WESTERN JUNIPER SUCCESSION:
CHANGING FUELS AND FIRE BEHAVIOR

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Curtis R. Yanish

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Major Professor: Stephen C. Bunting

AUTHORIZATION TO SUBMIT

THESIS

This thesis of Curtis R. Yanish, submitted for the degree of Master of Science with a major in Rangeland Ecology and Management and titled "Western Juniper Succession: Changing Fuels and Fire Behavior" has been reviewed in final form. Permission, as indicated by the signatures and dates given below, is now granted to submit final copies to the College of Graduate Studies for approval.

Major Professor ______________________________Date____________
Stephen C. Bunting

Committee
Members ______________________________Date____________
Kendall L. Johnson

______________________________Date____________
James L. Kingery

______________________________Date____________
Leon F. Neuenschwander

Department
Administrator______________________________Date____________
Kendall L. Johnson

Discipline's
College Dean______________________________Date____________
Steven B. Daley Laursen

Final Approval and Acceptance by the College of Graduate Studies

______________________________Date____________
Charles R. Hatch

Abstract

This study was conducted to evaluate whether western juniper (*Juniperus occidentalis* spp. *occidentalis*) encroachment and resulting succession affects fuels and fire behavior. Fuels data were collected by cover types, differentiated by western juniper encroachment (and resulting successional stages) into low sagebrush (*Artemisia arbuscula*) or mountain big sagebrush (*Artemisia tridentata* spp. *vasseyana*) potential vegetation types. Fuel models were created from collected data averages with the use of BEHAVE NEWMDL fuel modeling subsystem for use in BEHAVE DIRECT fire prediction subsystem and FARSITE 4.0.1 Fire Area Simulator. Fifteen new fuel models were created to represent the fuels for each cover type.

Fire behavior was tested using the fire behavior models BEHAVE and FARSITE. BEHAVE was used to predict flame length and rate of spread for the new models created from the collected data and the herbaceous fuel reduction models. FARSITE was used to predict fire behavior on a heterogeneous landscape to test the effect of succession on the size of a fire and the reduction of herbaceous fuels on fire growth with in cover types.

When total fuel weight and fuel bed depth for the mountain big sagebrush and low sagebrush encroachment and successional cover types were compared, it was apparent that they did not follow the same trends. Low sagebrush cover types herbaceous and shrub components persisted latter into the western juniper successional stages. The changes identified in fuel composition, total fuel weight, and fuel bed depth resulted in changes in modeled fire behavior. Changes in fuel bed depth where strongly reflected in the changes in modeled flame lengths and rates of spread.

Acknowledgments and Dedication

I take this opportunity to covey my sincerest gratitude to the entire Department of Rangeland Ecology and Management for giving me the opportunity to pursue a graduate education following my service in Kosovo. Special thanks go to Dr. Stephen Bunting for thinking of me when a funded project came along.

Acknowledgments go out to those who assisted me throughout this process, including committee members Dr. Kendall Johnson, Dr. Jim Kingery, and Dr. Leon Neuenschwander; field assistants Renan Bagley and Jeremy Kleinsmith; GIS and DO support Eva Strand; and all of the past and present graduate students in the department for their technical, spiritual, and menu advising. The Joint Fire Science Program provided funding for the project.

This thesis is dedicated to my wife, Renan Yanish (formerly Bagley), for insisting that she work for me during the first field season. I also dedicate it to my parents, David and Marlene Yanish, for always believing in me no matter how high I set the bar for myself. Thank you for all your support and understanding.

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Introduction

Western juniper (*Juniperus occidentalis* spp. *occidentalis*) encroachment into sagebrush communities and resulting succession has been studied for many years. Causes of encroachment and succession have been related to fire suppression, cattle grazing, and climate change (Burkhardt and Tisdale 1976). There are many ways to reverse these trends including the use of fire by allowing wildfires to burn or by prescribing fire (Blackburn and Tueller 1970, Burkhardt and Tisdale 1976).

The successional consequences of western juniper encroachment include changes in species composition and vigor (Burkhardt and Tisdale 1976, Miller et al. 2000, Young and Evans 1981). The changes in species composition and vigor could lead to changes in available fuel for wildfire and prescribed fire, limiting the effectiveness of fire as a control for western juniper (Agee 1993, Young and Evans 1981). It is impossible to predict the effectiveness of fire without identifying and understanding the changes in fuel loading due to western juniper encroachment and succession.

The objectives of this study are to 1) identify changes in fuel loading due to encroachment and succession of western juniper in sagebrush communities; 2) predict the resulting fire behavior using models to evaluate changes in fire growth; and 3) evaluate the effect of grazing on the resulting predicted fire behavior.

Literature Review

Since European settlement, western juniper woodlands have had one of the most dramatic expansions of any plant community in the Intermountain West (Burkhardt and Tisdale 1969, Burkhardt and Tisdale 1976, Miller and Rose 1995, Miller and Rose 1999, Miller et al. 2000, Young and Evans 1981). Burkhardt and Tisdale (1976) indicated that increased rates of western juniper encroachment on the Owyhee Plateau of southwestern Idaho started around 1880. Similarly, an increase of western juniper is thought to have begun in the Chewaucan river basin of Oregon between 1875 and 1885 (Miller and Rose 1999). The greatest expansion of western juniper in the Intermountain West occurred between 1870 and 1920 (Miller and Rose 1999).

Three frequently identified hypotheses attribute the expansion of western juniper to 1) climatic shifts, 2) suppression of wildfire and fires set by Native Americans, and 3) grazing by domestic livestock (Burkhardt and Tisdale 1976, Young and Evans 1981). Miller and Rose (1999) pointed out the increase in tree ring growth in the latter part of the 1800s through the 1920s, representing a period that was warmer and wetter then average. The occurrence of wildfire and set fires declined in the late 1800s and in recent years has been almost eliminated. This can be attributed to the cessation of fires set by Native Americans, fire control by land managers, construction of roads and trails, and grazing by domestic livestock (Burkhardt and Tisdale 1976, Shinn 1980). Extensive heavy grazing could lead to a reduction in fine fuels that carry the fire (Miller and Rose 1999).

The statement that grazing by domestic livestock reduces fine fuels and therefore the potential for fire has been made by many authors (Burkhardt and Tisdale 1976, Miller and Rose 1999, West 1988). All of the references to reductions in fire potential due to livestock grazing appear to be anecdotal. Similar statements were made by Johnsen (1962), Blackburn and Tueller (1970), Miller et al. (1994), West et al. (1984), and Young and Evans (1971 and 1981). These authors have then been cited by others. None of the authors explained the relationship between grazing and the effects on fire frequency and potential fire behavior based on scientifically collected data.

Blackmore and Vitousek (2000) studied the reductions in standing biomass due to grazing and the resulting effects on fire behavior. Their study characterized the standing biomass that affects fire behavior to create new fuel models. Custom fuel models were created using BEHAVE Fire Behavior Prediction and Fuel Modeling System. After evaluation of the custom models that were created, three models were retained and the resulting fire behavior was compared. The three fuel models used were ungrazed kikuyu (*Pennistum clamdestnum*), ungrazed fountain grass (*Penniseum setaceum*), and grazed kikuyu. The difference in ungrazed and grazed kikuyu was a reduction in mean biomass from 770 to 229 g/m^2 and in height from 26.8 to 6.1 cm, respectively. The results of their BEHAVE (described later in the document) fire behavior runs indicated that grazed grasslands had a much lower fire potential than that of ungrazed grasslands. They concluded that the removal of cattle could lead to the accumulation of grasses and make catastrophic fires possible.

Changes in fire frequency have many consequences that could have led to the expansion of western juniper. Historically, fire limited the potential habitat of western juniper primarily to rock outcrops on slopes and ridges (Burkhardt and Tisdale 1969). These areas make up the old-growth habitat of western juniper and comprise only three to five percent of the current western juniper woodlands in the Intermountain West (Burkhardt and Tisdale 1976, Waichler et al. 2001). Old-growth habitat has insufficient amount of fine fuels in the understory to carry a surface fire. Crown closure is insufficient to allow crown-to-crown heating needed for independent crown fire. Fire scarred snags in old-growth western juniper forests suggest the occurrence of lightning strikes that burn only individual trees (Clark and Starkey 1990).

Western juniper is susceptible to fire and can be readily killed if less than 3 m tall and reach that height in approximately 45 years in south central Oregon (Miller and Rose 1999). Burkhardt and Tisdale (1976) observed high mortality of western juniper less than 50 years old, especially among seedlings and saplings, even when there was no noticeable charring. This would indicate that where adequate fine fuels can carry fire, a fire return interval of 40 to 50 years would be sufficient to prevent western juniper expansion.

Mountain big sagebrush (*Artemisia tridentata* spp. *vaseyana*) communities are a product of an environment that includes frequent fires limiting the expansion of western juniper (Burkhardt and Tisdale 1976). A 12- to 15-year fire return interval is generally associated with mountain big sagebrush communities (Miller and Rose 1999). Grass, sagebrush, and accumulated litter provide the fuels to carry ground fires that can prevent the expansion of western juniper. Longer fire-free intervals will allow for the accumulation of fuels, however, natural fuels will shift from fine herbaceous fuels to larger diameter fuels from sagebrush and juniper (Agee 1993). Miller and Rose (1999) found from tree rings that large historical fires were usually preceded by at least one year of above average growth. This observation indicates that the accumulation of litter from a year of above average precipitation was important for providing adequate fuel to carry a ground fire.

Expansion of western juniper into mountain big sagebrush communities reduces herbaceous and shrubby vegetation. Young and Evans (1981) found that herbaceous production on encroached mountain big sagebrush sites was less than 50 Kg/ha. Miller et al. (2000) observed that mountain big sagebrush cover declined as much as 80% with increasing dominance of western juniper. Because the intensity of wildfires is a function of the fuels available, dense stands of western juniper growing on mountain big sagebrush sites can become almost fire proof (Agee 1993, Young and Evans 1981).

Encroachment of western juniper into low sagebrush (*Artemisia arbuscula*) communities has consequences that differ from those found in mountain big sagebrush communities. Fire return intervals in low sagebrush are much longer than those in mountain big sagebrush due to lower vegetative production. Growth of western juniper is slower in low sagebrush compared to those in mountain big sagebrush. Miller and Rose (1999) noted that a western juniper 3 m tall in a mountain big sagebrush stand would be 40 to 50 years old, but, 75 to 95 years may be required to reach the same height in a low sagebrush community. Therefore, they concluded that a 100-year fire return interval would be sufficient to control the expansion of western juniper in low sagebrush. Increasing dominance of western juniper had little effect on the composition of associated vegetation (Miller et al. 2000). Herbaceous cover did not change between young and mature western juniper stands. However, low sagebrush can become nearly fire proof if the perennial grasses are grazed (Young and Evans 1981). This is due to the reduced accumulation of fine fuels that aid the spread of fire (Agee 1993).

Increased grazing pressure and absence of fire in sagebrush-grass communities can cause a shift toward greater dominance of shrub cover (Miller and Rose 1999). Safe sites for western juniper seedling establishment are offered by the increased sagebrush cover (Miller and Rose 1995). The shift from herbaceous-dominated communities to sagebrush-dominated communities reduces the amount of fine fuels required to carry surface fires, allowing western juniper to increase its dominance over the sagebrush and herbaceous components of the community. Burkhardt and Tisdale (1976) concluded that herbaceous and shrub components will decline as western juniper mature, limiting the effectiveness of fire in controling the expansion of western juniper.

Changes in fuel loading can be measured by inventorying surface fuels along the successional gradient of western juniper expansion. Brown (1974) discusses methods to inventory weight, volume, and depth of downed woody material. Downed woody material is defined as dead twigs, branches, stems, and boles (trunks) of trees and shrubs that have fallen and lie on or above the ground. An inventory can provide detailed information of weights and volumes per area by diameter size class. The diameter size classes for woody material are defined as 0 – 0.6, 0.6 – 2.5, and 2.5 – 7.6 cm, for 1-hour, 10-hour, and 100-hour fuels respectively. Data are collected using the line intersect technique.

Brown et al. (1982) expands the inventorying of fuels beyond downed woody material to include duff, litter, herbaceous vegetation, shrubs, and small conifers. The inventory procedures described are useful for determining biomass of any vegetation up to 3 m in height. Inventory procedures are based on different techniques for different categories of vegetation, and can be limited to those vegetation types that are present in the area of concern. Although these inventory methods were originally designed for forested ecosystems, the methods have proven applicable for rangeland and woodland fuel inventory (Brown et al. 1982, Bushey 1985).

The data collected in the methods described above are used to create fuel models describing specific information regarding fuel loading, surface to volume ratio, fuel depth, fuel particle density, heat content and moisture of extinction for a given fuel type (Campbell et al. 1996). Anderson (1982) describes the 13 stylized fuel models, classified into 4 groups: grass and grass dominated, chaparral and shrub fields, timber litter, and logging slash. By choosing one of the fuel models that best represents the location and fuels of interest, the need for inventory work can be reduced or eliminated. Anderson (1982) suggested that the dormant shrub and hardwood slash model could be used in pinyon-juniper with sagebrush communities. But it may not adequately represent the fuels associated with western juniper-sagebrush communities. In such cases, a fuels inventory may provide a better representation of the associated fuels.

A fuel model is a list of numbers describing the fuels as required by a fire model's mathematical equations (Andrews and Queen 2001), and consists of fuel loading by size class (1-hour, 10-hour, 100-hour, live herbaceous, and live woody), fuel bed depth, heat content, moisture of extinction, surface to volume ratio, and fuel particle density (1-hour, live herbaceous, and live woody). Using the fuel model, the rate of spread and intensity of a fire can be predicted by a fire model based on mathematical equations (Rothermel 1972).

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YANI  NEW MODELS USING MEAN FUELS                          A

214ARAR STEPPE 40 33  7 1 15  49 7954 19 3506 1494 213A0
224ARTR STEPPE 62 49 21 1 19 129 7954 18 3506 1494 213A0
234W1 ARAR     70 64 19 1 29  67 7954 19 3506 1494 213A0
244W1 ARTR     87 76 54 1 28 145 7954 19 3506 1494 213A0
254W2 ARAR     74 70 12 1 31  69 7954 19 3506 1494 213A0
264W2 ARTR     63 57 28 1 21 102 7954 18 3506 1494 213A0
274W4 ARTR     78 30 30 3 13  44 7954 17 3506 1494 213A0
294W5 ARAR     53 19 19 2  8  24 7954 17 3506 1494 213A0
304W5 ARTR     67 14 98 3  4  13 7954 18 3506 1494 213A0
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For example, Rothermel's equation $R = (I_R \xi (1 + \Phi_w + \Phi_s))/\rho_b \varepsilon Q_{ig}$ predicts fire spread, where:

R is the rate of spread of the flaming front (m/min)

I_R is the reaction intensity, the energy release rate per unit area of the fire front

ξ is the propagating flux ratio, the proportion of the reaction intensity that heats adjacent fuel particles to ignition
Φ_w is a dimensionless multiplier that accounts for the effect of wind in increasing the propagating flux ratio
Φ_s is a dimensionless multiplier that accounts for the effect of slope in increasing the propagating flux ratio
ρ_b is bulk density, the amount of ovendry fuel per cubic centimeter of fuel bed
ε is the effective heating number, the proportion of a fuel particle that is heated to ignition temperature at the time the flaming combustion starts
Q_{ig} is the heat of preignition, the amount of heat required to ignite one kilogram of fuel

Fire models have traditionally been empirical, relating preburn conditions to fire characteristics (Andrews and Queen 2001). An example is Rothermel's (1972) model for predicting fire spread in wildland fuels. All that is required is the equation and inputs describing the physical and chemical makeup of the fuel and environmental conditions during the fire. Rothermel's (1972) model for fire spread in surface fuels is one of the most widely used fire models and is the basis for the BEHAVE Fire Behavior Prediction and Fuel Modeling System, FARSITE Fire Area Simulator, National Fire Danger Rating System (NFDRS), Rare Events Risk Assessment Process (RERAP), and many others (Andrews and Queen 2001, Rothermel 1972).

BEHAVE is a non-spatial fire behavior tool that calculates a fire’s intensity, rate of spread, and other characteristics (Campbell et al. 1996). It is divided into two subsystems; fuel modeling (FUEL) and fire behavior (BURN). The FUEL contains two programs, individual fuel model development (NEWMDL) and fuel model test and adjustment program (TSTMDL). The BURN subsystem also contains two fire behavior prediction programs, FIRE 1 and FIRE 2.

The fuel subsystem program NEWMDL allows for the construction of new site-specific fuel models (Burgan and Rothermel 1984). The methods provided by Brown (1974) and Brown et al. (1982) aid in the collection of the data needed for new model creation. The program is designed to prompt the user for the required data. TSTMDL allows for the examination of fire behavior characteristics of the fuel model under construction and provides a method to examine the effects of individual fuel model components on fire behavior (Burgan and Rothermel 1984).

The BURN subsystem programs, FIRE 1 and FIRE 2, contain modules offering a systematic method of predicting fire behavior for specific situations (Andrews 1986). The modules available in FIRE 1 include direct (rate of spread, flame length, and intensity), site, size, contain, dispatch, spot, scorch, mortality, map, and slope. FIRE 2 modules include moisture, ignite (spot fire ignition probability), and relative humidity. Andrews (1986) explains the use of most of the modeling functions offered in FIRE 1. Andrews and Chase (1989) explain the remaining functions in FIRE 1 and the functions found in FIRE 2.

FARSITE is a modeling tool for predicting fire spread and behavior across a landscape with heterogeneous fuels, weather, and topography (Finney 1998). It requires a database containing data layers for elevation, slope, aspect, fuels, canopy, weather, and wind to predict surface fire. With the addition of data layers describing canopy height, crown base height, and crown bulk density, crown fires can be predicted. Post-frontal combustion can be predicted as well, if layers describing coarse woody debris and duff are added (Andrews and Queen 2001).

All of the data layers required by FARSITE can be created with the use of a geographic information system (GIS) program. Photo interpretive delineation is one method of mapping areas with consistent fuel types. GIS data layers for FARSITE can then be created from the delineated map, which represent the landscape in an artificially homogeneous fashion. Satellite imagery better represents the natural heterogeneity of a landscape than photo interpretation. Satellite imagery expressed as a GIS raster data layer allows realistic descriptions of complex and heterogeneous fuels and tree crown densities across a landscape (Campbell et al. 1996).

Outputs from FARSITE are useful for conducting detailed analyses of fire behavior and fire effects on the landscape (Finney and Andrews 1999). Output data can be exported to a GIS program for further evaluation (Keane et al. 1998). The modeling program can be used to simulate past, active, and potential fires. Simulation of past fires is crucial in developing confidence in using FARSITE (Finney and Andrews 1999). The use of fire growth simulators aid in planning for potential wildland fires, prioritizing locations for fuels treatments, tactical support on active fires, fire incident support and activities, and fire incident reconstruction (Andrews and Queen 2001, Finney and Andrews 1999).

Differences between predicted and observed fire behavior can be caused by weaknesses in the model, changes in weather conditions, low accuracy of fuels characterization, changes in fuel moisture, and observer error (Andrews and Queen 2001). Designing a fire behavior fuel model is an interactive process of comparing predictions with observed or expected fire behavior. Adjustments should be made to the fuel model parameters until a satisfactory fire behavior prediction is achieved (Andrews and Queen 2001, Burgan 1987, Burgan and Rothermel 1984).

Bushey (1985) compared observed and predicted fire behavior in sagebrush-bunchgrass vegetation to test the effectiveness of using BEHAVE. Fuels data were collected using methods described by Brown et al. (1982). Fuels data collection was limited to herbaceous and shrub components; downed dead woody material was sparse and offered little to modeled fire behavior. Fuel models were created from the collected data using the NEWMDL program of BEHAVE. Prescribed fires where conducted to obtain rate of spread and flame length observations. The direct module of FIRE 1 program of BEHAVE was used to obtain predicted rate of spread using environmental data collected at the time of the prescribed burns. Bushey (1985) found that BEHAVE can be used to predict fire behavior in the sagebrush-bunchgrass vegetation.

Methods

Site descriptions

The Owyhee Plateau is located in Owyhee County, Idaho between the towns of Grand View, Idaho and Jordan Valley, Oregon. The Owyhee Plateau can be characterized by small mountains separated by deep canyons, rocky tablelands, and rolling plains ranging in elevation between 1200 and 2100 m. Average annual precipitation ranges between 30 and 56 cm, and is primarily received in fall, winter and early spring. Average temperatures range from –6.6 °C in January to 34.5 °C in July. Geologically, the area is mainly made up of a rhyolitic plateau. Soils vary from shallow rock outcrops to moderately deep gravelly, sandy, or silt loams (Harkness 1998).

Common tree species of the Owyhee Plateau include western juniper, curlleaf mountain-mahogany (*Cercocarpus ledifolius*), and quaking aspen (*Populus tremuloides*). Common shrub species include mountain big sagebrush, low sagebrush, shiny-leaf ceanothus (*Ceanothus velutinus*), green rabbitbrush (*Chrysothamnus viscidiflorus*), chokecherry (*Prunus virginiana*), and antelope bitterbrush (*Purshia tridentata*). Common grasses and grass-likes include bluebunch wheatgrass (*Agropyron spicatum*), Idaho fescue (*Festuca idahoensis*), basin wildrye (*Elymus cinereus*), Sandberg bluegrass (*Poa secunda*), bottlebrush squirrel-tail (*Sitanion hystrix*), elk sedge (*Carex geyeri*), and rush species (*Juncus spp.*). Smooth brome (*Bromus inermis*) and intermediate wheatgrass (*Agropyron intermedium*) are common introduced species in areas that were reseeded after a wildland fire event or prescribed fire. Common forbs include arrowleaf balsamroot (*Balsamorhiza sagittata*), wild buckwheat (*Eriogonum* spp.), paintbrush (*Castelleja* spp.), and mountain dandelion (*Agoseris* spp.).

Most of the land in the Owyhee Plateau region is managed by the Bureau of Land Management. The remaining land is owned by the State of Idaho and private entities. Current uses include livestock grazing, wildlife habitat, firewood cutting, and recreation. Livestock grazing occurs from spring green-up through mid-October (Harkness 1998). Firewood cutting occurs in designated areas. Hunting occurs in the late summer and fall. Wildlife species include mule deer *(Odocoileus hemionus)*, elk *(Cervus elaphus)*, big horn sheep *(Ovis canadenaia)*, mountain lion *(Puma concolor)* , black bear *(Ursus americanus)*, coyote *(Canis latrans)*, raccoon *(Procyon lator)*, skunk *(Spilogale* spp.*)*, snakes, lizards, grouse, and hawks.

