.

Ignition—Sites were ignited during the course of daily prescribed burning operations. Most experimental sites were ignited by hand with drip torches, although a few areas were aerially ignited using incendiary plastic spheres containing chemicals that undergo a rapid exothermic reaction when mixed (ethylene glycol and potassium permanganate). Experimental areas typically burned in a heading or flanking fire.

Data Analysis

Model Development—Pre-burn coverage and height data, and coverage and height data from the Natural Fuels Photo Series (Ottmar and others 2000) were combined to develop a model to estimate sagebrush loading. Models to predict consumption of biomass were constructed from the suite of fuel characteristics and environmental variables measured before and during the fires. A simple correlation matrix of all variables measured as part of this study identified those that were most promising for constructing the predictive models. Forward and backward stepwise multiple linear regression (Neter and others 1990) was used to identify preliminary models; expert opinion was used to select the final models. Criteria for model selection included parsimony as well as the presence of reasonable physical explanations for a given variable's inclusion in the full model. A generalized linear model (GLM; McCullagh and Nelder 1989) of the binomial family was also developed for predicting the proportion of biomass consumed using the same variables included in the multiple linear regression model. The binomial GLM predicts proportional shrub consumption between [0,1] and therefore avoids predictions of fuel consumption that are either less than zero or greater than the pre-fire fuel amount. The GLM was created in S-plus (Insightful 2002) and programmed into the CONSUME 3.0 software (Prichard and others, in press). Both models' predictive capabilities were compared to independent data sets reported by Kauffman and Cummings (1989) and Sapsis and Kauffman (1991).

Results

Tables 3, 4, and 5 summarize pre-fire fuel loading, pre- and post-fire coverage, and fuel consumption, respectively. Total aboveground pre-fire biomass ranged from 5.3 to 22.6 Mg ha^{-1}; sites dominated by mountain big sagebrush tended to have the most aboveground biomass. Pre-fire sagebrush loading ranged from 4.4 to 20.2 Mg ha^{-1} with site coverage of 14 to 67 percent. All, live and dead sagebrush represented from 46 to 92, 25 to 64, and 20 to 56 percent of the total site biomass, respectively; total sagebrush biomass was >80 percent of total biomass for 16 out of 17 sites. Mean sagebrush height ranged from 0.3 to 0.9 m, although many plants were taller than the mean height. Pre-fire herbaceous vegetation and other shrub loading (and coverage) ranged from 0.1 to 0.6 Mg ha^{-1} (5 to 38 percent) and zero to 3.7 Mg ha^{-1} (0 to 19 percent), respectively. Surface fuel loading ranged from 0.3 to 2.7 Mg ha^{-1}.

Table 3—Pre-fire fuel loading for experimental sagebrush burns.

Site name	Loading						
	Herbaceous vegetation	Live sagebrush	Dead sagebrush	Other shrubs	All vegetation	Surface fuels[a]	All fuels
	Megagrams hectare^{-1}						
Flook Lake 1	0.290	5.521	5.623	0.002	11.435	0.866	12.300
Flook Lake 2	0.109	7.141	5.763	0.000	13.013	1.523	14.536
Flook Lake 3	0.106	6.087	4.214	0.063	10.471	0.714	11.185
Stonehouse	0.614	4.621	1.995	0.580	7.810	2.211	10.021
V-Lake A	0.156	11.113	5.177	0.440	16.885	1.975	18.860
V-Lake 1	0.273	7.919	3.514	0.236	11.942	1.974	13.916
V-Lake 2	0.206	9.207	3.787	0.229	13.430	1.052	14.481
V-Lake 3	0.158	3.239	1.162	0.043	4.602	0.672	5.274
V-Lake 4	0.224	11.062	3.635	0.312	15.233	1.122	16.356
Gold Digger 1	0.543	4.522	3.796	0.191	9.052	0.339	9.391
Gold Digger 2	0.570	6.348	3.396	0.000	10.314	0.511	10.825
Escarpment 1	0.310	3.094	2.652	3.723	9.780	2.709	12.488
Escarpment 2	0.251	7.619	6.626	0.031	14.527	1.562	16.088
Sagehen	0.078	6.081	10.919	0.035	17.112	2.231	19.343
Heart Mtn HM	0.393	12.709	7.492	0.000	20.594	1.994	22.588
Heart Mtn OT	0.411	4.520	2.937	0.409	8.277	0.992	9.269
Heart Mtn SC	0.361	5.531	3.193	0.003	9.088	0.968	10.056

[a]Includes litter and all dead and down woody fuels.

Table 4—Pre- and post-fire coverage for experimental sagebrush burns.