Cover types

Cover types were differentiated by encroachment and resulting successional gradients of western juniper (Juoc) in low sagebrush (Arar) or mountain big sagebrush (Artr) steppe. Five stages of encroachment and succession were used to classify the change from sagebrush steppe to mature western juniper for each sagebrush type (Appendix I) (Bunting et al. 1999). These successional stages included: 1) Steppe– having less than 2% western juniper canopy coverage; 2) Woodland initiation (W1) - having less than 3 or 5% canopy cover of young to mid-aged western juniper, for low sagebrush and mountain big sagebrush, respectively; 3) Open young woodland (W2) - having 3-8 or 5-10% canopy cover of young and mid-aged western juniper; 4) Young multi-story woodland (W4) – having greater than 8 or 10% canopy cover of young and mid-aged western juniper with a few mature individuals present; 5) Old multi-story woodland (W5) – having greater than 8 or 15% canopy cover of primarily mature western juniper.

Sampling methods

Fuels data were collected using methods described by Brown et al. (1982), with some modifications to the sample plot design (Figure 3). Sampling methods to estimate biomass included four 25x25 cm herbaceous plots and four 25x12.5 cm litter plots using a double sampling technique. Three of the plots were estimated as a percentage of the plot containing the most biomass. The plot with the most biomass was clipped and the biomass was taken back to the lab for drying and weighing. Downed dead woody biomass was estimated using a 10-m transect. Shrub biomass was estimated with two 1-m radius plots, and tree density was estimated with a 4-m radius plot. If no trees were present in the 4-m radius plot a 10-m radius plot was used.

Samples were collected from Current Creek, Red Canyon Creek, and Smith Creek watersheds (Figure 4). All of the watersheds were previously identified as sixth order hydrologic unit code (HUC) watersheds. Samples were collected by cover type in locations previously identified by photo interpretation methods to delineate cover types (Figure 5) (Bunting et al. 2002). All samples were collected from paddocks that had not experienced grazing that year prior to the time the samples where collected.

Data analysis

Data from sampling were entered into Microsoft Excel 2000 and formatted for use in SAS 8.02[1] statistical software and BEHAVE 4.4[2] fire behavior modeling software. The ability to separate fuel loading by successional stages was evaluated statistically using the canonical discriminant analysis procedure. This allowed the components of the fuel model to be weighted against each other and then compared among cover types. The components included herbaceous, litter, downed dead woody, shrub biomass, herbaceous and shrub height, and tree density.

Fuel models were created with the use of BEHAVE NEWMDL for use in BEHAVE DIRECT and FARSITE[3]. Fifteen new fuel models were created to

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[1] SAS Institute Inc. Clay, NC.

[2] BEHAVE release 4.4. 1997. U. S. Department of Agriculture, Forest Service, Fire Science Laboratory, Missoula, MT

[3] FARSITE release 4.0.1. 2002. U. S. Department of Agriculture, Forest Service, Fire Science Laboratory, Missoula, MT.)

represent the fuels for each cover type. Three variations of each fuel model simulated the removal of herbaceous material by large herbivores. Herbaceous biomass was reduced by 25, 50, and 75%. Herbaceous height was reduced by 61, 82, and 87% of the mean herbaceous values for each cover type. The biomass removal-height relationship was extrapolated from Boyd (1987). The reduction of herbaceous biomass was accomplished by calculating the percentages and reducing the weight from the 1-hour fuel load and the height from the fuel bed depth.

BEHAVE was used to predict flame length and rate of spread for the new models created from the collected data and the herbaceous fuel reduction models. Fire behaviors for each fuel model were compared under a variety of environmental and topographic conditions. Predictions with BEHAVE were made at three fuel moisture levels: low (3%, 4%, 5% and 70%), medium (6, 7, 8 and 120%), and high (12, 13, 14 and 170%) for 1-, 10-, 100-hour and live fuel moisture conditions, respectively. The fuel moisture categories are the program defaults found in the TESTMDL fuel modeling subsystem of BEHAVE. Slope default was also used and set at 30%. Wind speeds were entered in as a range from 0 to 40 kph at 8 kph intervals.

There are certain assumptions and limitations associated with fire behavior models. First, fire behavior models are deterministic and fuels are considered uniform and continuous. Fire is predicted at the flaming front of a free-burning fire that is no longer affected by the ignition source. Fire behavior is largely determined by the fine fuel loading and does not consider fuels greater then 7.6 cm in diameter. Moreover, the models are designed for use during peak fire season conditions. BEHAVE only predicts surface fires under uniform fuel, fuel moisture, wind, and slope conditions, and are considered constant throughout the duration of the prediction (Andrews 1986, Rothermel and Rinehart 1983). These assumptions may lead to over predictions of fire behavior because the input data is more homogeneous than the real environment (Finney 1998).

FARSITE uses the same surface fire spread model and includes the same assumptions; however, it does not have the same limitations as BEHAVE. FARSITE can calculate fire behavior over a complex environment with temporally and spatially varying fuels, weather, and topography (Finney 1998).

FARSITE was used to predict fire behavior on a heterogeneous landscape. ASCII grids with 30-m resolution were used to represent the heterogeneity of the landscape. These grids included elevation, slope, aspect, cover types (derived from LANDSAT imagery), and crown cover. Model runs were conducted to test the effect of succession on the size of a fire and the reduction of fine fuels on fire growth within cover types. Weather data for FARSITE was created using data from a remote access weather station

(RAWS) located at Brace Flat in southwestern Idaho for August 2000. Averages from August 2000 are considered wildfire conditions. Relative humidity was increased to create weather conditions more consistent with prescribed fire conditions.

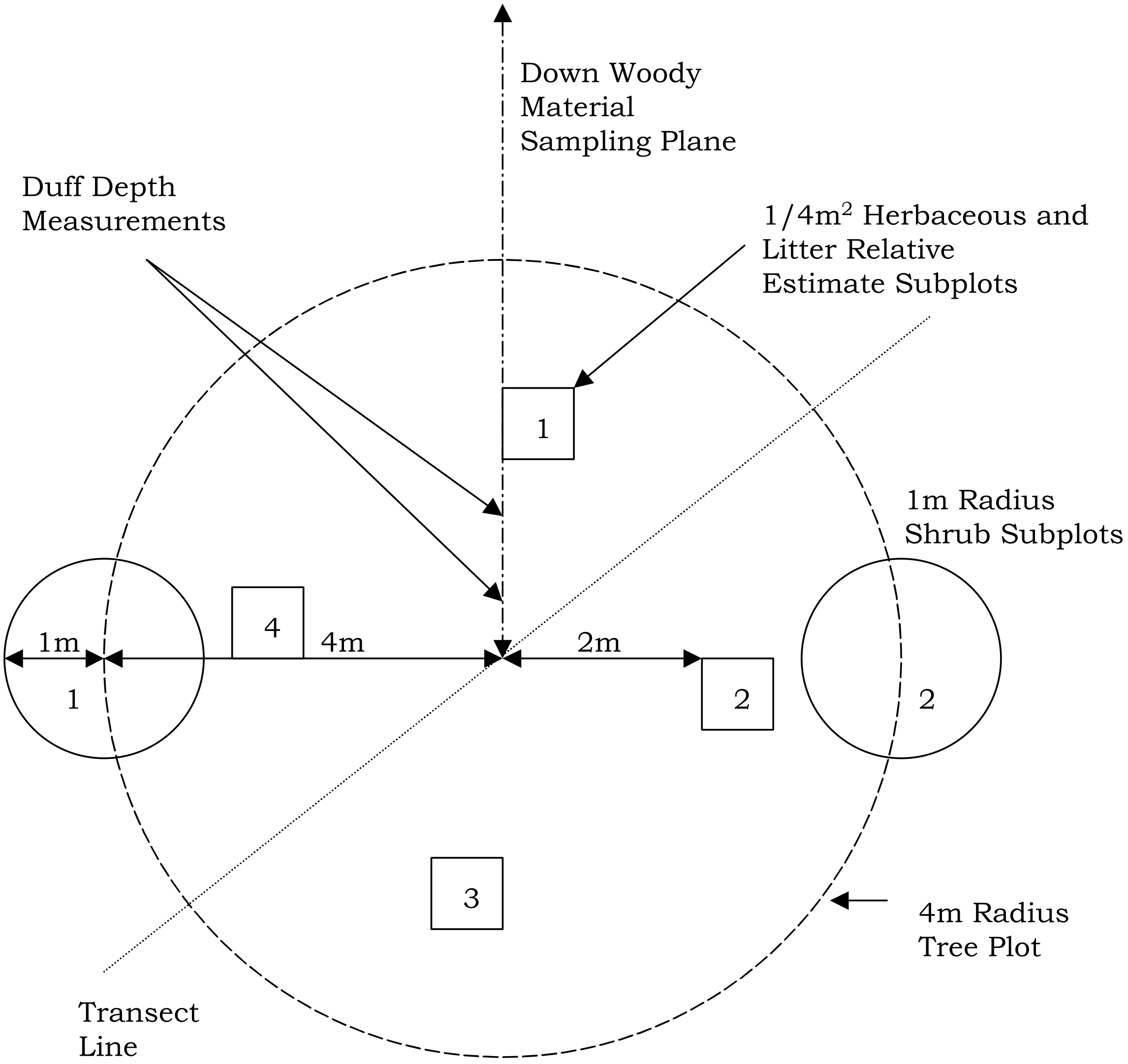

Fig. 1. Sample plot layout derived from Brown (1982) "Handbook for Inventorying Surface Fuels and Biomass in the Interior West".

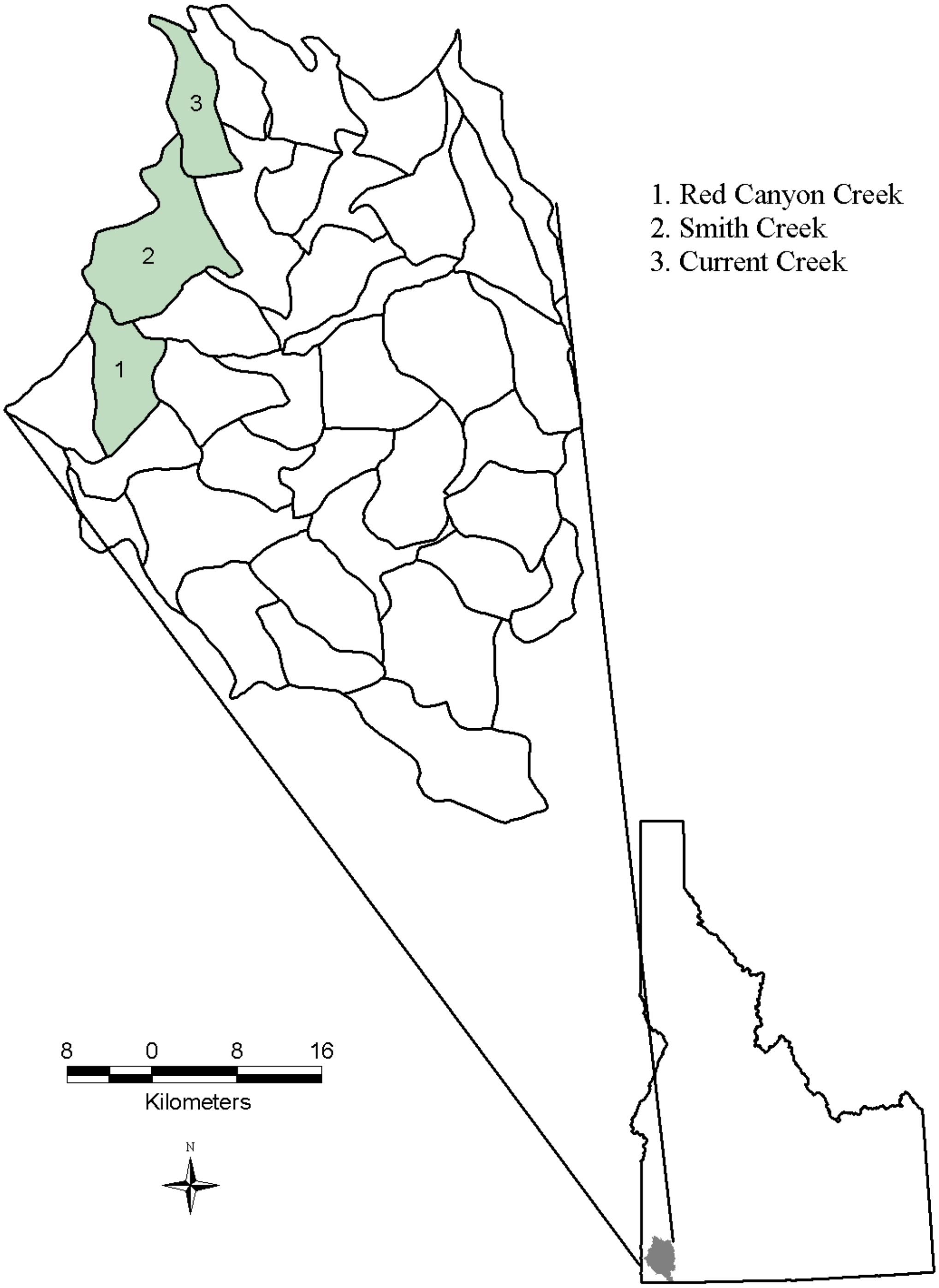

Fig. 2. Location of the three watersheds sampled in southwestern Idaho.

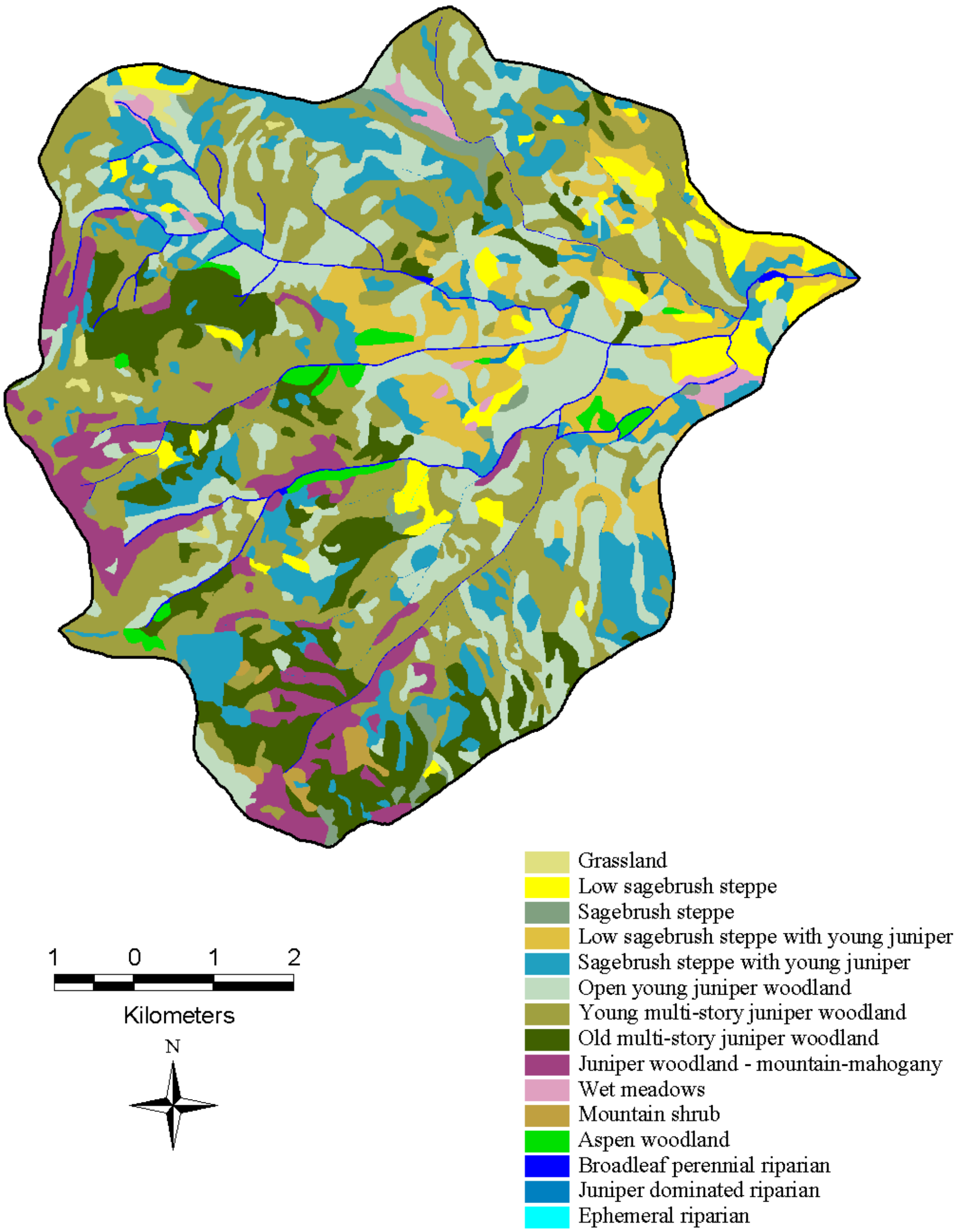

Fig. 3. Example of cover type map for Smith Creek watershed produced by photo interpretation method.

Results and Discussion

Successional change

Fuel loads for cover types across a landscape inherently have high variation (Levin 1992). Sample variance within cover types and fuel types was high, however, the variation among cover types was greater than that found within the cover types. Thus, successional stages could be separated. All of the dependent variables, such as herbaceous biomass, were significantly different when compared among cover types steppe, W1, W2, W4, and W5 ($p < 0.0001$). To test the effect of succession on the dependent variables a canonical discriminant analysis procedure was performed. An average of the successional variables affected the canonical correlation ($p < 0.0001$), which was heavily weighted toward western juniper crown cover, shrub biomass, and herbaceous biomass. Those three components explained 92% of the variation due to the successional stages. All western juniper encroachment and successional stages can be distinguished from one another with $r^2 = 0.72$.

Successional stages were further separated by the associated sagebrush species. Western juniper encroachment into mountain big sagebrush and low sagebrush sites have displayed different successional rates (Burkhardt and Tisdale 1976, Miller and Rose 1999). Separation factors include the rate of juniper encroachment and succession, species composition, and soil type (Burkhardt and Tisdale 1969). As a result, changes in fuels due to species composition and the corresponding fire behavior can be evaluated separately based on the sagebrush species.

In the mountain big sagebrush cover types, changes in fuels due to western juniper encroachment and resulting succession can be identified when the data are plotted on a graph (Figure 6). The trend shows initial increases followed by slow declines, with minor exceptions in W4 Artr 1-hour and W5 Artr 100-hour fuels. There is an initial increase in fuel bed depth followed by decline (Table 1). As the cover type shifts from Artr steppe to W1 Artr there is a 62% increase in total fuels and a 12% increase in fuel bed depth, giving W1 Artr the greatest total fuel load and fuel bed depth. The largest proportion of this increase is made up of 100-hour fuels (154%), corresponding with a 35% increase in shrub cover and in shrubs having basal diameters greater then 2 cm. An increase in 1-hour (41%) and 10-hour (55%) fuels can also be observed. The increase in 1-hour fuels is made up of litter and shrub material, which offset a decline in herbaceous biomass from its high in the Artr steppe cover type. Values for each component that were used to make the fuel model can be found in Appendix II.

The downward trend of total fuels and fuel bed depth initiate as succession continues from W1 Artr to W2 Artr with declines of 31% and 29%, respectively. A reduction in total shrub biomass by 32% accounts for nearly all of the reduction in fuels and fuel bed depth. Shrub biomass continues to decline as the cover types shift from W2 Artr to W4 Artr. However, the reduction in shrub total biomass (45%) is mitigated by a sharp increase in litter (440%). Litter in the W4 Artr cover type is largely made up of western juniper needle cast found under the canopy. The overall result is a decline in total fuels (10%) and fuel bed depth (57%). At the final successional stage, W5 Artr, a total fuels increase of 20% was primarily composed of a large increase in downed dead woody material mainly from dead mountain-mahogany. Fuel bed depth continued to decrease by 69% to a low at 0.4 cm.

The low sagebrush cover type also exhibits changes in fuels that follow encroachment and successional change (Figure 7). The W4 successional stage has been omitted from the low sagebrush cover type due to a lack of available sampling locations, but it appears to be similar to the W2 cover type. Miller et al. (2000) indicated that herbaceous cover did not change between early western juniper stands and stands with maximum cover, making it difficult to distinguish between the two cover types. There is an increase in total fuels throughout the majority of the successional stages except for the shift to W5 when there is a decline. A 90% increase in total fuel weight from steppe to W1 is followed by another 3% increase for W2. The only decline is observed between W2 and W5, with a 47% reduction in total fuels. The majority of the increase in total weight and fuel bed depth can be attributed to the increase in shrub biomass. There is a simultaneous increase in herbaceous biomass as well. The fuel bed depth follows total fuel weight closely; the only decline is in the shift from W2 to W5 (Table 1).

When total fuel weight and fuel bed depth for the mountain big sagebrush and low sagebrush encroachment and successional cover types were compared, it is apparent that they did not follow the same trends. The dissimilarities are related to the differing reactions of the sagebrush component to western juniper encroachment and succession. In the low sagebrush cover types the sagebrush component persisted in the mid-successional stages whereas it declines in the mountain big sagebrush cover types with advancing succession.

The mountain big sagebrush and low sagebrush cover type fuel models differed from the values seen in the stylized fuel models. Fuel model 2 (sagebrush and grass) was compared to the steppe and W1 cover types and fuel model 6 (sagebrush and juniper) was compared to the W2, W4, and W5 cover types because of the similarities in the descriptions presented by Anderson (1982). On average the 1- and 100-hour fuel loads were lower and the live fuel loads were higher than those seen in the stylized models. The 10-hour fuel loads were mixed between types, with the steppe and W1 cover types averaging higher fuel loads and the W2, W4, and W5 averaging lower fuel loads. The same pattern was seen in fuel bed depth with the steppe and W1 cover types averaging higher fuel bed depths and the W2, W4, and W5 averaging lower fuel bed depths.

The changes identified in fuel composition, total fuel weight, and fuel bed depth resulted in changes in modeled fire behavior. For mountain big sagebrush, flame length (FL) and rate of spread (ROS) increased between the steppe and W1 cover types and then declined throughout the remaining successional stages, similar to changes observed in the 10-hour and live fuel loading (Figure 6). Flame lengths for Steppe ranged from 0.5 to 2 m with winds ranging from 0 to 40 kph at high fuel moisture conditions, which often occur during prescribed fire conditions (Figure 8). At low fuel moisture conditions, which often occur during wildland fire conditions, flame lengths reached 3.8 m (Figure 9). Because of the nearly linear increase in flame length with changing fuels moisture, the mean values in fuel moisture conditions will not be reported.

Along the successional gradient from Artr Steppe to W1, flame lengths increased as total fuel weight and fuel bed depth increased. Flame length averaged a 44% increase over steppe, with values ranging from 0.7 m at 0 kph to 3.7 m at 40 kph and a maximum flame length of 6.8 m at 40 kph and low fuel moisture conditions. Rate of spread averaged an 82% increase from steppe to W1 (Figures 10 & 11). Most of the increase was attributed to steppe reaching its modeled wind limit (the point when the model predicts there will no longer be an increase in FL or ROS with an increase in wind speed) (Andrews 1986) at a lower wind speed than that of W1 (Table 2). At the point where steppe reaches the modeled wind limit (11.0 kph) there is only a 6% difference in ROS between the two cover types (Figures 10 & 11). Due to the modeled wind limit steppe had a maximum ROS 61% lower than that of W1 at high fuel moisture. The differences between the two modeled ROS is even greater at low fuel moisture conditions with W1 having a 137% increase over steppe (Figure 11). The effects of the modeled wind limit are more pronounced when comparing ROS then in FL.

W1 had the highest FL and ROS for any of the mountain big sagebrush successional stages. W2, W4, and W5 averaged 38, 59, and 91% reductions, respectively, in FL at high fuel moisture conditions. Similarly, ROS decreases by an average of 49, 77, and 99% for W2, W4, and W5, respectively. Once again, wind limit plays a role in differences among successional stages.

The modeled fire behavior for low sagebrush cover types reflected the changes in fuel composition, total fuel weight, and fuel bed depth similar to those observed in the mountain big sagebrush cover types (Figures 12 & 13). Flame length increased between steppe and W2, first by an average of 130% from steppe to W1 and another 9% to W2, at high fuel moisture conditions. A 73% average reduction was observed from the high at W2 to the low at W5. Slightly lower rates of change are observed at low fuel moisture conditions due to the fuel model having higher wind limits.

Rate of spread had a pattern similar to that observed in the FL (Figures 14 & 15). ROS increased from Arar steppe to W2 by an average of 270% from steppe to W1 and another 12% to W2. The reduction in ROS from W2 to W5 was 80%. The percent change for ROS was similar at the low fuel moisture conditions even with the changing wind limits.

Mountain big sagebrush had higher FL and ROS than those observed in low sagebrush for the early-successional stages (steppe and W1), attributed to the greater biomass and height associated with mountain big sagebrush. In the mid- and late-successional cover types (W2, W4, and W5), low sagebrush exhibits higher FL and ROS. This can be explained by the retention of the sagebrush component in the later successional stages for low sagebrush cover types.

Of the fuel model parameters, fuel bed depth appeared to have the largest impact on FL and ROS in mountain big sagebrush (Figures 16 & 17). For example, the difference between W1 and W5 was a 25% reduction in total fuel and a 91% reduction in fuel bed depth leading to the 91% decrease in FL and 99% decrease in ROS.

Both mountain big sagebrush and low sagebrush cover types had lower predicted FL then those seen in the stylized fuel models. The ROS for the mountain big sagebrush were lower then those predicted for the stylized models for the steppe, W4, and W5 and higher for the W1 and W2. The W2 was the only low sagebrush cover type that consistently had a higher ROS than the stylized models.

On the landscape, western juniper encroachment and succession caused shifts in fuel composition, total fuel load, and fuel bed depth resulting in variations in FL and ROS that affected fire size. With the use of FARSITE, five fires were started randomly in each of the encroachment and successional cover types across the Owyhee landscape. Total burned area ranged from 0.14 to 248.08 ha over the 6-hour burn period (Table 3 and Appendix III). The encroachment and successional stages were grouped into early- (steppe, mid shrub, and meadow), mid- (W1 and W2) and late- (W4, W5, Cele, Rock, and Aspen) successional stages. Cele, Rock, and Aspen were added to the late-successional stage because of the age of the western juniper component and similarities in fire behavior. The percent cover of each successional group within the fire perimeter and a 100-m buffer around the perimeter was compared to fire size. The early- successional group had no correlation with the resulting fire size (Figure 18). The predicted fire size increased as mid-successional stages increased in the landscape ($r^2 = 0.78$, Figure 19) and decreased as late-successional stages increased in the landscape ($r^2 = 0.76$, Figure 20).

Table 1. Description of fuel loads by size class and fuel bed depth for fuel models created from collected data averages.

	Fuel loading (Mton / ha)				
Cover type	1-hour	10-hour	100-hour	Live	Fuel bed depth (cm)
Artr steppe	1.39	1.10	0.48	0.45	39.4
W1 Artr	1.96	1.70	1.22	0.65	44.2
W2 Artr	1.41	1.28	0.63	0.51	31.2
W4 Artr	1.74	0.67	0.68	0.35	13.3
W5 Artr	1.50	0.30	2.19	0.15	4.1
Arar steppe	0.90	0.75	0.16	0.34	15.0
W1 Arar	1.56	1.45	0.42	0.66	20.3
W2 Arar	1.66	1.57	0.27	0.72	21.2
W5 Arar	1.20	0.44	0.43	0.16	7.2

Table 2. Modeled wind limit in kph. Wind limit is the point when the model predicts there will no longer be an increase in FL or ROS with an increase in wind speed.

	Fuel moisture (%)		
Cover type	Low	Medium	High
Artr steppe	20.1	17.3	15.3
W1 Artr	30.7	26.6	23.9
W2 Artr	21.8	18.9	16.7
W4 Artr	22.6	19.2	16.3
W5 Artr	11.8	9.9	8.6
Arar steppe	14.3	12.3	11
W1 Arar	27.4	23.9	21.3
W2 Arar	29.2	25.5	22.8
W5 Arar	15	12.7	10.8

Table 3. Description of fires started in 90 m^2 area of each cover type comparing percent cover of successional stage to the resulting FARSITE 6-hour fire size. Averages are of the five trials for each cover type.

Cover type	Percent cover of successional stages									Mean fire area (ha)		
	Early			Mid			Late					
	Avg.	Max	Min	Avg.	Max	Min	Avg.	Max	Min	Avg.	Max	Min
Arar Steppe	41	91	8	31	58	9	30	74	0	68	144	12
Artr Steppe	43	59	31	28	49	5	33	67	5	107	172	33
W1 Arar	28	53	11	48	66	31	27	41	7	143	248	41
W1 Artr	31	41	16	40	48	30	30	45	12	134	209	93
W2 Arar	51	52	13	79	68	24	77	59	17	181	178	25
W2 Artr	27	42	18	39	56	13	38	80	11	90	170	26
W4 Artr	21	32	8	7	33	0	87	100	45	5	7	2
W5 Arar	13	21	6	8	22	1	84	97	64	4	8	2
W5 Artr	11	25	4	1	2	0	94	98	90	0	0	0

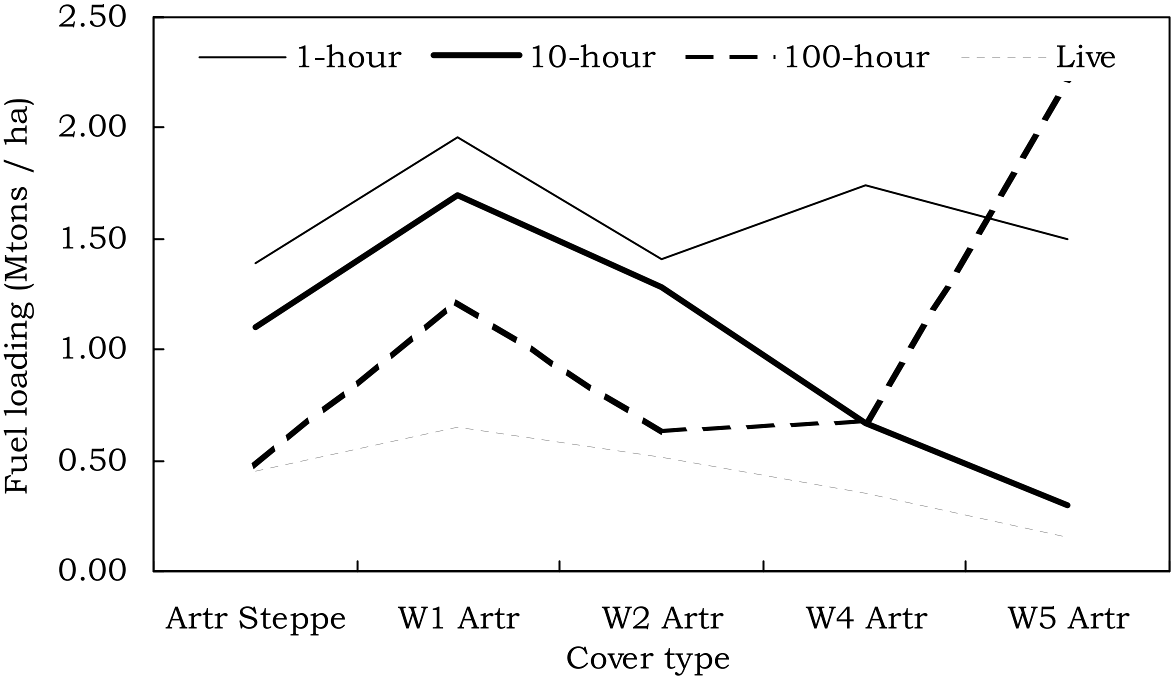

Fig. 4. Changes in fuel loading associated with western juniper encroachment and advancing succession in mountain big sagebrush cover types.

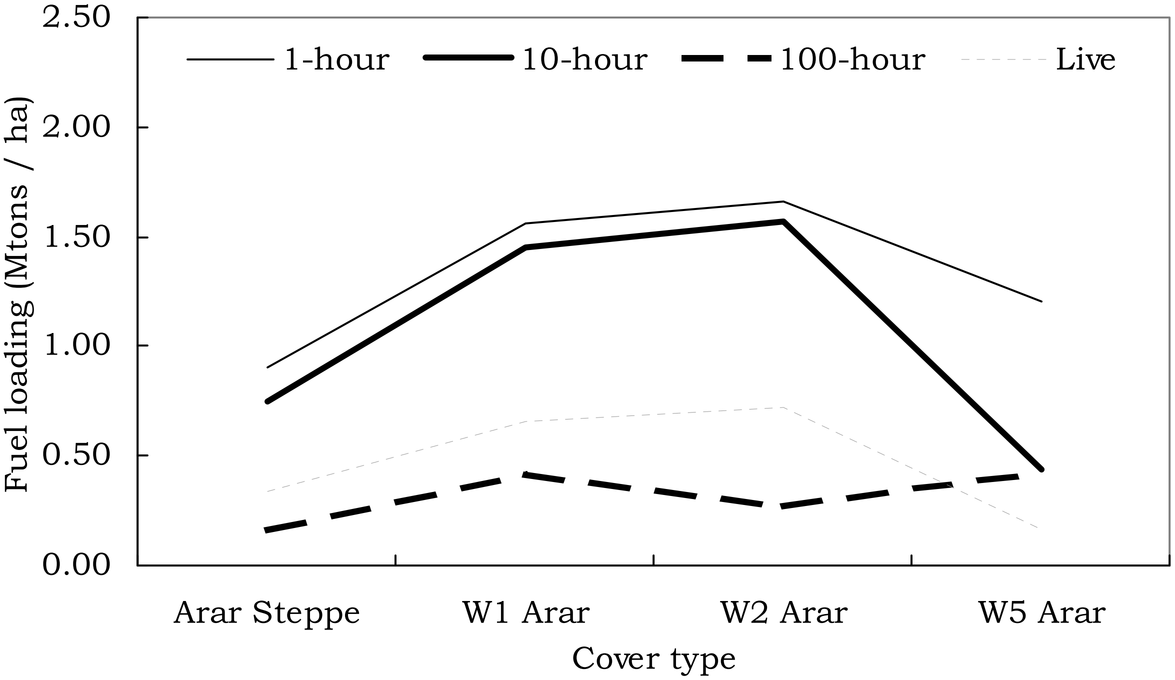

Fig. 5. Changes in fuel loading associated with western juniper encroachment and advancing succession in low sagebrush cover types.

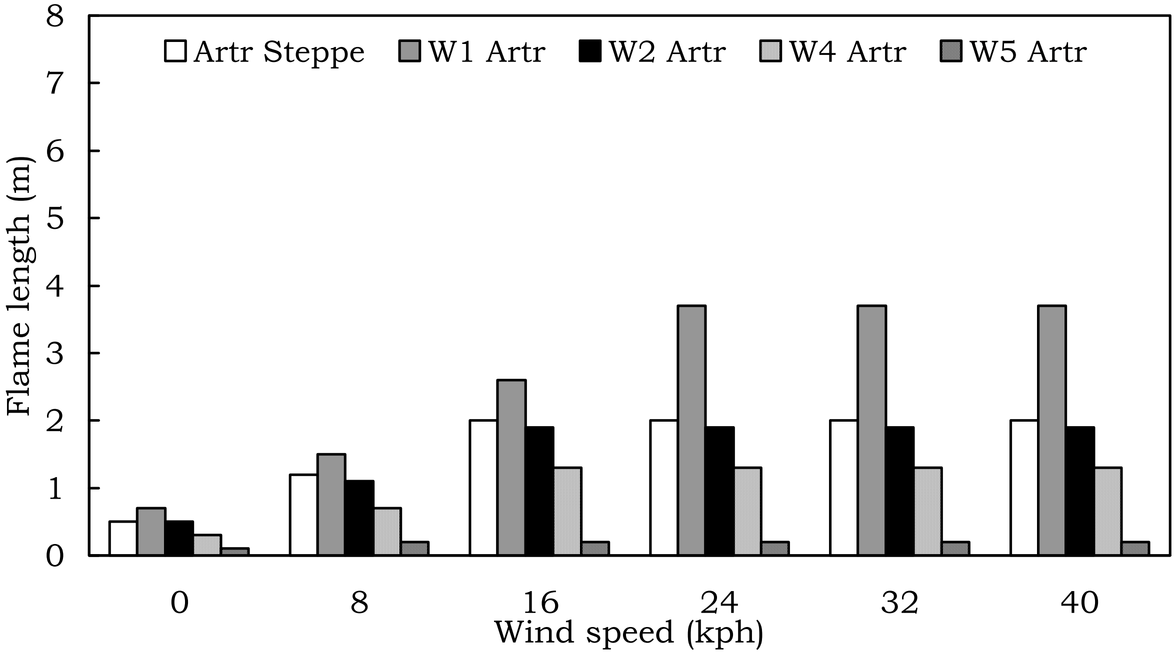

Fig. 6. Changes in flame length compared among mountain big sagebrush juniper encroachment and successional cover types at high fuel moisture conditions. Fuel moistures equal 12% for 1-hour, 13% for 10-hour, 14% for 100-hour, and 170% for live fuel.

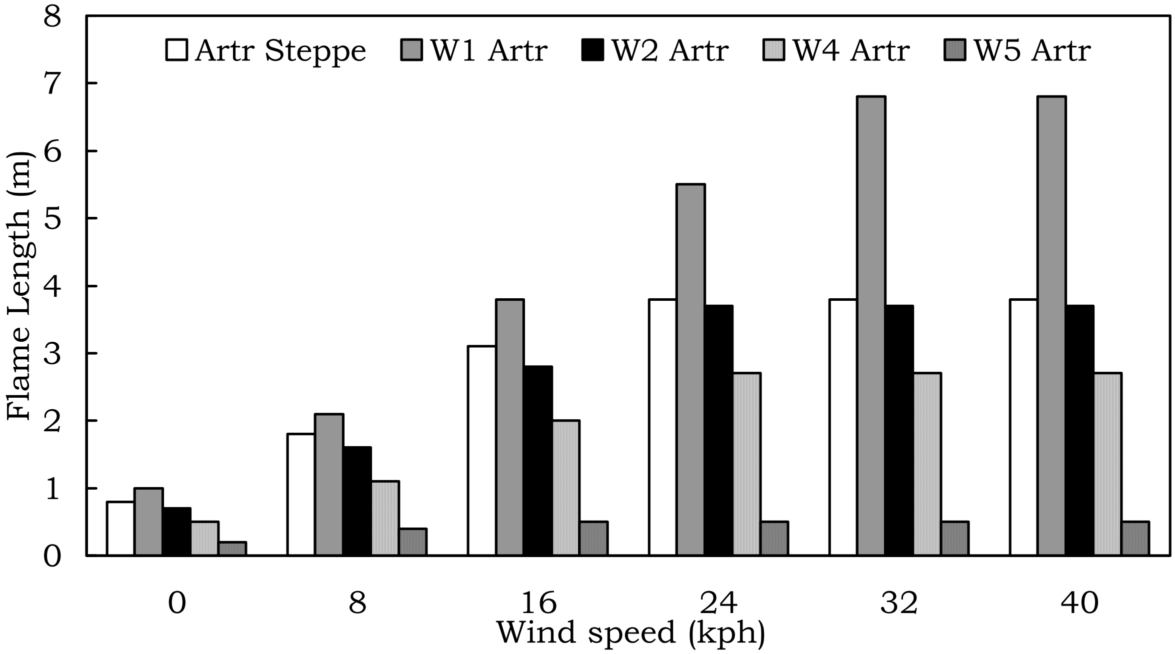

Fig. 7. Changes in flame length compared among mountain big sagebrush juniper encroachment and successional cover types at low fuel moisture conditions. Fuel moistures equal 3% for 1-hour, 4% for 10-hour, 5% for 100-hour, and 70% for live fuel.

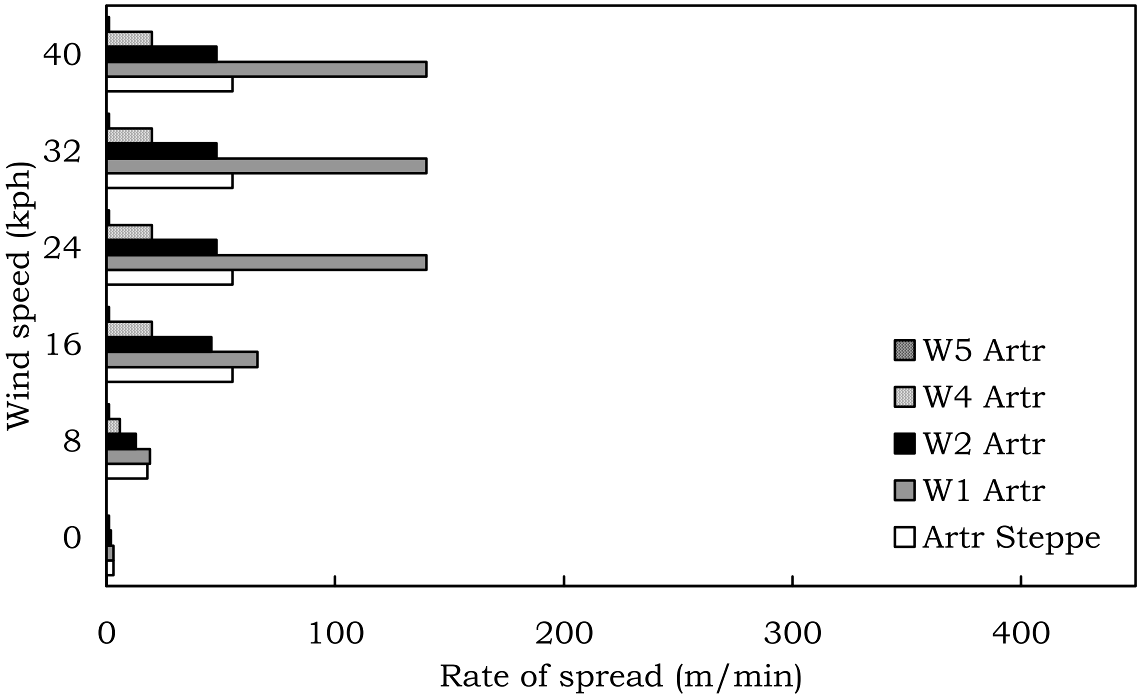

Fig. 8. Changes in rate of spread compared among mountain big sagebrush juniper encroachment and successional cover types at high fuel moisture conditions.

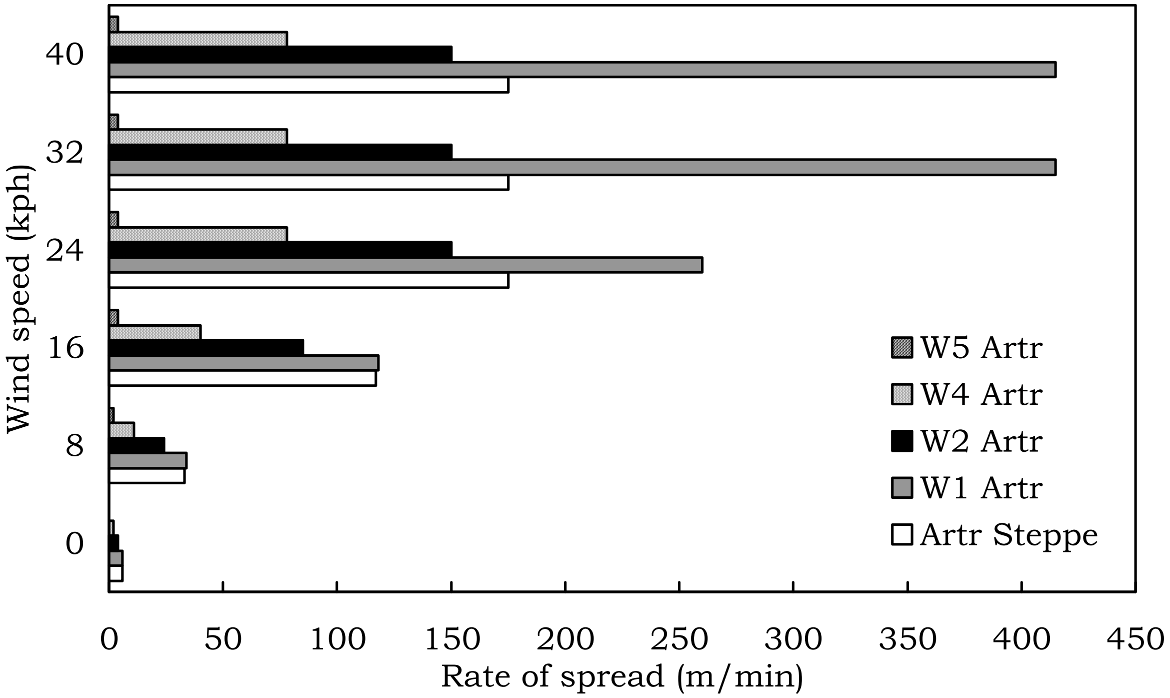

Fig. 9. Changes in rate of spread compared among mountain big sagebrush juniper encroachment and successional cover types at low fuel moisture conditions.