Site name	Pre-fire coverage				Post-fire coverage	
	Herbaceous vegetation	sagebrush	Other shrubs	All vegetation	Area burned	Unburned sagebrush
	percentage					
Flook Lake 1	10.8	35.9	0.2	46.8	32.7	21.5
Flook Lake 2	20.1	38.1	0.0	58.1	38.6	22.6
Flook Lake 3	4.6	29.0	0.2	33.8	36.9	24.6
Stonehouse	20.0	35.7	6.9	62.5	39.8	29.0
V-Lake A	20.0	49.8	6.1	75.8	50.6	21.9
V-Lake 1	12.3	43.9	9.3	65.4	74.6	13.8
V-Lake 2	14.8	43.2	3.7	61.7	53.8	21.3
V-Lake 3	15.1	34.5	1.5	51.2	23.9	20.0
V-Lake 4	23.0	59.5	3.1	85.6	96.9	1.6
Gold Digger 1	22.9	24.5	5.6	53.0	36.4	19.5
Gold Digger 2	23.7	30.3	2.6	56.6	60.4	10.7
Escarpment 1	13.7	13.5	19.1	46.3	75.9	4.3
Escarpment 2	22.0	35.1	0.5	57.6	78.2	7.2
Sagehen	5.0	43.3	5.9	54.2	14.5	33.1
Heart Mtn HM	37.6	66.5	0.3	98.3	98.4	0.6
Heart Mtn OT	34.3	29.7	2.7	66.7	94.8	0.5
Heart Mtn SC	31.5	42.0	0.1	73.6	99.8	0.3

Table 5—Fuel consumed during experimental sagebrush burns.

	Consumption					
Site name	Herbaceous vegetation	Sagebrush	Other shrubs	All vegetation	Surface fuels[a]	All fuels
	- - - - - - - - - - - - - - - - *Megagrams hectare^{-1} (percentage of pre-fire loading)* - - - - - - - - - - - - - -					
Flook Lake 1	0.097 (33.6)	3.132 (28.1)	0.001 (33.6)	3.230 (28.2)	0.291 (33.6)	3.521 (28.6)
Flook Lake 2	0.042 (38.6)	4.020 (31.2)	—	4.062 (31.2)	0.588 (38.6)	4.650 (32.0)
Flook Lake 3	0.040 (38.0)	4.999 (48.5)	0.024 (38.0)	5.064 (48.4)	0.271 (38.0)	5.335 (47.7)
Stonehouse	0.246 (40.0)	1.992 (30.1)	0.232 (40.0)	2.469 (31.6)	0.885 (40.0)	3.354 (33.5)
V-Lake A	0.082 (53.0)	9.750 (59.9)	0.233 (53.0)	10.065 (59.6)	1.046 (53.0)	11.112 (58.9)
V-Lake 1	0.205 (75.3)	7.571 (66.2)	0.177 (75.3)	7.954 (66.6)	1.486 (75.3)	9.440 (67.8)
V-Lake 2	0.129 (62.4)	9.457 (72.8)	0.143 (62.4)	9.728 (72.4)	0.656 (62.4)	10.384 (71.7)
V-Lake 3	0.050 (31.6)	1.322 (30.0)	0.013 (31.6)	1.385 (30.1)	0.212 (31.6)	1.597 (30.3)
V-Lake 4	0.218 (97.2)	13.648 (92.9)	0.304 (97.2)	14.170 (93.0)	1.091 (97.2)	15.260 (93.3)
Gold Digger 1	0.201 (37.0)	4.660 (56.0)	0.070 (37.0)	4.931 (54.5)	0.125 (37.0)	5.057 (53.8)
Gold Digger 2	0.346 (60.7)	5.655 (58.0)	—	6.001 (58.2)	0.310 (60.7)	6.311 (58.3)
Escarpment 1	0.242 (78.1)	3.116 (54.2)	2.906 (78.1)	6.264 (64.1)	2.114 (78.1)	8.379 (67.1)
Escarpment 2	0.197 (78.6)	12.662 (88.9)	0.024 (78.6)	12.884 (88.7)	1.227 (78.6)	14.111 (87.7)
Sagehen	0.016 (20.5)	2.737 (16.1)	0.007 (20.5)	2.761 (16.1)	0.763 (34.2)	3.524 (18.2)
Heart Mtn HM	0.390 (99.2)	19.916 (98.6)	0.000 (99.2)	20.306 (98.6)	1.978 (99.2)	22.284 (98.7)
Heart Mtn OT	0.411 (100.0)	7.341 (98.4)	0.409 (100.0)	8.161 (98.6)	0.992 (100.0)	9.153 (98.8)
Heart Mtn SC	0.361 (100.0)	8.525 (97.7)	0.003 (100.0)	8.889 (97.8)	0.968 (100.0)	9.857 (98.0)

[a]Includes litter and all dead and down woody fuels.