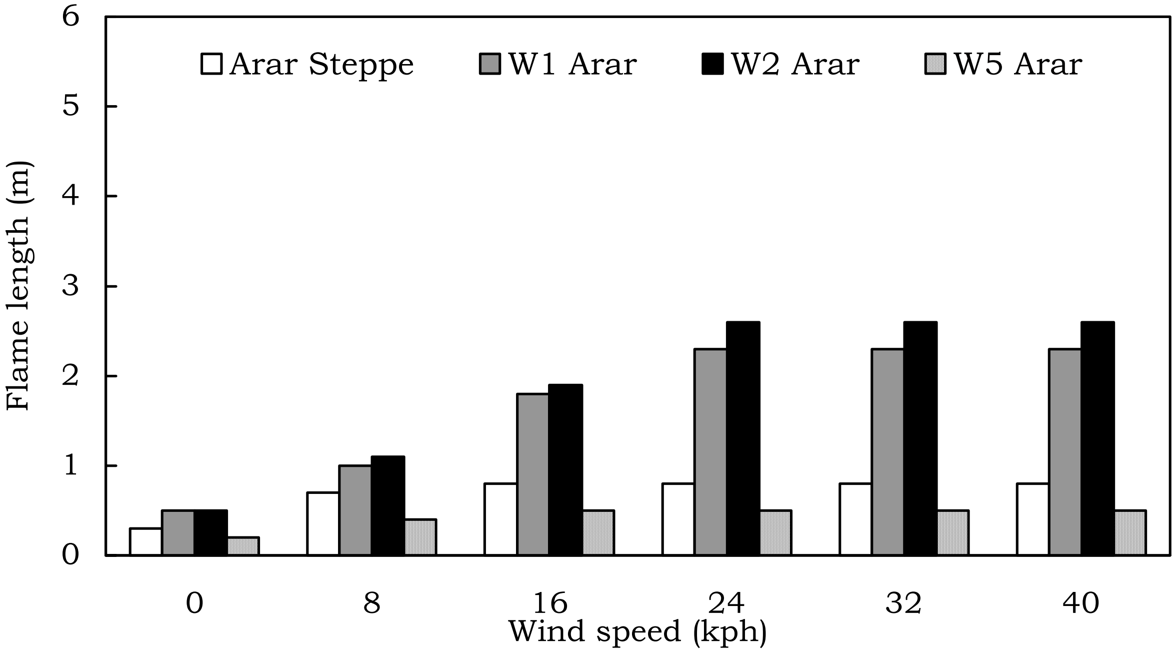

Fig. 10. Changes in flame length compared among low sagebrush juniper encroachment and successional cover types at high fuel moisture conditions. Fuel moistures equal 12% for 1-hour, 13% for 10-hour, 14% for 100-hour, and 170% for live fuel.

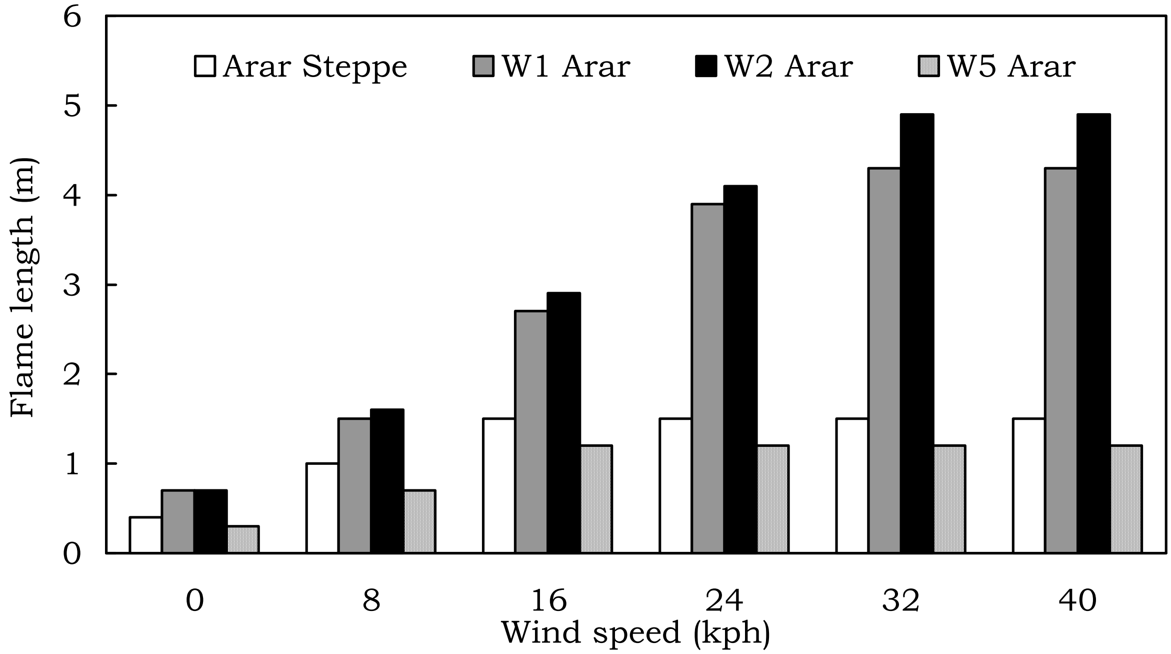

Fig. 11. Changes in flame length compared among low sagebrush juniper encroachment and successional cover types at low fuel moisture conditions. Fuel moistures equal 3% for 1-hour, 4% for 10-hour, 5% for 100-hour, and 70% for live fuel.

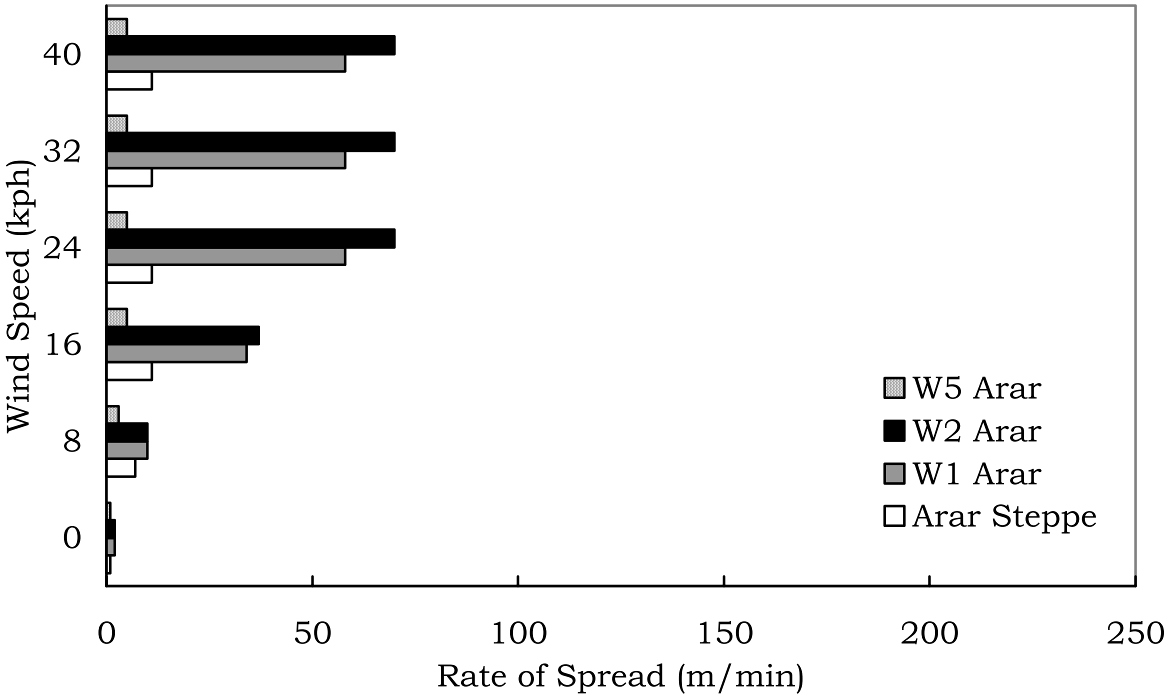

Fig. 12. Changes in rate of spread compared among low sagebrush juniper encroachment and successional cover types at high fuel moisture conditions.

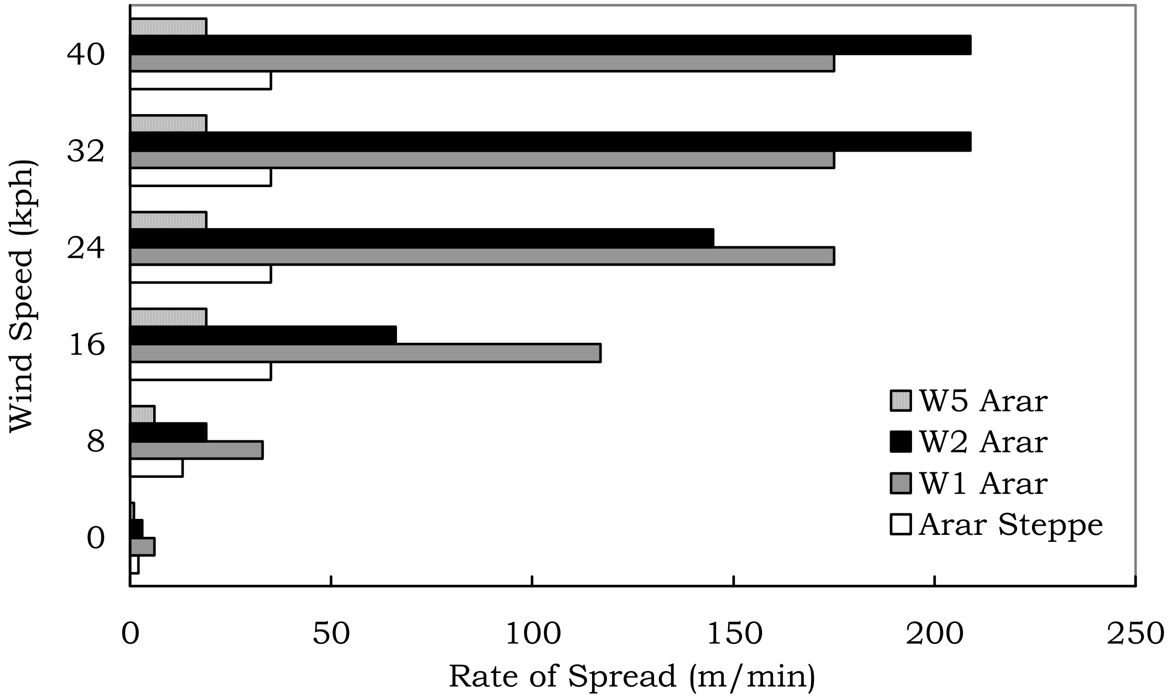

Fig. 13. Changes in rate of spread compared among low sagebrush juniper encroachment and successional cover types at low fuel moisture conditions.

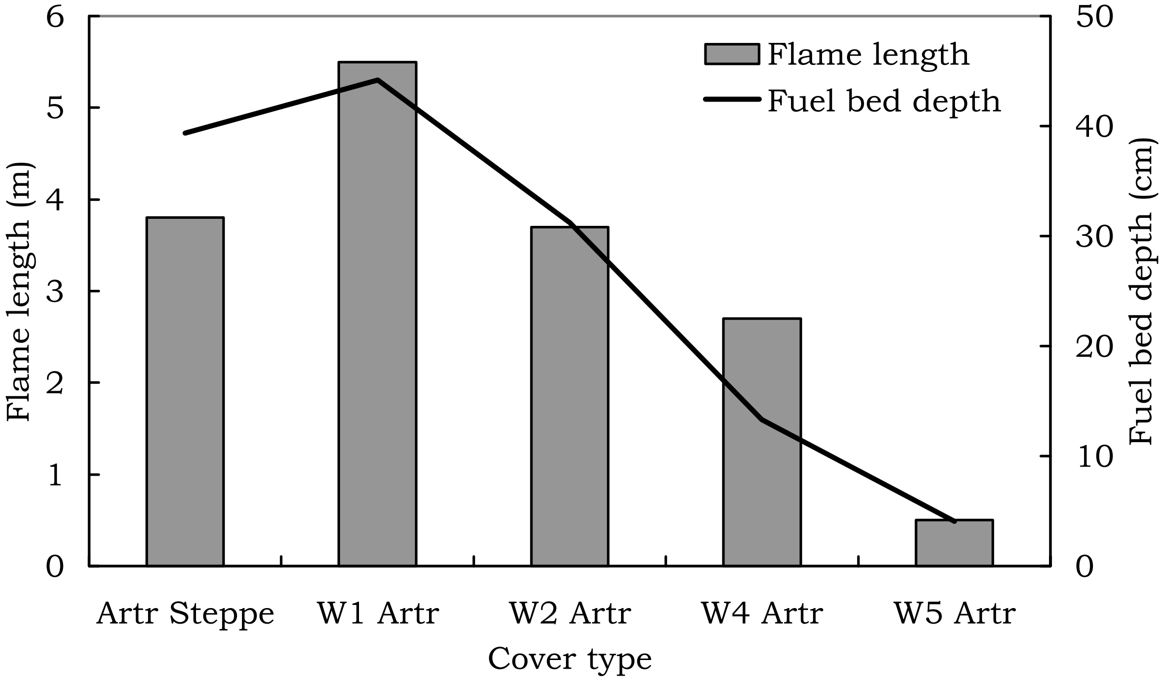

Fig. 14. Comparison of changes in flame length and fuel bed depth for mountain big sagebrush encroachment and successional stages.

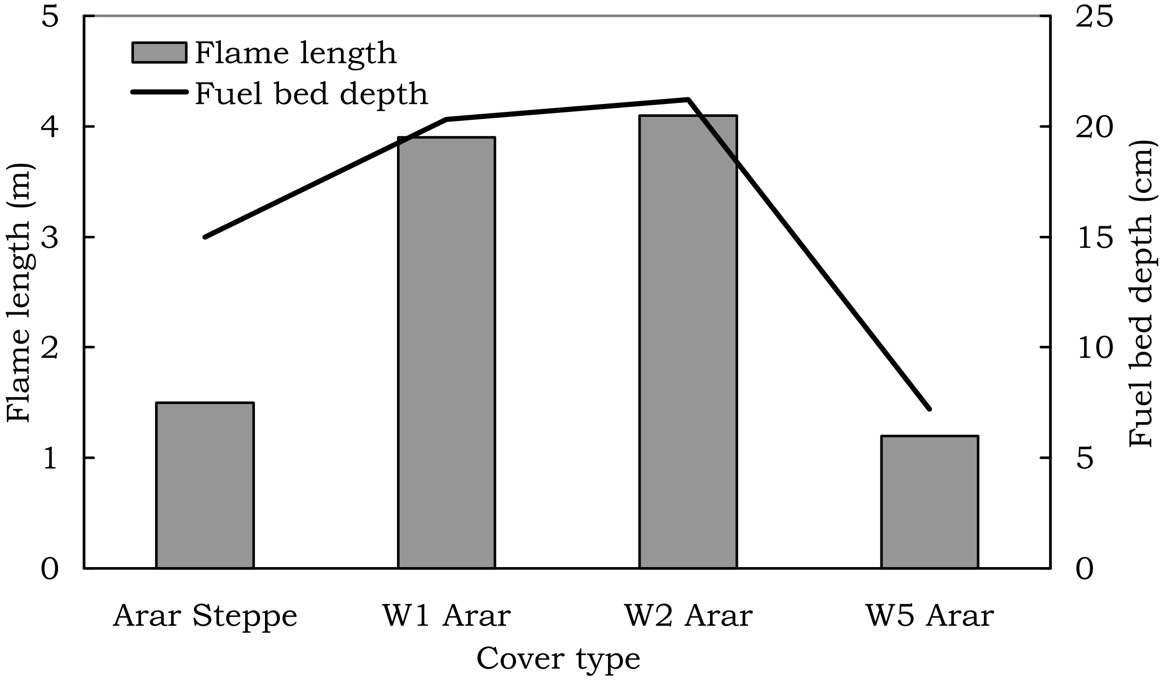

Fig. 15. Comparison of changes in flame length and fuel bed depth for low sagebrush encroachment and successional stages.

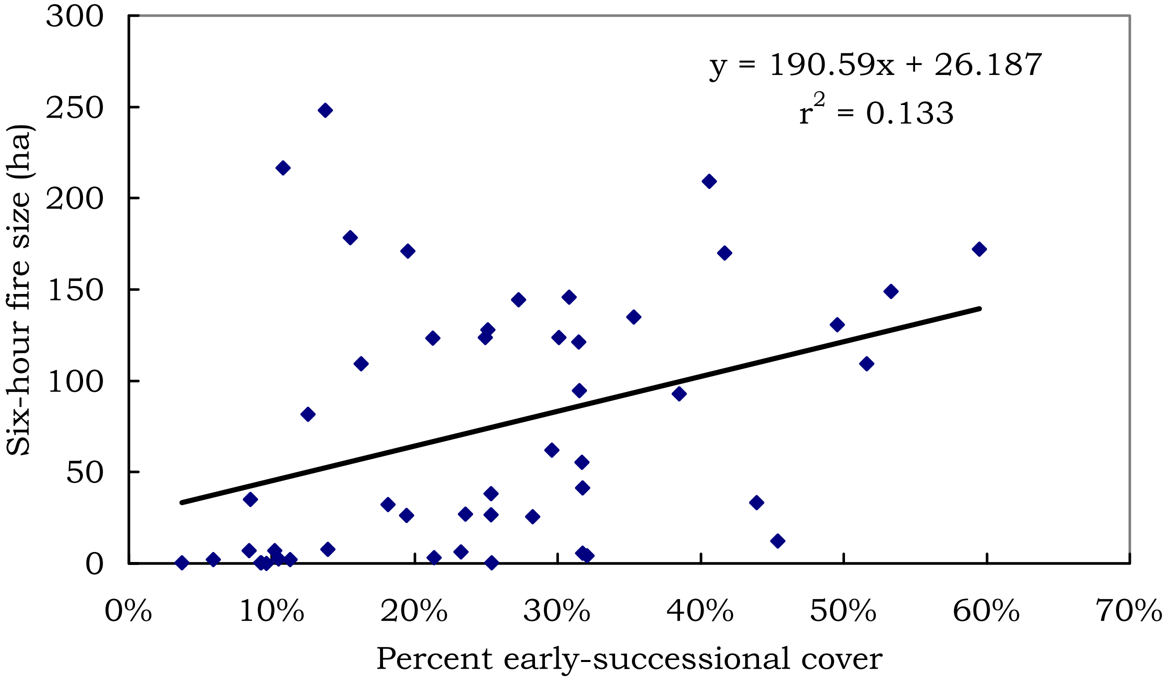

Fig. 16. Percent early-successional cover within the fire perimeter and adjacent area compared to total 6-hour fire size.

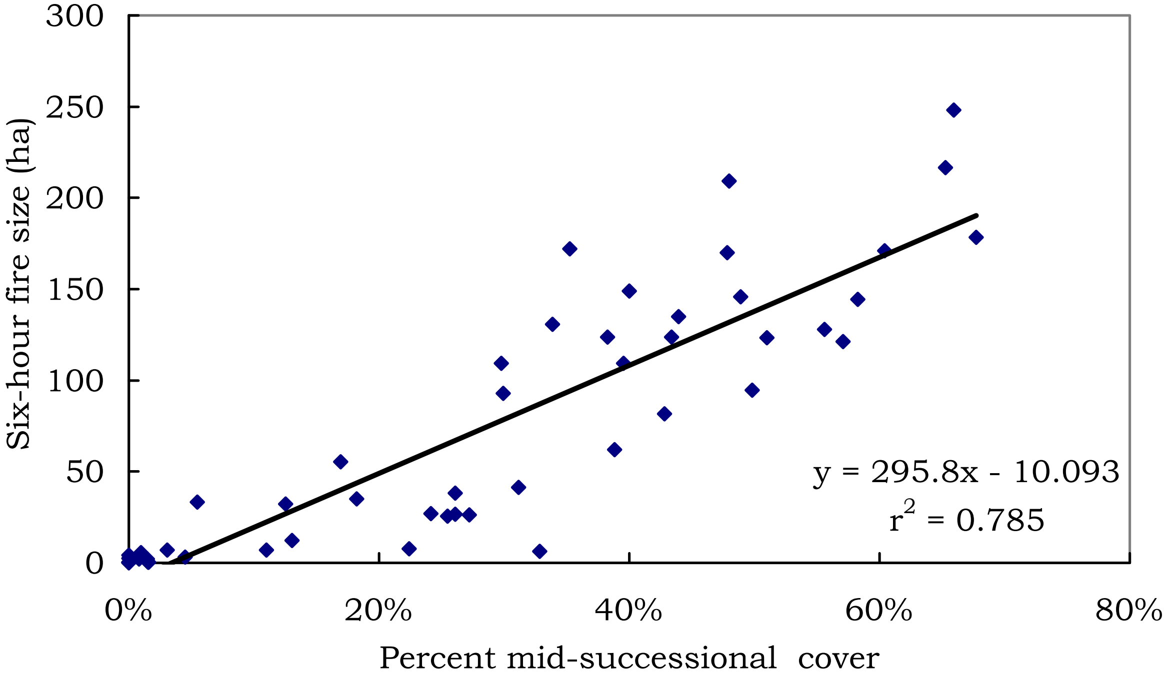

Fig. 17. Percent mid-successional cover within the fire perimeter and adjacent area compared to total 6-hour fire size.

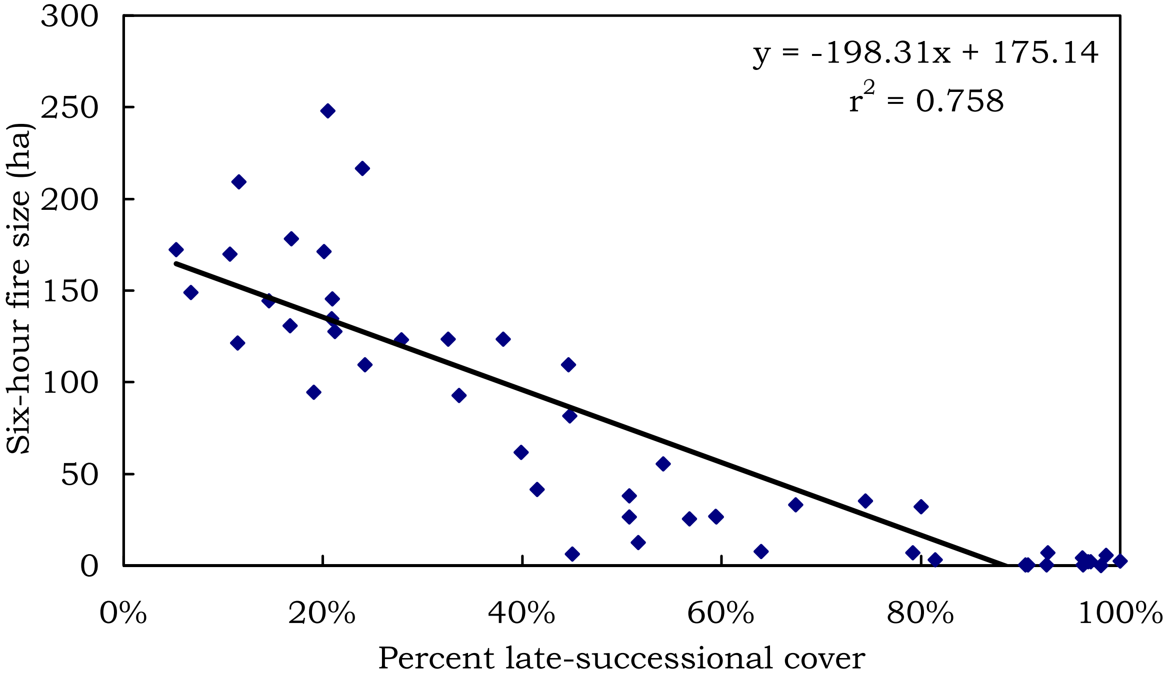

Fig. 18. Percent late-successional cover within the fire perimeter and adjacent area compared to total 6-hour fire size.

Herbaceous Reduction

Herbaceous biomass and height were adjusted to simulate grazing, resulting in a change in fire behavior. The greatest reduction in flame length (8 to 50%) for mountain big sagebrush at high fuel moisture conditions was observed at the 25% herbaceous biomass and corresponding 61% height reduction level (Figure 21). Predicted Artr steppe FL was reduced 25, 30, and 40%, respectively, when 25, 50, and 75% reduction levels are compared to no reduction. When compared between reduction levels (25 to 50, and 50 to 75%), a 7 and 14% reduction in flame length was observed.

For the mountain big sagebrush encroachment and successional cover type the changes in flame length are different for each cover type. W5 has the greatest reduction at 50% followed by steppe, W2, W1, and W4 at 25, 16, 14, and 8% at high fuel moisture conditions. As would be expected, changes in flame length are greater at the low fuel moisture conditions, ranging between 11 and 80% (Figure 22).

Similar results are observed for rates of spread in the mountain big sagebrush cover types (Figures 23 & 24). At high fuel moisture conditions, rates of spread decreased from 15 and 100%. Again, the highest average rate of decrease is at the 25% herbaceous biomass and 61% height reduction level. The W5 predicted rate of spread was zero for all levels of fuel reduction at both fuel moisture conditions.

Rates of change due to reduction in herbaceous biomass and height in the low sagebrush cover types are similar to those observed in mountain big sagebrush (Figures 25, 26, 27 & 28). The low sagebrush steppe cover type is different with its greatest changes in flame length and rate of spread occurring between the 25 and 50% reduction levels.

The effect that a reduction in herbaceous biomass and height has on overall fire size is indicated in Figure 29 (Arcview output). Total fire size was greatly reduced by the reduction of herbaceous biomass and height. At the 25% reduction rate, the decrease in fire size ranged from 25 to 73% as compared to no reduction. At 75%, the decrease from no reduction was as high as 88% for W5 Artr. Artr steppe fire size was reduced 78% at the 75% reduction level, but, there is only a 2% decrease in fire size from the 50% reduction level. The greatest decrease was usually observed with the first 25% reduction in herbaceous biomass and corresponding height (Table 4).

With the effects of simulated grazing applied, there is less correlation between fire size and age class of cover (Figures 30, 31, & 32). The mid-successional stage is highly correlated to the 6-hour fire size when the no reduction fuel model is used (r^2 = 0.78). The r^2 values decline (0.67 at 25%, 0.68 at 50%, and 0.66 at 75%) when the reduction models are used (Figures 33, 34, & 35). The late-successional stage had a similar decrease in r^2 and was lowest at 0.57 with the 75% reduction fuel model. There is no correlation of fire size and early-successional stages under any reduction model. The lack of correlation may be due to the differences in rates of spread for Artr steppe and Arar steppe. This could also be affected by the slow rate of spread observed in the herbaceous fuel dominated model, used to describe meadow and broadleaf riparian areas, at high fuel moisture conditions.

No one level of herbaceous utilization is evenly distributed across the landscape. Heterogeneous landscapes make it difficult to achieve uniform grazing. Likewise, no two plants will be utilized to the same degree because of animal selectivity. Furthermore, the levels of utilization and selectivity may vary across the landscape (Bailey et al. 1996, Heady and Child 1994). The fire behavior models assume that the fuels are uniformly distributed across the landscape, or at least within each pixel. As biomass reduction increases this assumption would become even more misleading, because there would be larger and more frequent areas with very little fuel. Continued biomass reduction can lead to a situation where fuels become increasingly discontinuous similar to those described by Agee (1993), where herbaceous material grazed out of the low sagebrush made it nearly fireproof.

Predicting fire size becomes more difficult because of the uneven use. When all of the reduction level fire sizes were compared across all successional stages, very little correlation was found. When the mid-successional stages are analyzed in this way, the r^2 value is 0.39 (Figure 36). Similarly, the r^2 value for the late-successional stage is 0.35 (Figure 37).

Table 4. Description of fires started in 90 m^2 area of cover types under different reductions levels comparing percent cover of successional stage to the resulting FARSITE 6-hour fire size. Averages are of the trials for each cover type.

Cover type	Percent cover of successional stages									Mean fire area (ha)		
	Early			Mid			Late					
	Avg.	Max	Min	Avg.	Max	Min	Avg.	Max	Min	Avg.	Max	Min
Artr Steppe												
No Reduction	37	50	24	30	49	5	30	67	5	**150**	367	33
25% Reduction	43	56	24	28	51	6	25	61	2	**67**	151	21
50% Reduction	47	58	34	26	42	8	22	56	2	**43**	97	15
75% Reduction	48	61	29	26	45	9	21	55	2	**36**	78	13
W1 Artr												
No Reduction	27	33	20	39	48	30	27	43	12	**164**	220	92
25% Reduction	23	37	9	52	74	37	19	36	7	**83**	121	43
50% Reduction	26	35	2	44	50	37	23	37	5	**66**	100	36
75% Reduction	26	36	20	44	49	38	22	36	4	**57**	91	34
W2 Artr												
No Reduction	13	15	9	31	55	13	56	80	29	**118**	295	26
25% Reduction	12	16	9	35	60	16	54	76	22	**57**	142	12
50% Reduction	11	14	9	38	65	17	53	75	20	**44**	108	10
75% Reduction	11	14	8	38	67	17	52	75	18	**38**	92	9
W4 Artr												
No Reduction	8	10	5	1	2	0	95	99	0	**9**	17	4
25% Reduction	8	10	5	1	2	0	95	99	0	**6**	13	3
50% Reduction	8	10	5	1	1	0	96	99	0	**5**	11	2
75% Reduction	8	10	5	1	1	0	96	99	0	**5**	10	2
W5 Artr												
No Reduction	23	24	22	1	2	0	92	93	91	**0**	0	0
25% Reduction	24	24	23	1	2	0	94	96	92	**0**	0	0
50% Reduction	28	29	27	1	2	0	93	95	90	**0**	0	0
75% Reduction	28	29	27	1	2	0	93	95	90	**0**	0	0

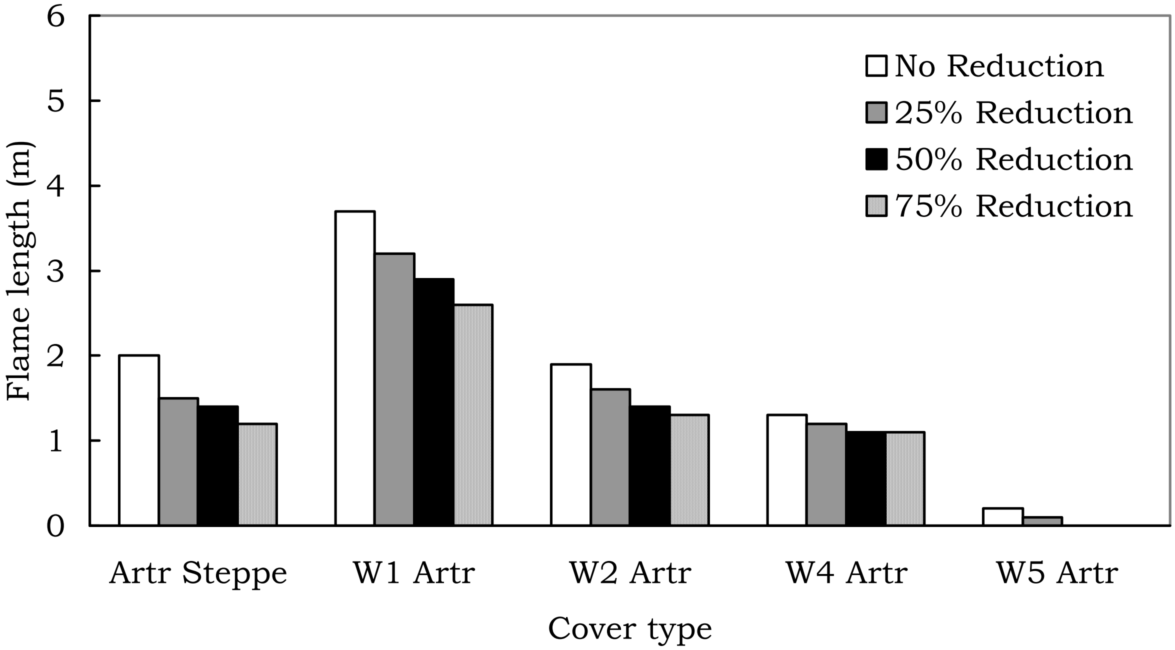

Fig. 19. Herbaceous biomass and height reduction comparison for mountain big sagebrush cover types flame length at high fuel moisture conditions.

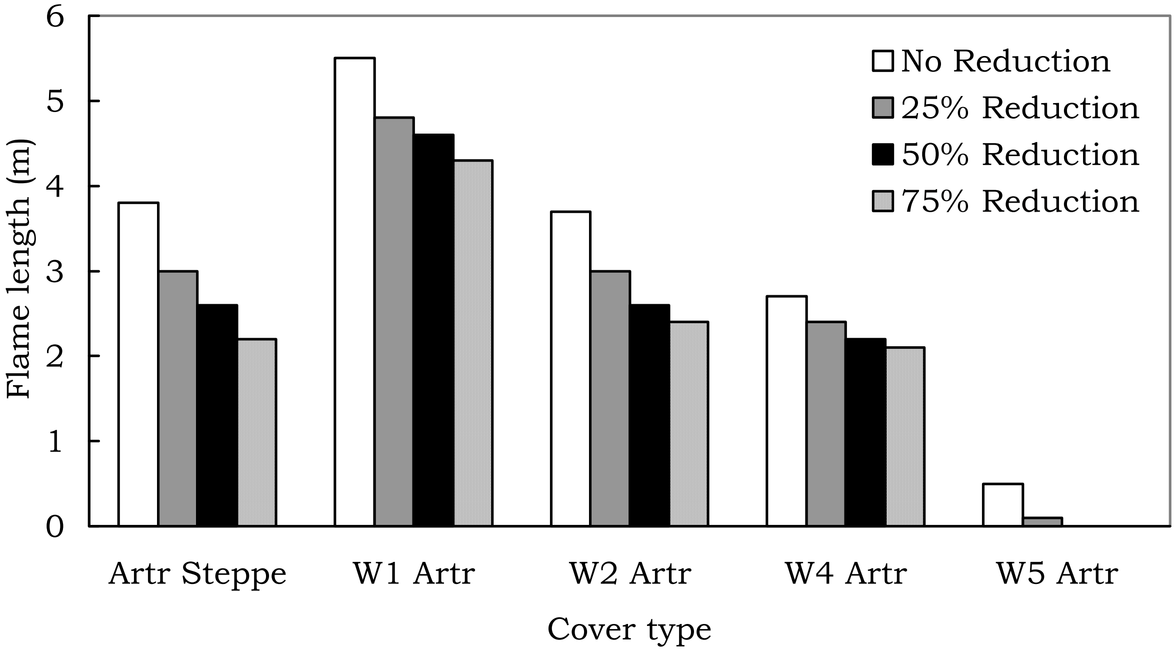

Fig. 20. Herbaceous biomass and height reduction comparison for mountain big sagebrush cover types flame length at low fuel moisture conditions.

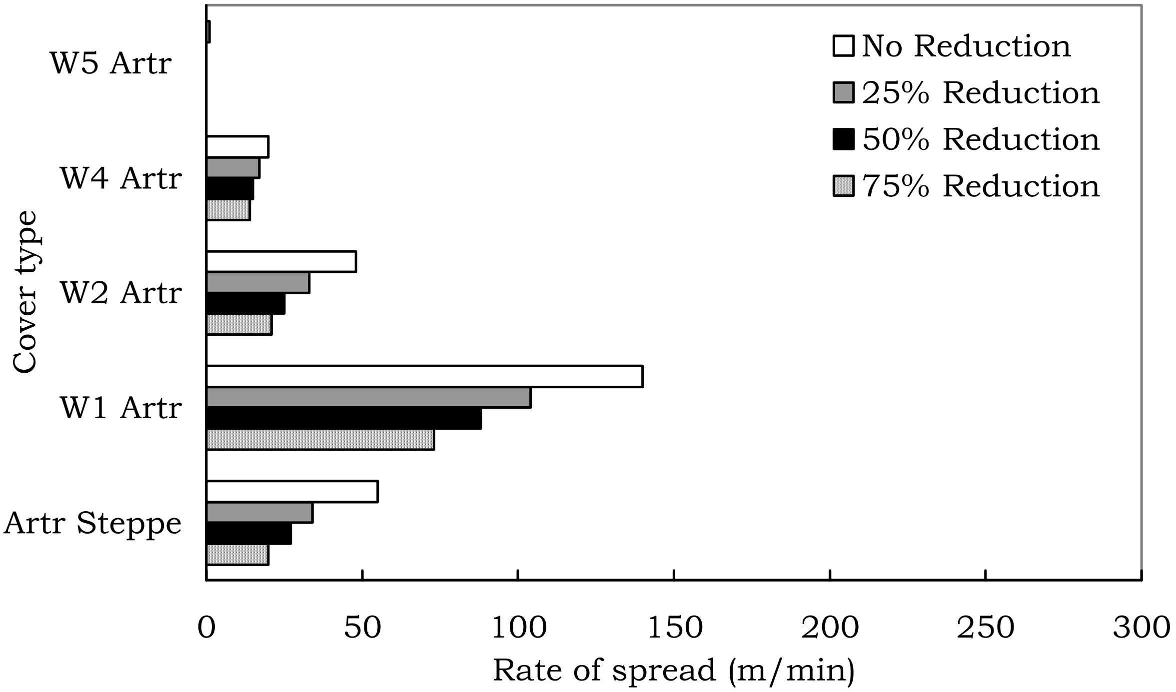

Fig. 21. Herbaceous biomass and height reduction comparison for mountain big sagebrush cover types rate of spread at high fuel moisture conditions.

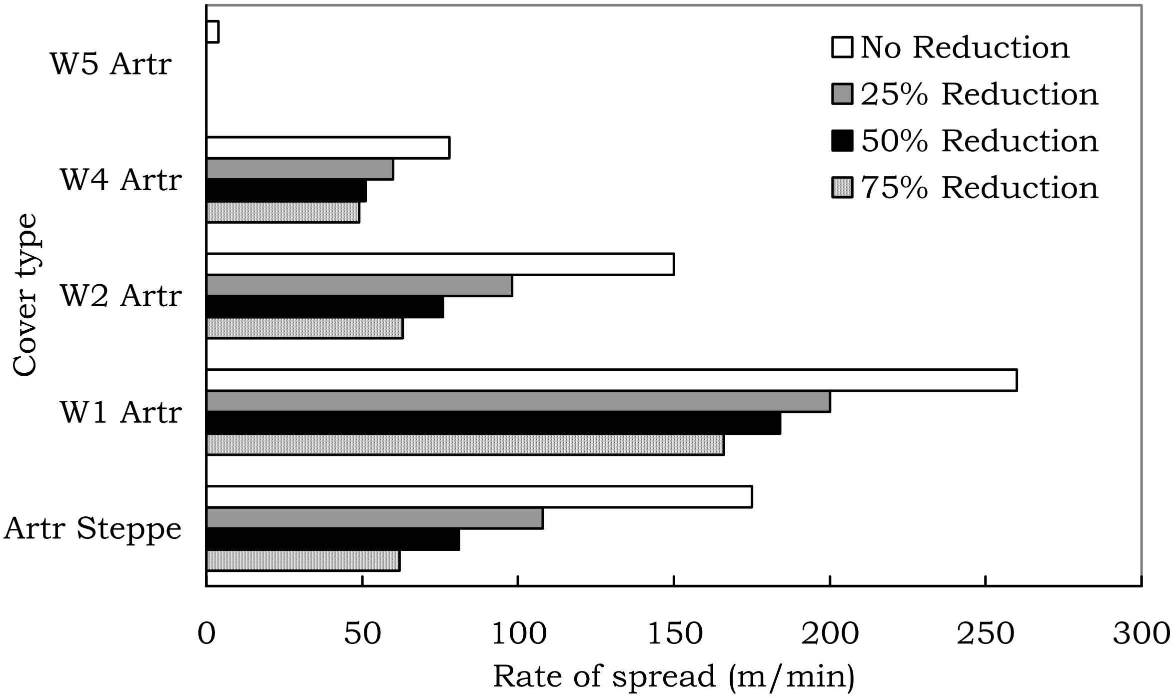

Fig. 22. Herbaceous biomass and height reduction comparison for mountain big sagebrush cover types rate of spread at low fuel moisture conditions.

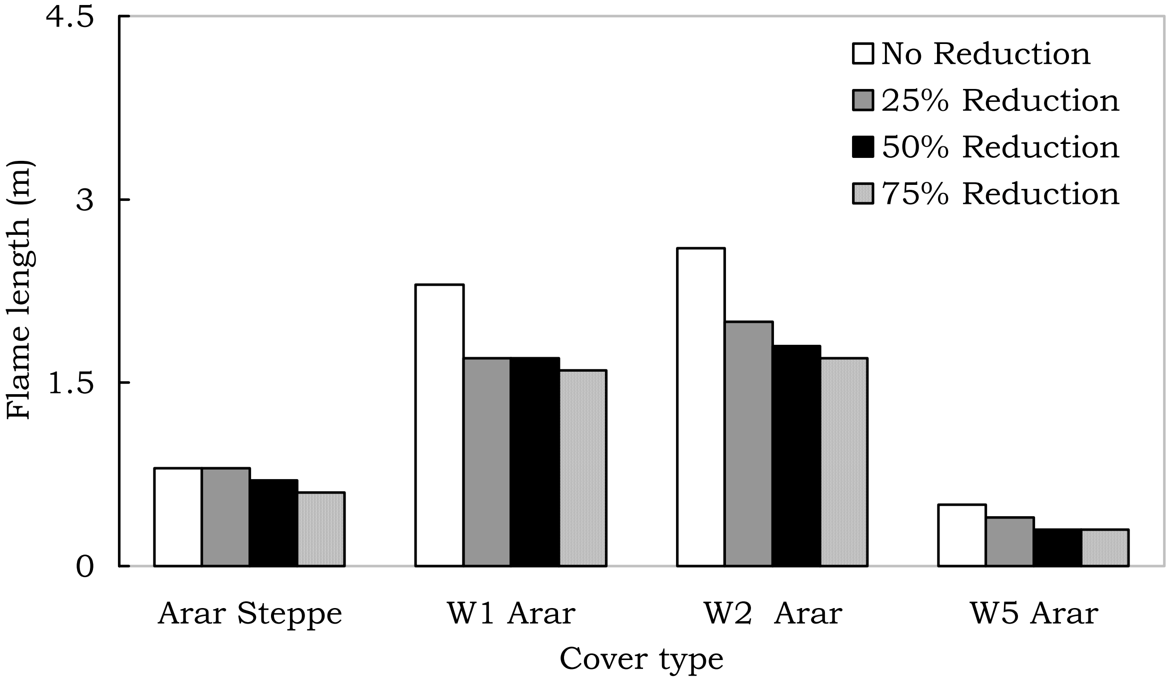

Fig. 23. Herbaceous biomass and height reduction comparison for low sagebrush cover types flame length at high fuel moisture conditions.

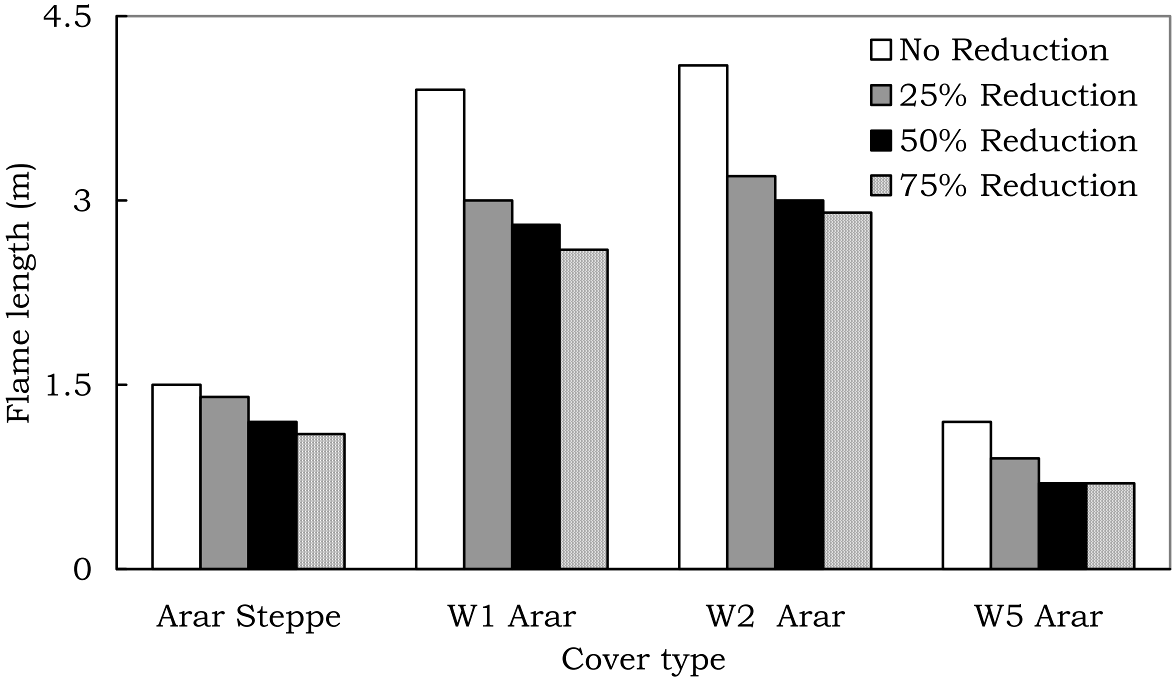

Fig. 24. Herbaceous biomass and height reduction comparison for low sagebrush cover types flame length at low fuel moisture conditions.