Total aboveground biomass consumption varied from 1.6 to 22.3 Mg ha^{-1} (18 to 99 percent) among the 17 experimental areas, with 15 to 100 percent of the experimental area burned. Most fires were patchy, although in excess of 90 percent of the area burned for four of the 17 sites. Post-fire coverage of unburned live sagebrush ranged from <1 to 33 percent. Fire spread was most limited in the single spring burn (Sagehen) despite temperature, relative humidity, and windspeed conditions similar to the fall burns (all others). Five out of seven of the study sites where fire burned less than 40 percent of the experimental area had dead 10hr sagebrush fuel moisture values in excess of eight percent. Fuel consumption was highest at sites where dead 10hr fuel moisture was 6.1 percent and less.

Multiple linear regression and generalized linear models are reported in table 6. Percentage of area burned and pre-burn sagebrush loading were strong predictors of sagebrush consumption (fig. 1a). Similarly, percentage of area burned and pre-burn loading of non sagebrush fuels were predictors of non sagebrush consumption (fig. 1b). Pre-burn coverage of herbaceous vegetation, slope, windspeed, 10hr fuel moisture were chosen as variables to predict percentage of area blackened (fig. 2).

Because of our relatively small sample size (n=17), we chose to retain all data points in the model building data set. However, using the generalized linear and multiple linear regression models, predicted total fuel consumption averaged within ±3.1 and ±1.9 percent, respectively, of observed values for four fall prescribed fires, and within ±11.9 and ±12.6 percent, respectively, of observed values for four spring fires measured by Kauffman and Cummings (1989) and Sapsis and Kauffman (1991).

Table 6—Regression equations for sagebrush loading, sagebrush and non sagebrush consumption, and area burned. The generalized linear model (GLM) gives the proportion of the area burned or biomass consumed and follows the form: Y = EXP(y)/(1+EXP(y)); multiply Y_{AB} by 100 to get AB, Y_{C_s} by L_s to get C_s, and YC_n by L_n to get C_n.

Equations	a	b_1	b_2	b_3	R^2
Multiple Linear Regression					
$L_s = a + b_1(P_s) + b_2(H_s)$	–1.364	0.292	1.365		0.85
$AB = a + b_1(P_h) + b_2(FM) + b_3(W \times S)$	30.582	1.951	–4.369	1.737	0.69
$C_s = a + b_1(L_s) + b_2(AB)$	–7.171	0.681	0.111		0.87
$C_n = a + b_1(L_n) + b_2(AB)$	–1.056	0.706	0.016		0.96
Generalized Linear Model					
$y_{AB} = a + b_1(P_h) + b_2(FM) + b_3(W \times S)$	–1.734	0.114	–0.209	0.110	0.75[a]
$y_{C_s} = a + b_1(L_s) + b_2(AB)$	–2.657	0.043	0.047		0.82[a]
$y_{C_n} = a + b_1(L_n) + b_2(AB)$	–2.206	–0.050	0.052		0.89[a]

[a](null deviance - residual deviance) ÷ null deviance; (analogous to R^2 for GLM)

Symbols:

L_s = pre-burn loading of sagebrush, Mg ha^{-1};
L_n = pre-burn loading of non sagebrush biomass, Mg ha^{-1};
P_s = pre-burn coverage of sagebrush;
H_s = pre-burn height of sagebrush, meters;
AB = area burned, percentage of total area;
P_h = pre-burn coverage of herbaceous vegetation, percentage;
FM = day of burn 10hr fuel moisture, percentage by dry weight;
W = day of burn windspeed, km hr^{-1};
S = slope category, <5%=1, 5-15%=2, 16-25%=3, 26-35%=4, >35%=5;
C_s = consumption of sagebrush, Mg ha^{-1};
C_n = consumption of non sagebrush, Mg ha^{-1}.