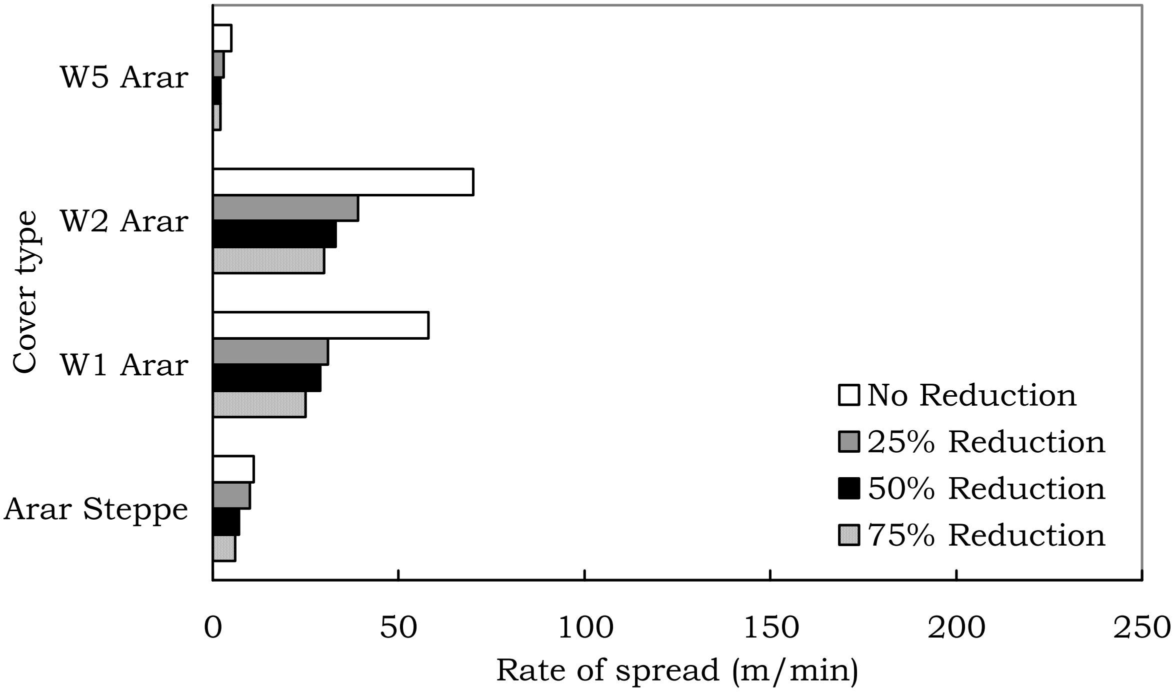

Fig. 25. Herbaceous biomass and height reduction comparison for low sagebrush cover types rate of spread at high fuel moisture conditions.

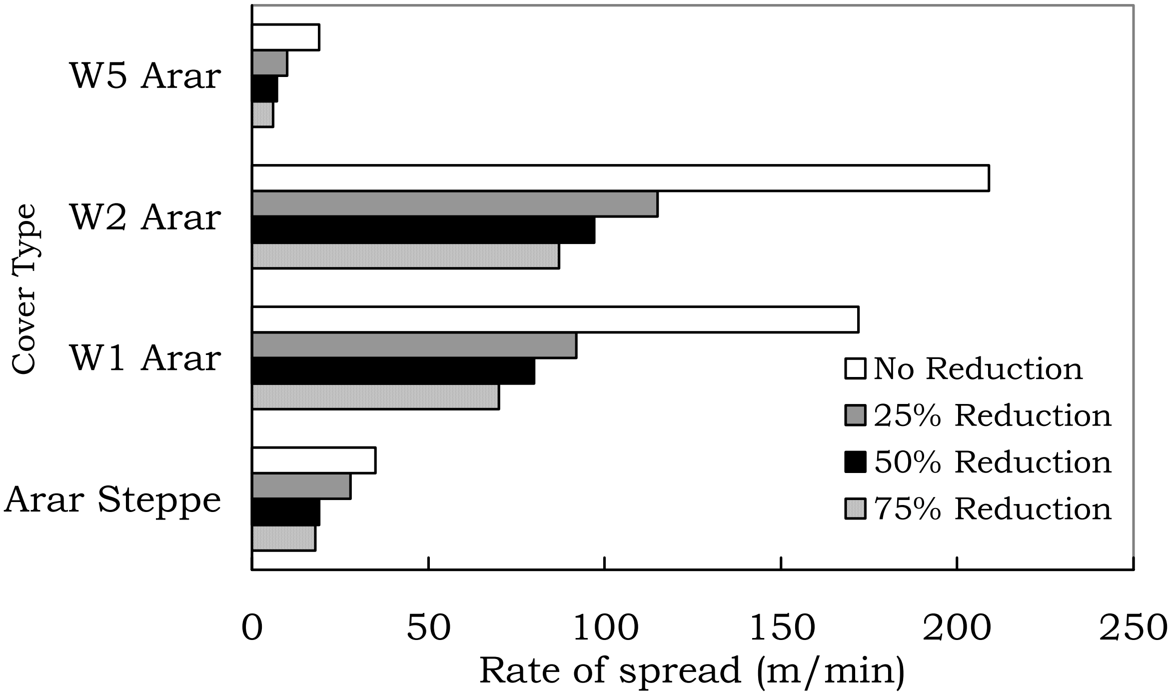

Fig. 26. Herbaceous biomass and height reduction comparison for low sagebrush cover types rate of spread at low fuel moisture conditions.

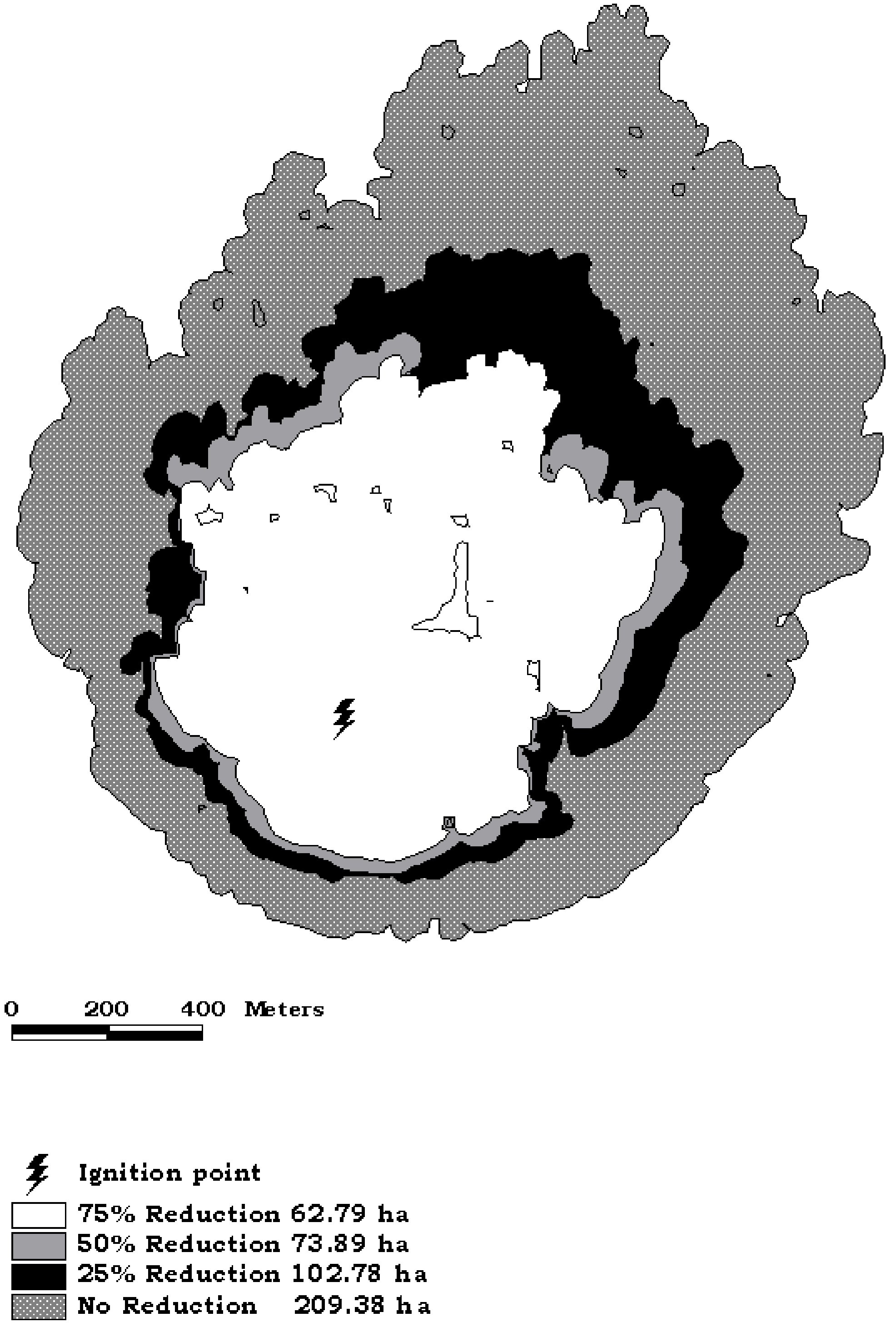

Fig. 27. Comparison of reduction in levels 6-hour fire size for landscapes dominated by W1 Artr. Spots within fire perimeters are remnant enclaves from fire advances.

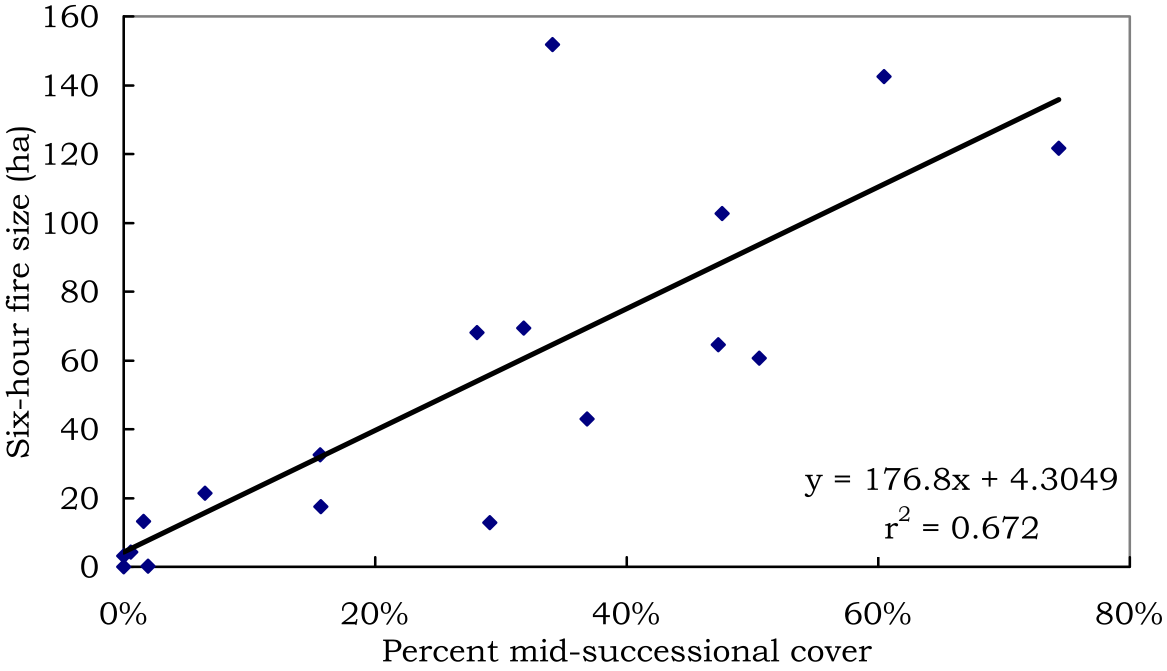

Fig. 28. Effect of 25% biomass reduction on percent mid-successional cover compared to total 6-hour fire size.

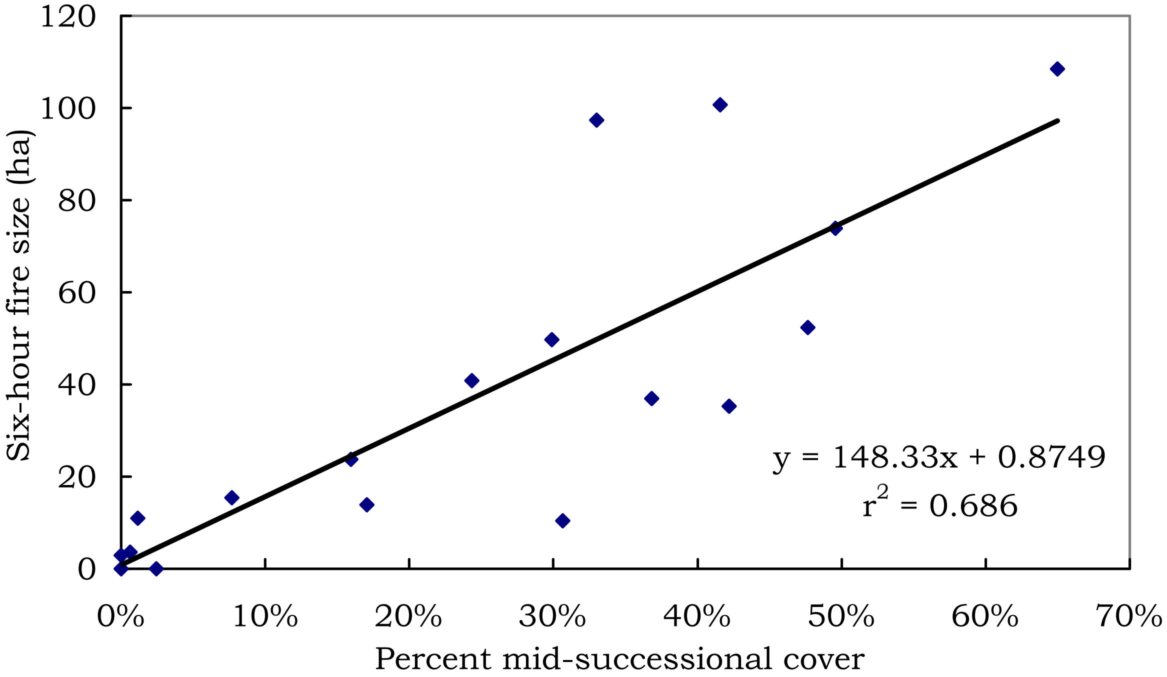

Fig. 29. Effect of 50% biomass reduction on percent mid-successional cover compared to total 6-hour fire size.

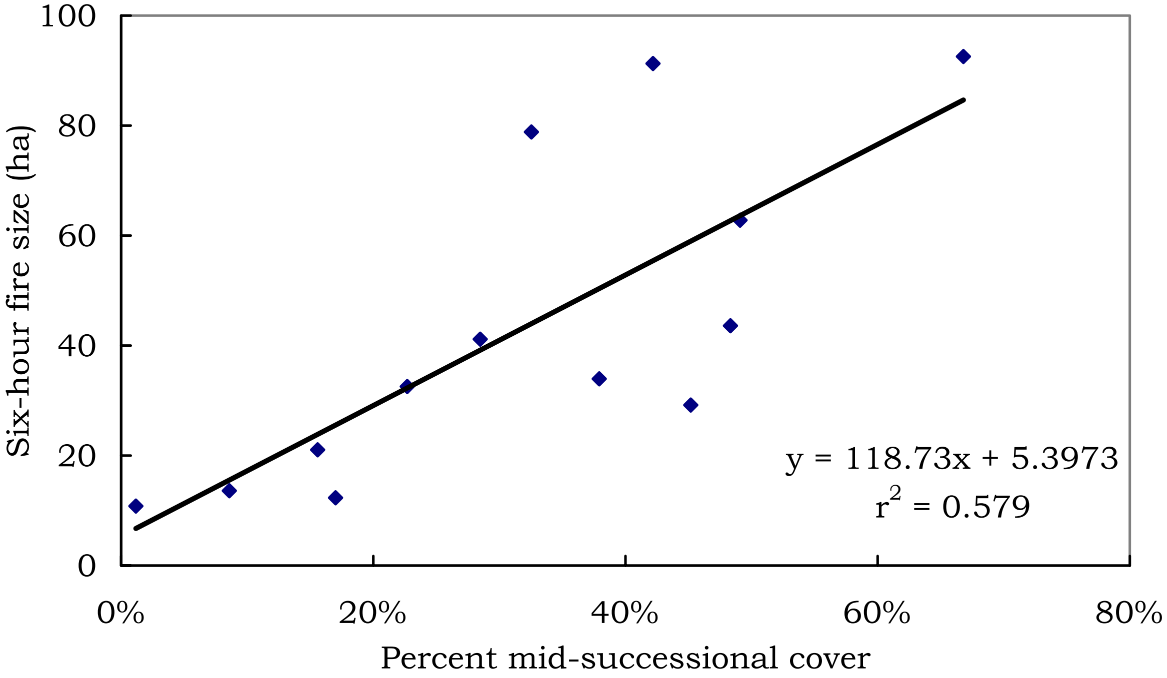

Fig. 30. Effect of 75% biomass reduction on percent mid-successional cover compared to total 6-hour fire size.

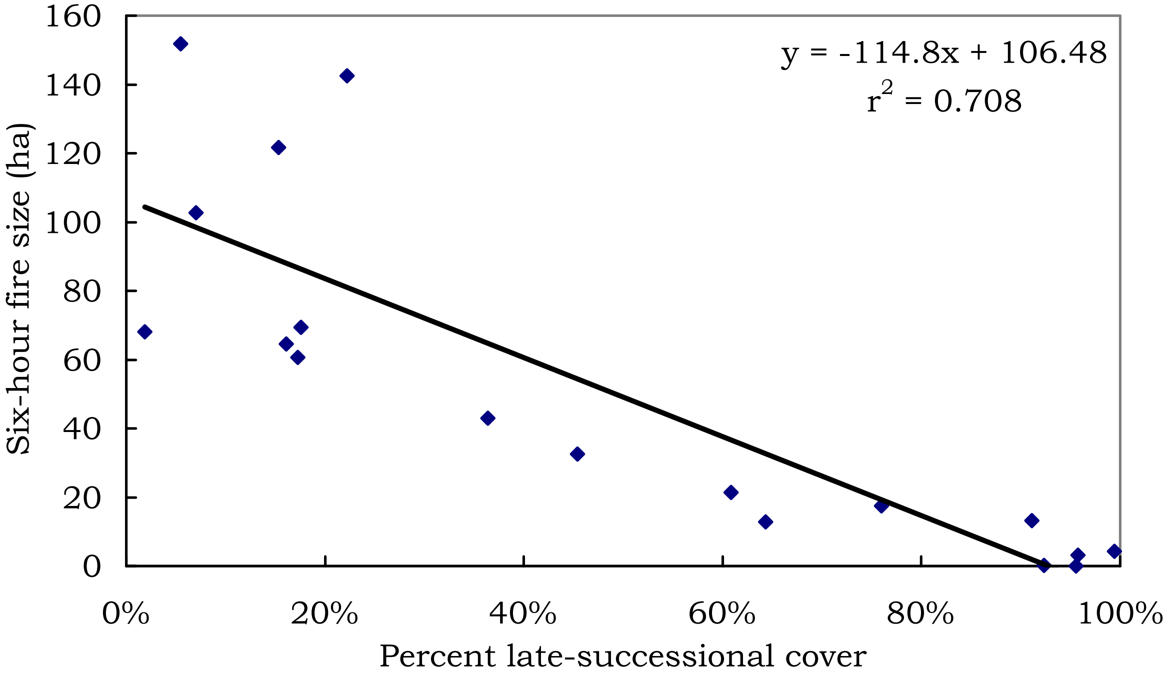

Fig. 31. Effect of 25% biomass reduction on percent late-successional cover compared to total 6-hour fire size.

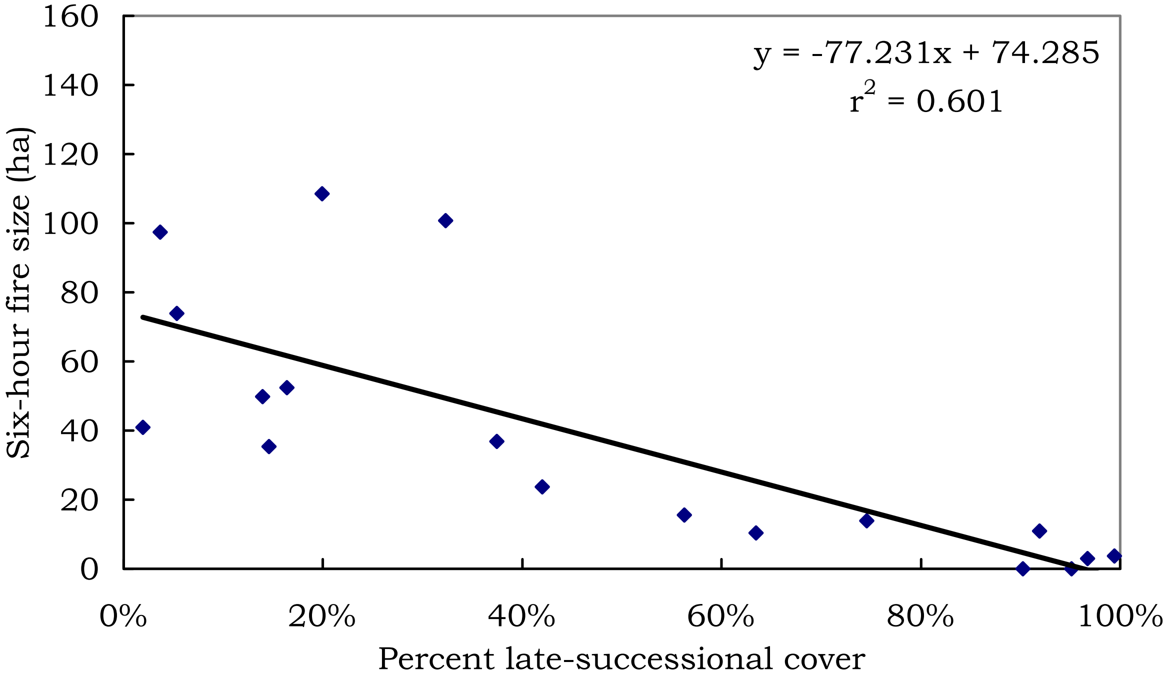

Fig. 32. Effect of 50% biomass reduction on percent late-successional cover compared to total 6-hour fire size.

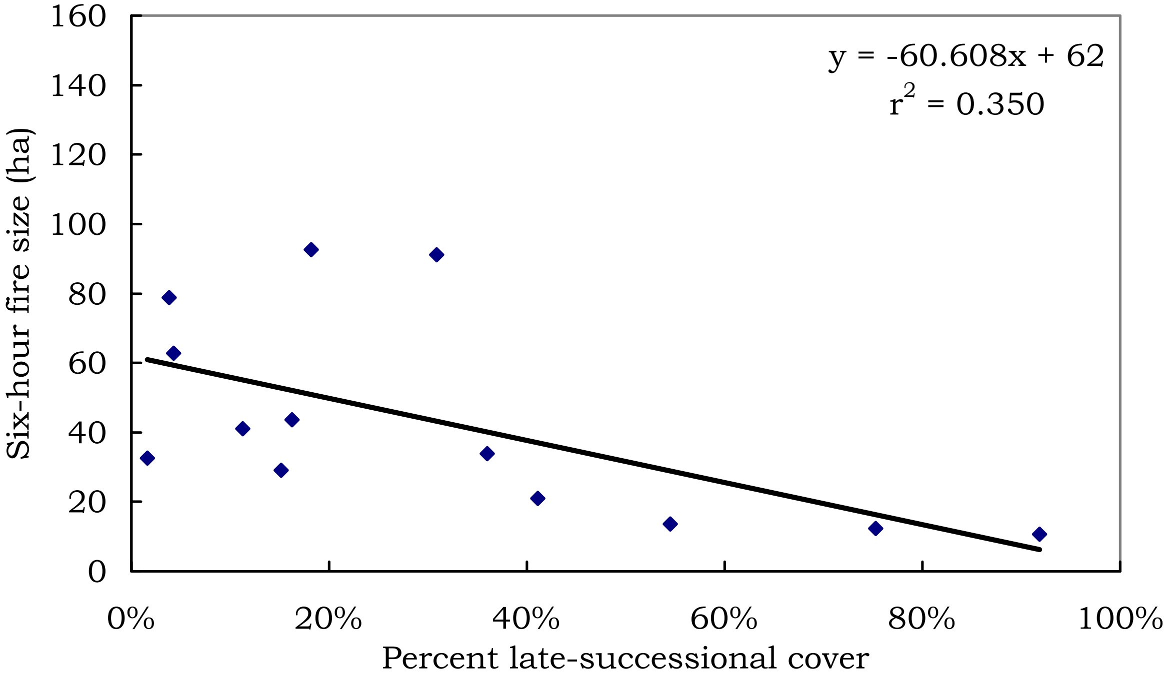

Fig. 33. Effect of 75% biomass reduction on percent late-successional cover compared to total 6-hour fire size.

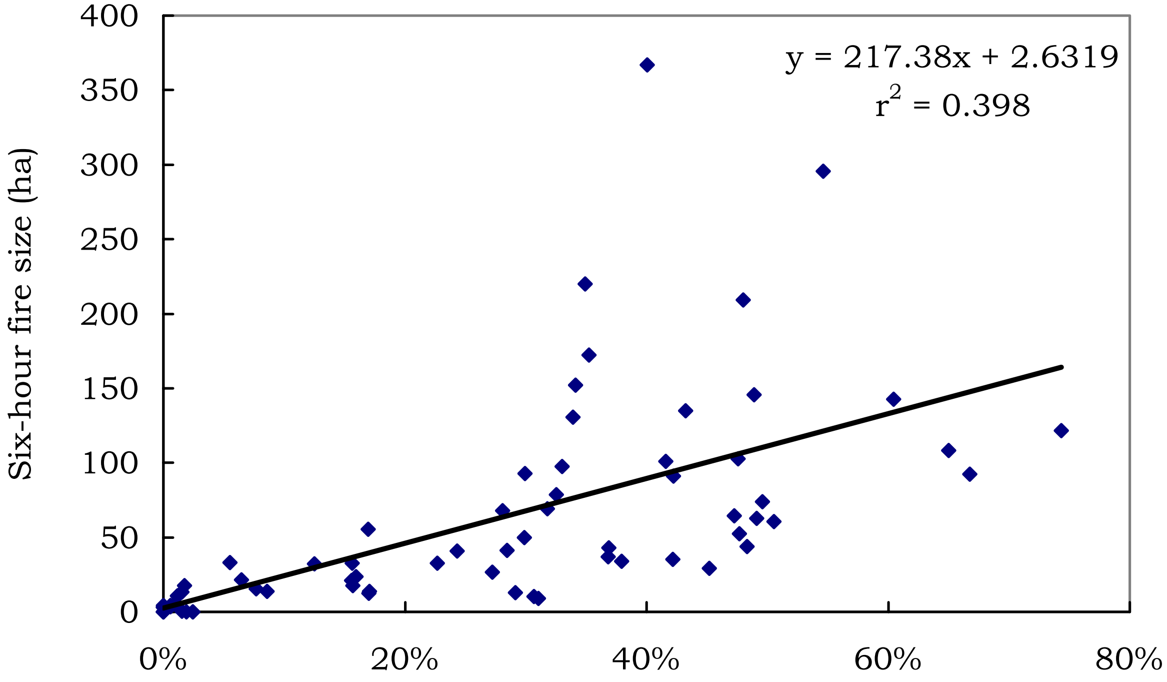

Fig. 34. Percent late successional cover at all levels of reduction compared to total 6-hour fire size.

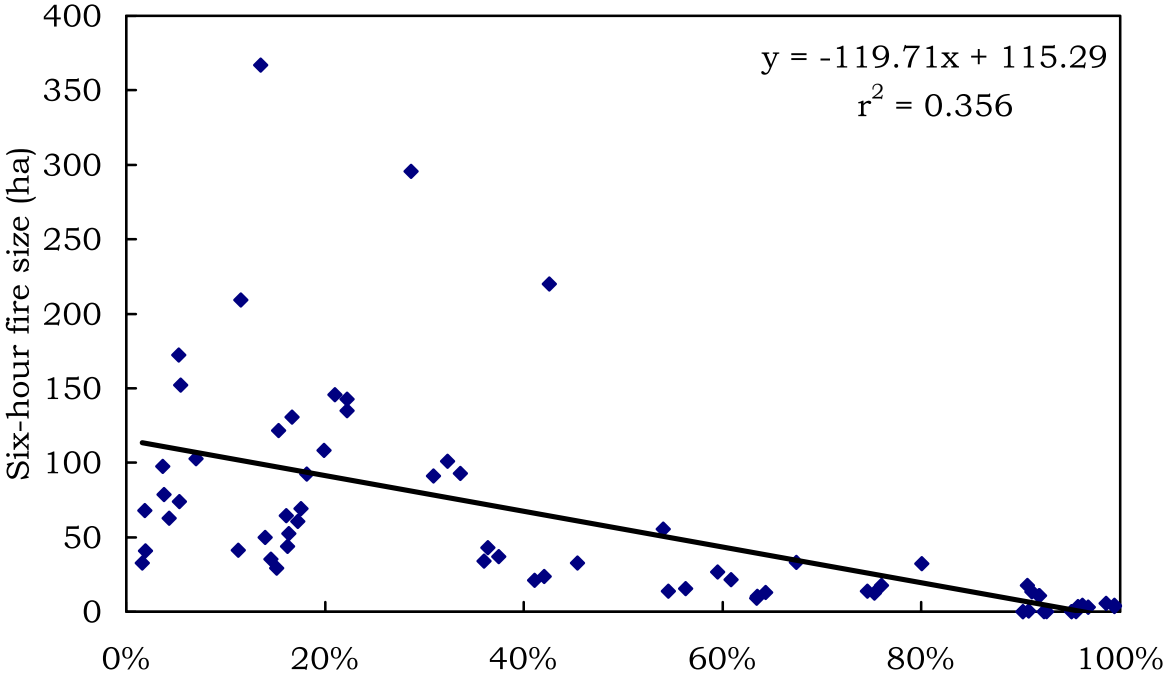

Fig. 35. Percent late successional cover at all levels of reduction compared to total 6-hour fire size.

Summary and Conclusions

Changes in fuels and fire behavior are effected by western juniper encroachment and resulting succession. The mountain big sagebrush cover types were characterized by increasing fuel loads in the early- and early mid-successional stages followed by declining fuel loads in the remaining mid- and late-successional stages. Fuel loads were also dominated by differing components across the successional gradient, early-successional stages by herbaceous and shrub components, mid-successional stages by shrub and litter, and late-successional stages by downed dead woody components.

The low sagebrush cover types were also affected by western juniper encroachment and resulting succession. Low sagebrush cover types had increasing fuel loads and fuel bed depth in the early- and mid-successional stages and declining fuel loads in the late-successional stage. Again, variations in fire behavior were strongly related to the changes in fuel loads, composition, and fuel bed depth.

Changes in fuel loads, composition, fuel bed depth, and resulting fire behavior affected fire size on the landscape. The percent cover that consisted of mid- or late-successional stages had the strongest influence on the resulting fire size.

Reductions in herbaceous biomass and height caused reductions in predicted fire behavior for all cover types. Changes in fire behavior resulting from the reduction in herbaceous biomass and height reduced the predicted fire size on the landscape. The ability to predict fire size based on the successional stage was impaired by reductions in herbaceous biomass and height.

Prescribed fires and fire use strategies will be more effective in controlling western juniper encroachment if they occur in the earlier stages of succession before the shift to declining fuel loads takes place. Greater flexibility in environmental conditions for prescribed fire prescriptions are offered for all successional stages when there is no reduction in herbaceous biomass and height. As advancing succession occurs, this becomes an increasingly important consideration. Reductions in herbaceous biomass and height in areas adjacent to prescribed burns could limit the chances of fire escape.

Conclusions and management suggestions mentioned here should only be applied to western juniper woodlands without the presence of pinyon pine (*Pinus spp.*). Results may vary because juniper does not burn as readily as pinyon pine. This may be due to the higher flammability of pinyon pine foliage. Pinyon pine also grows in more mesic sites with more understory fuels and higher tree densities (Bradley et al. 1991).

Literature Cited

Agee, J.K. 1993. Fire ecology of Pacific Northwest forests. Island Press, Washington, D.C. 493p.

Anderson, H.E. 1982. Aids to determining fuel models for estimating fire behavior. National Wildfire Coordinating Group NFES-1574. U. S. Department of Agriculture, U. S. Department of Interior, and National Association of State Foresters. 22p.

Andrews, P.L. 1986. BEHAVE: fire behavior prediction and fuel modeling system - BURN subsystem, part 1. National Wildfire Coordinating Group NFES-0276. U. S. Department of Agriculture, U. S. Department of Interior, and National Association of State Foresters.130p.

Andrews, P.L., and C.H. Chase. 1989. BEHAVE: fire behavior prediction and fuel modeling system - BURN subsystem, part 2. National Wildfire Coordinating Group NFES-0277. U. S. Department of Agriculture, U. S. Department of Interior, and National Association of State Foresters. 93p.

Andrews, P.L., and L.P. Queen. 2001. Fire modeling and information system technology. International Journal of Wildland Fire 10:343-352.

Bailey, D.W., J.E. Gross, E.A. Lace, L.R. Rittenhouse, M.B. Coughenour, D.M. Swift, and P.L. Sims. 1996. Mechanisms that result in large herbivore grazing distribution patterns. Journal of Range Management 49:386-400.

Blackburn, W.H., and P.T. Tueller. 1970. Pinyon and juniper invasion in black sagebrush communities in east-central Nevada. Ecology 51:841-848.

Blackmore, M., and P.M. Vitousek. 2000. Cattle grazing, forest loss, and fuel loading in dry forest ecosystem at Pu'u Wa'aWa'a Ranch Hawai'i. Biotropica 32:625-632.

Boyd, C. 1987. Evaluation of the grazed-class method for estimating forage utilization in transitory rangelands in northern Idaho. M.S. Thesis, University of Idaho, Moscow. 126p.

Bradley, A.F., N.V. Noste, and W.C. Fischer. 1991. Fire ecology of forest and woodland in Utah. U. S. Department of Agriculture, Forest Service, General Technical Report INT-287. Intermountain Research Station Ogden, UT. 128 p.

Brown, J.K. 1974. Handbook for inventorying downed woody material. U. S. Department of Agriculture, Forest Service, General Technical Report INT-16. Intermountain Research Station Ogden, UT. 48p.

Brown, J.K. 1982. Fuel and fire behavior prediction in big sagebrush. U. S. Department of Agriculture, Forest Service, General Technical Report INT-290. Intermountain Research Station Ogden, UT. 10p.

Brown, J.K., R.D. Oberheu, and C.M. Johnston. 1982. Handbook for inventorying surface fuels and biomass in the interior west. National Wildfire Coordinating Group NFES-2125. U. S. Department of Agriculture, U. S. Department of Interior, and National Association of State Foresters. 48p.

Bunting, S.C., J.L. Kingery, and E.K. Strand. 1999. Effects of succession on species richness of the western juniper woodland/sagebrush steppe mosaic, p. 76-81. *In* S. B. Monsen and R. Stevens (eds.). Ecology and management of pinyon-juniper communities within the interior west., RMRS-P-9. U.S. Department of Agriculture, Forest Service, Rocky Mountain Research Station, Ogden, UT.

Bunting, S.C., E.K. Strand, and J.L. Kingery. 2002. Landscape dynamics of the western juniper woodland/sagebrush steppe mosaic. Final Report. Department of Rangeland Ecology and Management and College of Natural Resources Remote Sensing and Geographic Information Systems Laboratory. University of Idaho, Moscow.19p.

Burgan, R.E. 1987. Concepts and interpreted examples in advanced fuel modeling. U. S. Department of Agriculture, Forest Service, General Technical Report INT-238. Intermountain Research Station Ogden, UT. 40p.

Burgan, R.E., and R.C. Rothermel. 1984. BEHAVE: behavior prediction and fuel modeling system - fuel subsystem. National Wildfire Coordinating Group NFES-0275. U. S. Department of Agriculture, U. S. Department of Interior, and National Association of State Foresters. 126p.

Burkhardt, J.W., and E.W. Tisdale. 1969. Nature and successional status of western juniper vegetation in Idaho. Journal of Range Management 22:264-270.

Burkhardt, J.W., and E.W. Tisdale. 1976. Cause of juniper invasion in southwestern Idaho. Ecology 57:427-484.

Bushey, C.L. 1985. Comparison of observed and predicted fire behavior in the sagebrush-bunchgrass vegetation type, p. 187-201. *In* J. N. Long, (ed.). Fire management: The challenge of protection and use. Utah State University, Logan.

Campbell, J., D. Weinstein, and M.A. Finney. 1996. Integrating GIS and BEHAVE for forest fire behavior modeling, p. 363-375. *In* J. D. Greer, (ed.). Remote sensing: People in partnership with technology. American Society for Photogrammetry and Remote Sensing, Bethesda, MD.

Clark, R.G., and E.E. Starkey. 1990. Use of prescribed fire in rangeland ecosystems. *In* J. D. Walstad, S. R. Radosevich, and D. V. Sandberg, (eds.). Natural and prescribed fire in Pacific Northwest forests. Oregon State University Press, Corvallis.

Finney, M.A. 1998. FARSITE: Fire Area Simulator - Model development and evaluation. U. S. Department of Agriculture Forest Service. Research Paper RMRS-RP-4. Rocky Mountain Research Station Missoula, MT. 47p.

Finney, M.A., and P.L. Andrews. 1999. FARSITE: A program for fire growth simulations. Fire Management Notes 59:13-15.

Harkness, A.L. 1998. Soil survey of Owyhee county area, Idaho. U. S. Department of Agriculture, Natural Resources Conservation Service 809p.

Heady, H.F., and R.D. Child. 1994. Range ecology & management. Westview Press, Boulder. 519p.

Jensen, J.R. 2000. Remote sensing of the environment: An earth resource Perspective Perntice Hall, Upper Saddle River, NJ. 544p.

Johnsen, T.N. 1962. One-seed juniper invasion of northern Arizona grasslands. Ecological Monograph 32:187-207.

Keane, R.E., J.L. Garner, K.M. Schmidt, D.G. Long, J.P. Menakis, and M.A. Finney. 1998. Development of input data layers for the FARSITE fire growth model for the Selway-Bitterroot Wilderness Complex, USA. U. S. Department of Agriculture, Forest Service, General Technical Report RMRS-GTR-3. Rocky Mountain Research Station Ogden, UT. 66p.

Levin, S.A. 1992. The problem of pattern and scale in ecology. Ecology 73:1943-1967.

Miller, R.F., and J.A. Rose. 1995. Historic expansion of *juniper occidentalis* (western juniper) in southeastern Oregon. Great Basin Naturalist 55:37-45.

Miller, R.F., and J.A. Rose. 1999. Fire history and western juniper encroachment in sagebrush steppe. Journal of Range Management 52:550-559.

Miller, R.F., T.J. Svejcar, and N.E. West. 1994. Implications of livestock grazing in the intermountain sagebrush region: Plant composition, p. 101-146. *In* M. Vavra, W. A. Laycook, and R. D. Pieper, (eds). Ecological implications of livestock herbivory in the west. Society for Range Management, Denver, C0.

Miller, R.F., T.J. Svejcar, and J.A. Rose. 2000. Impacts of western juniper on plant community composition and structure. Journal of Range Management 53:574-585.

Rothermel, R.C. 1972. A mathematical model for predicting fire spread in wildland fuels. U. S. Department of Agriculture, Forest Service, Research Paper INT-115. Intermountain Forest and Range Experiment Station Ogden, UT. 40p.

Rothermel, R.C., and G.C. Rinehart. 1983. Field procedures for verification and adjustment of fire behavior predictions. U. S. Department of Agriculture Forest Service. General Technical Report INT-142. Intermountain Forest and Range Experiment Station Ogden, UT. 25p.

Shinn, D.A. 1980. Historical prespectives in range burning in the inland Pacific Northwest. Journal of Range Management 33:415-423.

Waichler, W.S., R.F. Miller, and P.S. Doescher. 2001. Community characteristics of old-growth juniper woodlands. Journal of Range Management 54:518-527.

West, N.E. 1988. Intermountain deserts, shrub steppes, and woodlands, p. 209-230. *In* M. G. Barbour and W. D. Billings, (eds.). North American terrestrial vegetation. Cambridge University Press, Cambridge.

West, N.E., F.D. Provenza, P.S. Johnson, and M.K. Owens. 1984. Vegetation change after 13 years of livestock grazing on sagebrush semidesert in west central Utah. Journal of Range Management 37:262-264.

Young, J.A., and R.A. Evans. 1971. Medusahead invasion as influenced by herbicides and grazing on low sagebrush sites. Journal of Range Management 24:451-454.

Young, J.A., and R.A. Evans. 1981. Demography and fire history of a western juniper stand. Journal of Range Management 34:501-505.

Appendix I

Sagebrush steppe-western juniper mosaic cover type/encroachment and resulting successional stage descriptions.

Low sagebrush *(Artemisia arbuscula)* sere (Arar)

Steppe	Open low to med height shrubland: canopy of low (<50 cm) shrubs with a canopy coverage <67%, tree coverage < 2%. Sometimes very open stands of large mature juniper trees are present. (Two categories are described but these cannot be readily distinguished on either aerial photographs or Landsat images.)
W1	Woodland initiation: juniper canopy (<3%) of usually young-, sometimes mid-aged, junipers present. Juniper is having minor effects on competition and environment of the site and the sagebrush community is intact except directly under juniper trees.
W2	Open young woodland: canopy (3-8%) of young- and mid-aged junipers present. Juniper is beginning to have an effect on the interspace environment of the site. Sagebrush steppe species declining and sagebrush skeletons present. However, low sagebrush still common in interspaces.
W4	Young multi-story juniper woodland: canopy (>8%) of young- and mid-aged junipers present. Usually a few mature junipers present. Sagebrush skeletons often present in understory. However, low sagebrush still common in interspaces.
W5	Old multi-story juniper woodland: overstory canopy >8% composed of primarily mature individuals (flat topped trees and lichen (*Letharia vulpina*) usually present). Trees may not necessarily be large sized. Sagebrush usually present in openings except in the most dense stands of juniper.

Mountain big sagebrush *(Artemisia tridentata vaseyana)* sere (Artr)

Steppe	Open low to med height shrubland: canopy of low (<50 cm) and/or medium 50-200 cm shrubs with a canopy coverage <67%, tree coverage < 2%. (Two categories are described but these cannot be readily distinguished on either aerial photographs or Landsat images.)
W1	Woodland initiation: canopy (<5%) of usually young-, sometimes mid-aged, junipers present. Juniper is having only minor effects on competition and environment of the site and the sagebrush community is intact except directly under juniper trees.
W2	Open young woodland: canopy (5-10%) of young- and mid-aged junipers present. Juniper is beginning to have an effect on the environment of the site. Sagebrush steppe species declining and sagebrush skeletons often present.
W4	Young multi-story juniper woodland: canopy (>10%) of young- and mid-aged junipers present. Few or no mature junipers present. Sagebrush skeletons often numerous in understory.
W5	Old multi-story juniper woodland: overstory canopy >15% composed of primarily mature individuals (flat topped trees and lichen (*Letharia vulpina*) usually present). Few sagebrush remain except in larger openings. Some stands are completely dominated by old mature trees. [Note: These single aged stands were referred to as W6 in the old system.] Other stands may have open canopy of mature trees and a co-dominant layer of various height, mid-aged junipers.

Curlleaf mountain-mahogany (*Cercocarpus ledifolius*) sere (Cele)

R3	Open low to med height shrubland: canopy of low (<50 cm) and/or medium 50-200 cm shrubs with a canopy coverage <67%, tree coverage < 2%. (Two categories are described but these cannot be readily distinguished on either aerial photographs or Landsat images. See *Artemisia tridentata vaseyana* sere.)
R5	Open tall shrubland: canopy of tall (>2m) shrubs with <67% coverage. Tree coverage <5%, usually composed of young- to mid-aged individuals.
R5a	Open tall shrubland: canopy of tall (>2m) shrubs with <10% coverage. Tree coverage <5%, usually composed of young to mid-aged individuals.
R5b	Open tall shrubland: canopy of tall (>2m) shrubs with 10-67% coverage. Tree coverage <5%, usually composed of young to mid-aged individuals.
R7	Multi-strata tall shrubland: canopy of tall (>2m) shrubs with <67% coverage. Tree coverage 5-10%, usually composed of young-, mid-aged and mature individuals.
W4	Young multi-story juniper woodland: canopy (>10%) of young and mid-aged junipers present. Few or no mature junipers present. Sagebrush skeletons often numerous in understory.
W5	Old multi-story juniper woodland: overstory canopy >15% composed of primarily mature individuals (flat topped trees and lichen (*Letharia vulpina*) usually present). Few sagebrush remain except in larger openings.