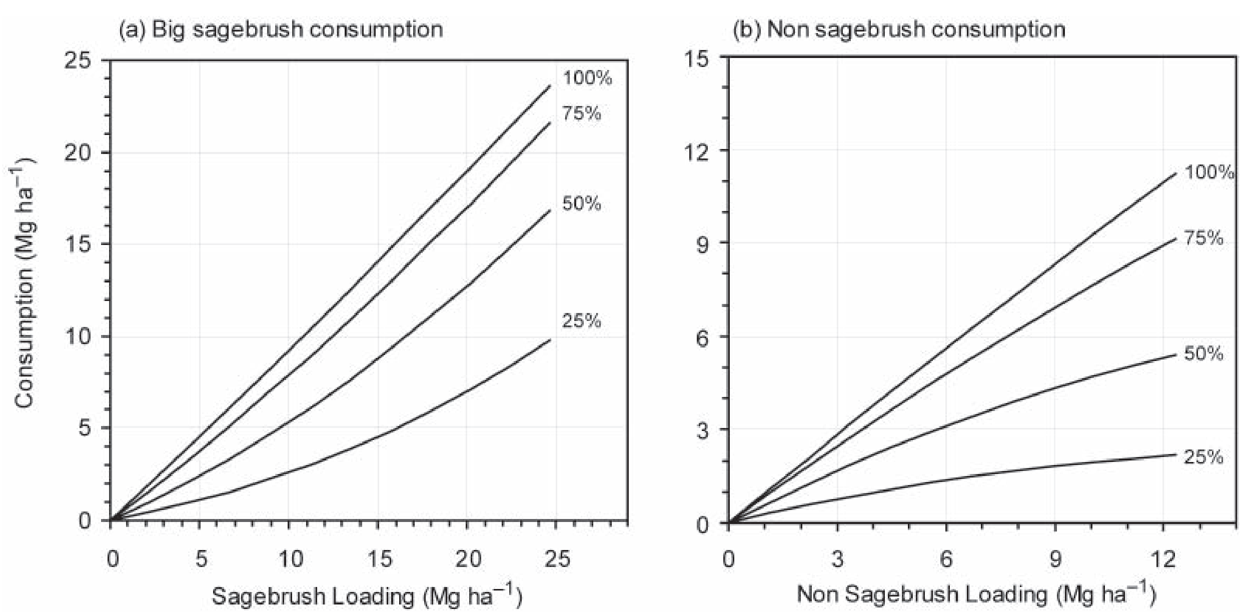

Figure 1—Generalized linear models showing (a) sagebrush and (b) non sagebrush consumption as a function of loading at 25, 50, 75, and 100 percent of area burned (lines).

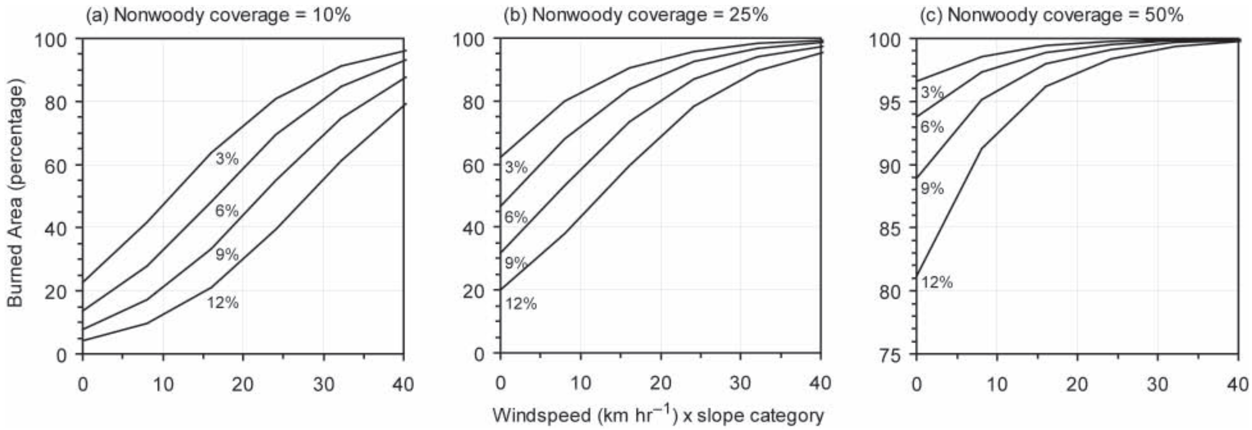

Figure 2—Generalized linear model showing area burned as a function of windspeed × slope category at 3, 6, 9, and 12 percent 10hr fuel moisture content (lines) where herbaceous vegetation coverage is (a) 10 percent, (b) 25 percent, and (c) 50 percent.

Discussion

Two conditions contribute to fuel consumption (and post-fire fuel loading); partially consumed fuel particles, and fuel left in unburned patches. Fuel loading and coverage, fuel moisture, weather (windspeed), and site characteristics (slope) are incorporated in the predictive equations reported here. These equations encapsulate all of the consumption that occurs because of partial burning of fuels and patchy burning of an area. Sites where fire spread was patchier and fire carried through less of the plot area typically experienced lower overall fuel consumption, although a high proportion of the fuels in the burned areas may have consumed.

The final models are relatively simple and incorporate predictor variables for which users are likely to have, or can readily acquire the necessary data. Pre-burn biomass is a key variable for predicting fuel consumption. Biomass can be estimated from locally available inventory data, from fuels assessments using photo guides (for example, Ottmar and others 1998, 2000) or calculated using the equation for estimating sagebrush biomass (L_s) from sagebrush coverage (P_s) and height (H_s; table 6). While managers and planners typically do not have biomass data at their disposal, they often have coverage and height data, or can easily acquire it from a variety of sources. Percentage of area burned is the other key variable for predicting fuel consumption. We include an equation to predict this value (AB), again, based on data that fire managers and planners are likely to have at their disposal and routinely include in prescribed fire burn plans and prescriptions, including windspeed (W), slope (S), and 10hr fuel moisture (FM; table 6).

Users of CONSUME 3.0 can easily predict how environmental, site, and fuel conditions will affect potential percentage of area burned and fuel consumption. This is a tool that can be used for developing burning prescriptions that meet specific management objectives. For example, if one objective of a prescribed fire project is to create a mosaic of burned and unburned vegetation in a specific area for wildlife habitat improvement, users can modify windspeed and fuel moisture inputs until the model yields the desired amount or range of percentage of area burned, thereby defining the prescription parameters. Similarly, a desired percentage of area burned can then be used as an input along with information about site biomass, to predict potential fuel consumption and smoke emissions or other fire effects.

Energy (heat) is required to drive off fuel moisture, to heat fuel particles to pyrolysis and combustion temperatures, and to sustain flaming combustion. Dead 10hr fuel moisture content is an indicator of how readily combustion occurs, how effectively fire spreads from particle to particle and from dead to live fuels, and subsequently how much fuel consumes. Increasing amounts of fuel become available to burn as live and dead fuel moisture decline, however, once fuel moisture has fallen below a critical value, weather and fuel loading appear to become the elements affecting fuel consumption. Where sufficient amounts of fuel are available to burn, prevailing weather conditions (windspeed in our model) appear critical for determining fire spread and fuel consumption. The effects of windspeed can be exacerbated or mitigated to some degree by slope. The multiplier for slope incorporated in the windspeed × slope variable in the equation for predicting area burned is comparable to values suggested by Brown (1982). Poor fuel consumption conditions (elevated fuel moisture, elevated relative humidity, low windspeeds, lack of carrier fuels, etc.) may be mitigated to some degree by an aggressive burning operation. If enough fire can be introduced to the site at once, fire spread can be facilitated, and fuel consumption increased. Use of heli-torches, terra-torches and large numbers of hand igniters can be effective for mass ignition.

Individual plant height, plant to plant spacing, interplant "understory" vegetation amount, overall biomass, and live fuel:dead fuel ratios all may have an effect on how well fire spreads, how much heat and energy are generated, how long flaming and smoldering combustion persist, and therefore how much fuel consumes. Other weather variables, such as temperature, solar insolation (or shading), and relative humidity; and other fuel characteristics, such as live fuel moisture, likely are also important, although they were not useful as predictors of fire spread and fuel consumption given their limited range in our data set. A larger data set with a greater range of values may help identify if or how they are correlated with fuel consumption.

The predictive models reported here are empirical. They represent correlations among variables, and not cause and effect relationships. However, variables were included in the various models only if there was a reasonable physical explanation. For example, cover of herbaceous vegetation was included in the model to predict how much of an area was likely to burn, as the grasses and forbs growing between and under individual sage plants provide a vector for fire to spread from plant to plant. Similarly, windspeed was included as if influences convective heat transfer and flame contact among adjacent shrubs and other fuel particles.

Fuel characterization, fuel moisture, site characterization and onsite weather sampling during the burning experiments allowed us to develop models for predicting fuel consumption that will be useful to fire managers and planners. The ability to predict fuel consumption under varying environmental conditions will facilitate prescription development, burn planning and burn scheduling. The tools available in CONSUME 3.0 will allow resource managers to better assess landscapes for opportunities and hazards, and to develop science-based treatment and mitigation strategies to most effectively manage fuel consumption, fire effects and smoke production.

Acknowledgments

This research was supported by the Joint Fire Science Program and the National Fire Plan. Roger Ottmar, David L. Peterson, and Donald McKenzie reviewed the manuscript.

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