Other vegetation cover types

Meadow	Herbland: predominantly herbaceous cover with <5% shrub cover.
Mid shrub	Shrubland: canopy of mid-size (<2m) shrubs with <67% coverage. Tree coverage <5%, usually composed of young to mid-aged individuals.
Aspen	Multi-story aspen: tree coverage >50%, usually composed of young- to mid-aged individuals.

Appendix II

Data used to create fuel models are the averages from the collected data. 1-hour surface to volume ratio based on NFFL model 1 at 115 cm^2/cm^3, live herbaceous on NFFL model 2 at 49 cm^2/cm^3, and live woody surface to volume ratio based on NFFL model 6 at 7 cm^2/cm^3. Heat content based on NFFL fuel models at 18500 J/g.

Cover Type: Arar table **Model #** 20

Herbaceous Fuels

Grass load (Mton/ha)	0.23	Litter load (Mton/ha)	0.02
Grass depth (cm)	10	Area covered (%)	100.00

Litter (DDW)

1-hour (Mton/ha)	0.0002	Litter depth (cm)	8
10-hour (Mton/ha)	0.03	Area covered (%)	7
100-hour (Mton/ha)	0.00		

Shrub Fuels

1-hour (Mton/ha)	0.27	Shrub depth (cm)	12
10-hour (Mton/ha)	0.31	Area covered (%)	100.00
100-hour (Mton/ha)	0.05		
Live (Mton/ha)	0.14		

Cover Type: Arar steppe **Model #** 21

Herbaceous Fuels

Grass load (Mton/ha)	0.22	Litter load (Mton/ha)	0.04
Grass depth (cm)	10	Area covered (%)	100.00

Litter (DDW)

1-hour (Mton/ha)	0.0003	Litter depth (cm)	8
10-hour (Mton/ha)	0.25	Area covered (%)	11
100-hour (Mton/ha)	0.06		

Shrub Fuels

1-hour (Mton/ha)	0.65	Shrub depth (cm)	16
10-hour (Mton/ha)	0.74	Area covered (%)	100.00
100-hour (Mton/ha)	0.13		
Live (Mton/ha)	0.33		

Cover Type: Artr steppe **Model #** 22

Herbaceous Fuels

Grass load (Mton/ha)	0.52	Litter load (Mton/ha)	0.12
Grass depth (cm)	19	Area covered (%)	100.00

Litter (DDW)

1-hour (Mton/ha)	0.0003	Litter depth (cm)	8
10-hour (Mton/ha)	0.06	Area covered (%)	13
100-hour (Mton/ha)	1.31		

Shrub Fuels

1-hour (Mton/ha)	0.78	Shrub depth (cm)	47
10-hour (Mton/ha)	1.09	Area covered (%)	100.00
100-hour (Mton/ha)	0.31		
Live (Mton/ha)	0.42		

Cover Type: W1 Arar **Model #** 23

Herbaceous Fuels

Grass load (Mton/ha)	0.25	Litter load (Mton/ha)	0.07
Grass depth (cm)	13	Area covered (%)	100.00

Litter (DDW)

1-hour (Mton/ha)	0.0006	Litter depth (cm)	8
10-hour (Mton/ha)	0.09	Area covered (%)	17
100-hour (Mton/ha)	1.00		

Shrub Fuels

1-hour (Mton/ha)	1.25	Shrub depth (cm)	22
10-hour (Mton/ha)	1.43	Area covered (%)	100.00
100-hour (Mton/ha)	0.25		
Live (Mton/ha)	0.46		

Cover Type: W1 Artr **Model #** 24

Herbaceous Fuels

Grass load (Mton/ha)	0.43	Litter load (Mton/ha)	0.24
Grass depth (cm)	15	Area covered (%)	100.00

Litter (DDW)

1-hour (Mton/ha)	0.0010	Litter depth (cm)	8
10-hour (Mton/ha)	0.12	Area covered (%)	20
100-hour (Mton/ha)	2.13		

Shrub Fuels

1-hour (Mton/ha)	1.32	Shrub depth (cm)	16
10-hour (Mton/ha)	1.68	Area covered (%)	100.00
100-hour (Mton/ha)	0.79		
Live (Mton/ha)	0.62		

Cover Type: W2 Arar **Model #** 25

Herbaceous Fuels

Grass load (Mton/ha)	26.00	Litter load (Mton/ha)	0.06
Grass depth (cm)	12	Area covered (%)	100.00

Litter (DDW)

1-hour (Mton/ha)	0.0006	Litter depth (cm)	8
10-hour (Mton/ha)	0.07	Area covered (%)	23
100-hour (Mton/ha)	0.00		

Shrub Fuels

1-hour (Mton/ha)	1.36	Shrub depth (cm)	22
10-hour (Mton/ha)	1.55	Area covered (%)	100.00
100-hour (Mton/ha)	0.27		
Live (Mton/ha)	0.70		

Cover Type: W2 Artr **Model #** 26

Herbaceous Fuels

Grass load (Mton/ha)	0.36	Litter load (Mton/ha)	0.20
Grass depth (cm)	16	Area covered (%)	100.00

Litter (DDW)

1-hour (Mton/ha)	0.0011	Litter depth (cm)	8
10-hour (Mton/ha)	0.21	Area covered (%)	13
100-hour (Mton/ha)	2.04		

Shrub Fuels

1-hour (Mton/ha)	0.89	Shrub depth (cm)	37
10-hour (Mton/ha)	1.25	Area covered (%)	100.00
100-hour (Mton/ha)	0.36		
Live (Mton/ha)	0.48		

Cover Type: W4 Artr **Model #** 27

Herbaceous Fuels

Grass load (Mton/ha)	0.16	Litter load (Mton/ha)	1.08
Grass depth (cm)	4	Area covered (%)	100.00

Litter (DDW)

1-hour (Mton/ha)	0.0009	Litter depth (cm)	8
10-hour (Mton/ha)	0.19	Area covered (%)	17
100-hour (Mton/ha)	3.37		

Shrub Fuels

1-hour (Mton/ha)	0.56	Shrub depth (cm)	25
10-hour (Mton/ha)	0.64	Area covered (%)	100.00
100-hour (Mton/ha)	0.11		
Live (Mton/ha)	0.29		

Cover Type: Cele **Model #** 28

Herbaceous Fuels

Grass load (Mton/ha)	0.22	Litter load (Mton/ha)	0.56
Grass depth (cm)	6	Area covered (%)	100.00

Litter (DDW)

1-hour (Mton/ha)	0.0022	Litter depth (cm)	8
10-hour (Mton/ha)	0.47	Area covered (%)	60
100-hour (Mton/ha)	7.29		

Shrub Fuels

1-hour (Mton/ha)	0.23	Shrub depth (cm)	19
10-hour (Mton/ha)	0.26	Area covered (%)	100.00
100-hour (Mton/ha)	0.05		
Live (Mton/ha)	0.12		

Cover Type: W5 Arar **Model #** 29

Herbaceous Fuels

Grass load (Mton/ha)	0.11	Litter load (Mton/ha)	0.76
Grass depth (cm)	4	Area covered (%)	100.00

Litter (DDW)

1-hour (Mton/ha)	0.0006	Litter depth (cm)	8
10-hour (Mton/ha)	0.11	Area covered (%)	14
100-hour (Mton/ha)	2.59		

Shrub Fuels

1-hour (Mton/ha)	0.37	Shrub depth (cm)	12
10-hour (Mton/ha)	0.42	Area covered (%)	100.00
100-hour (Mton/ha)	0.07		
Live (Mton/ha)	0.19		

Cover Type: W5 Artr **Model #** 30

Herbaceous Fuels

Grass load (Mton/ha)	0.11	Litter load (Mton/ha)	1.29
Grass depth (cm)	3	Area covered (%)	100.00

Litter (DDW)

1-hour (Mton/ha)	0.0011	Litter depth (cm)	8
10-hour (Mton/ha)	0.31	Area covered (%)	37
100-hour (Mton/ha)	5.85		

Shrub Fuels

1-hour (Mton/ha)	0.16	Shrub depth (cm)	13
10-hour (Mton/ha)	0.19	Area covered (%)	100.00
100-hour (Mton/ha)	0.03		
Live (Mton/ha)	0.08		

Cover Type: Rock **Model #** 31

Herbaceous Fuels

Grass load (Mton/ha)	0.07	Litter load (Mton/ha)	0.83
Grass depth (cm)	3	Area covered (%)	100.00

Litter (DDW)

1-hour (Mton/ha)	0.0010	Litter depth (cm)	8
10-hour (Mton/ha)	0.27	Area covered (%)	34
100-hour (Mton/ha)	5.08		

Shrub Fuels

1-hour (Mton/ha)	0.04	Shrub depth (cm)	3
10-hour (Mton/ha)	0.05	Area covered (%)	100.00
100-hour (Mton/ha)	0.01		
Live (Mton/ha)	0.02		

Cover Type: Aspen **Model #** 32

Herbaceous Fuels

Grass load (Mton/ha)	0.60	Litter load (Mton/ha)	1.14
Grass depth (cm)	11	Area covered (%)	100.00

Litter (DDW)

1-hour (Mton/ha)	0.0016	Litter depth (cm)	8
10-hour (Mton/ha)	0.33	Area covered (%)	100
100-hour (Mton/ha)	8.70		

Shrub Fuels

1-hour (Mton/ha)	0.52	Shrub depth (cm)	49
10-hour (Mton/ha)	0.73	Area covered (%)	100.00
100-hour (Mton/ha)	0.21		
Live (Mton/ha)	0.28		

Cover Type: Mid shrub **Model #** 33

Herbaceous Fuels

Grass load (Mton/ha)	0.09	Litter load (Mton/ha)	1.57
Grass depth (cm)	3	Area covered (%)	100.00

Litter (DDW)

1-hour (Mton/ha)	0.0013	Litter depth (cm)	8
10-hour (Mton/ha)	0.23	Area covered (%)	47
100-hour (Mton/ha)	5.49		

Shrub Fuels

1-hour (Mton/ha)	4.23	Shrub depth (cm)	84
10-hour (Mton/ha)	4.77	Area covered (%)	100.00
100-hour (Mton/ha)	3.00		
Live (Mton/ha)	1.64		

Cover Type: Meadow **Model #** 34

Herbaceous Fuels

Grass load (Mton/ha)	1.62	Litter load (Mton/ha)	0.21
Grass depth (cm)	22	Area covered (%)	100.00

Litter (DDW)

1-hour (Mton/ha)	0.0000	Litter depth (cm)	0
10-hour (Mton/ha)	0.00	Area covered (%)	0
100-hour (Mton/ha)	0.00		

Shrub Fuels

1-hour (Mton/ha)	0.00	Shrub depth (cm)	0
10-hour (Mton/ha)	0.00	Area covered (%)	0.00
100-hour (Mton/ha)	0.00		
Live (Mton/ha)	0.00		

Appendix III

The data presented in this appendix indicates the number of pixels representing each cover type that was within the fire perimeter created by FARSITE and a 100-m buffer. The percentage represented by each cover type was then calculated and those percentages were combined into successional stages. Letters (A, B, C, D, and E) correspond to different simulated fire events.

	Arar Steppe					Artr Steppe				
Model	A	B	C	D	E	A	B	C	D	E
Arar Steppe	501	134	160	29	68		80		41	287
Arar Table					3					26
Artr Steppe	25	61	119		11	12	101	1	285	809
Artr Steppe	14	342	30	1	1	1	53		316	34
Artr Steppe		110	72	11	11	322	91	172	119	192
Aspen			3		6	5	76	11		2
Meadow		11		9		9	200			58
Cele			1	10	37	42	18	141	2	
Meadow		33	273		2	12	157		9	289
Mid Shrub		1	40	14	34	85	95	54	6	16
W1 Arar	26	452	337	17	27	2	315		154	159
W1 Artr		51	563		1	32	307	2	13	362
W2 Arar	23	624	357	69	18	43	252	3	257	338
W2 Artr	2	128	228	73	2	181	388	41	108	155
W4 Arar		203	157	306	6	51	163	6	143	63
W4 Artr		2	52	48	52	399	33	215	47	27
W5 Arar		45	114	193	23	108	131	61	47	55
W5 Artr			23	25	39	208	57	117	2	4
Rock		1	15	46	18	12	15		6	
Rock			6	21	9		48	14	15	
TOTAL	591	2198	2550	872	368	1524	2580	838	1570	2876
Arar Steppe	85%	6%	6%	3%	18%	0%	3%	0%	3%	10%
Arar Table	0%	0%	0%	0%	1%	0%	0%	0%	0%	1%
Artr Steppe	7%	23%	9%	1%	6%	22%	9%	21%	46%	36%
Aspen	0%	0%	0%	0%	2%	0%	3%	1%	0%	0%
Cele	0%	0%	0%	1%	10%	3%	1%	17%	0%	0%
Meadow	0%	2%	11%	1%	1%	1%	14%	0%	1%	12%
Mid Shrub	0%	0%	2%	2%	9%	6%	4%	6%	0%	1%
W1 Arar	4%	21%	13%	2%	7%	0%	12%	0%	10%	6%
W1 Artr	0%	2%	22%	0%	0%	2%	12%	0%	1%	13%
W2 Arar	4%	28%	14%	8%	5%	3%	10%	0%	16%	12%
W2 Artr	0%	6%	9%	8%	1%	12%	15%	5%	7%	5%
W4 Arar	0%	9%	6%	35%	2%	3%	6%	1%	9%	2%
W4 Artr	0%	0%	2%	6%	14%	26%	1%	26%	3%	1%
W5 Arar	0%	2%	4%	22%	6%	7%	5%	7%	3%	2%
W5 Artr	0%	0%	1%	3%	11%	14%	2%	14%	0%	0%
Rock	0%	0%	1%	8%	7%	1%	2%	2%	1%	0%
Early	91%	31%	27%	8%	45%	32%	31%	44%	50%	59%
Mid	9%	57%	58%	18%	13%	17%	49%	5%	34%	35%
Late	0%	11%	15%	74%	52%	54%	21%	67%	17%	5%
Burn area (ha)	25.4	121	144	35.1	12.4	55.5	146	33.2	131	172

	W1 Arar					W1 Artr				
Model	A	B	C	D	E	A	B	C	D	E
Arar Steppe	105	112	83	1	551	7	49	97	105	105
Arar Table			3		344		2		4	
Artr Steppe	32	30	29	1	50	277	759	119	95	5
Artr Steppe	23	110	1	43	329		2	30	20	21
Artr Steppe	168	216	89	156	4	217	223	205	97	36
Aspen	1	3	5	3		9	6	11	5	
Meadow	16	29				85	16	77	45	23
Cele	1	6	40	103	3	38	4	4	28	8
Meadow	26	34	7	18	3	71	283	275	73	88
Mid Shrub	12	11	37	43	15	21	49	32	89	42
W1 Arar	1079	1251	107	343	570	20	140	172	94	143
W1 Artr	79	82	25	4	17	210	907	356	348	126
W2 Arar	967	1096	107	87	199	130	401	378	176	182
W2 Artr	188	204	45	45	189	197	192	138	236	346
W4 Arar	543	576	45	99	68	77	227	209	433	413
W4 Artr	45	53	97	88	17	185	27	51	70	70
W5 Arar	117	114	84	80	35	161	103	203	164	288
W5 Artr	2	2	63	83	22	148	3	14	47	31
Rock	140	64	20	12	6	1	21	1	42	66
Rock	1	1	24	24	14	7	3	3	60	24
TOTAL	3545	3994	911	1233	2436	1861	3417	2375	2231	2017
Arar Steppe	3%	3%	9%	0%	23%	0%	1%	4%	5%	5%
Arar Table	0%	0%	0%	0%	14%	0%	0%	0%	0%	0%
Artr Steppe	6%	9%	13%	16%	16%	27%	29%	15%	10%	3%
Aspen	0%	0%	1%	0%	0%	0%	0%	0%	0%	0%
Cele	0%	0%	4%	8%	0%	2%	0%	0%	1%	0%
Meadow	1%	2%	1%	1%	0%	8%	9%	15%	5%	6%
Mid Shrub	0%	0%	4%	3%	1%	1%	1%	1%	4%	2%
W1 Arar	30%	31%	12%	28%	23%	1%	4%	7%	4%	7%
W1 Artr	2%	2%	3%	0%	1%	11%	27%	15%	16%	6%
W2 Arar	27%	27%	12%	7%	8%	7%	12%	16%	8%	9%
W2 Artr	5%	5%	5%	4%	8%	11%	6%	6%	11%	17%
W4 Arar	15%	14%	5%	8%	3%	4%	7%	9%	19%	20%
W4 Artr	1%	1%	11%	7%	1%	10%	1%	2%	3%	3%
W5 Arar	3%	3%	9%	6%	1%	9%	3%	9%	7%	14%
W5 Artr	0%	0%	7%	7%	1%	8%	0%	1%	2%	2%
Rock	4%	2%	5%	3%	1%	0%	1%	0%	5%	4%
Early	11%	14%	32%	30%	53%	38%	41%	35%	25%	16%
Mid	65%	66%	31%	39%	40%	30%	48%	44%	38%	40%
Late	24%	21%	41%	40%	7%	34%	12%	21%	38%	45%
Burn area (ha)	217	248	41.4	61.9	149	92.8	209	135	124	109

	W2 Arar									
Model	A	B	C	D	E	F	G	H	I	J
Arar Steppe	176	65	154		63	6		77	111	9
Arar Table										
Artr Steppe	33	277	49	7	25	13	7		24	1
Artr Steppe	12	424	85	6	55	15	6	13	137	
Artr Steppe	55	105	62	170	215	50	170	21	179	49
Aspen		1	41	2	4		2			4
Meadow	11	26	95		69			11	6	23
Cele	72	110	1	19	2	61	19	2	2	46
Meadow		2	80	5	44	7	5	21	10	
Mid Shrub	5	6	41	15	3	12	15	65	4	25
W1 Arar	97	184	486	27	287	17	27	176	922	10
W1 Artr		4	228	12	39		12	46	41	1
W2 Arar	314	306	471	109	708	81	109	204	925	78
W2 Artr	114	92	572	81	108	50	81	291	181	68
W4 Arar	79	126	386	82	433	49	82	412	411	52
W4 Artr	100	64	48	103	34	63	103	38	9	98
W5 Arar	71	83	55	155	128	90	155	203	75	85
W5 Artr	43	43	2	75	1	65	75	13	1	94
Rock	20	14	40		21	1		72	17	1
Rock	9	35	12	9	1	1	9	10		6
TOTAL	1211	1967	2908	877	2240	581	877	1675	3055	650
Arar Steppe	15%	3%	5%	0%	3%	1%	0%	5%	4%	1%
Arar Table	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%
Artr Steppe	8%	41%	7%	21%	13%	13%	21%	2%	11%	8%
Aspen	0%	0%	1%	0%	0%	0%	0%	0%	0%	1%
Cele	6%	6%	0%	2%	0%	10%	2%	0%	0%	7%
Meadow	1%	1%	6%	1%	5%	1%	1%	2%	1%	4%
Mid Shrub	0%	0%	1%	2%	0%	2%	2%	4%	0%	4%
W1 Arar	8%	9%	17%	3%	13%	3%	3%	11%	30%	2%
W1 Artr	0%	0%	8%	1%	2%	0%	1%	3%	1%	0%
W2 Arar	26%	16%	16%	12%	32%	14%	12%	12%	30%	12%
W2 Artr	9%	5%	20%	9%	5%	9%	9%	17%	6%	10%
W4 Arar	7%	6%	13%	9%	19%	8%	9%	25%	13%	8%
W4 Artr	8%	3%	2%	12%	2%	11%	12%	2%	0%	15%
W5 Arar	6%	4%	2%	18%	6%	15%	18%	12%	2%	13%
W5 Artr	4%	2%	0%	9%	0%	11%	9%	1%	0%	14%
Rock	2%	2%	2%	1%	1%	0%	1%	5%	1%	1%
Early	30%	52%	19%	25%	21%	28%	25%	13%	15%	24%
Mid	43%	30%	60%	26%	51%	25%	26%	43%	68%	24%
Late	33%	24%	20%	51%	28%	57%	51%	45%	17%	59%
Burn area (ha)	124	109	171	38.1	123	25.5	26.7	81.5	178	26.8

	W2 Artr					W4 Artr				
Model	A	B	C	D	E	A	B	C	D	E
Arar Steppe		54	12	110	63					
Arar Table										
Artr Steppe		6	644	85	94			1		
Artr Steppe	2			18	20					
Artr Steppe	14	22	252	108	53	1		32		4
Aspen			8	4	1	1	6			
Meadow	20		23	38	133		6			
Cele	80	39	6	7	43	65	52	3	15	11
Meadow		1	203	97	84			8		
Mid Shrub	20	2	69	102	80		1	21		7
W1 Arar	12	66	72	131	211			1		
W1 Artr			791	137	466			37		
W2 Arar	28	81	198	390	223	1				2
W2 Artr	54	27	326	236	363	1		54		6
W4 Arar	56	62	107	106	242	1		4		12
W4 Artr	183	130	62	49	45	69	47	43	58	120
W5 Arar	65	89	107	133	91	9	6	49	10	32
W5 Artr	21	52	10	43	44	54	66	27	27	54
Rock	96	4	10		7	4			31	14
Rock	100	4			8	2			2	
TOTAL	751	639	2900	1794	2271	208	184	280	143	262
Arar Steppe	0%	8%	0%	6%	3%	0%	0%	0%	0%	0%
Arar Table	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%
Artr Steppe	2%	4%	31%	12%	7%	0%	0%	12%	0%	2%
Aspen	0%	0%	0%	0%	0%	0%	3%	0%	0%	0%
Cele	11%	6%	0%	0%	2%	31%	28%	1%	10%	4%
Meadow	3%	0%	8%	8%	10%	0%	3%	3%	0%	0%
Mid Shrub	3%	0%	2%	6%	4%	0%	1%	8%	0%	3%
W1 Arar	2%	10%	2%	7%	9%	0%	0%	0%	0%	0%
W1 Artr	0%	0%	27%	8%	21%	0%	0%	13%	0%	0%
W2 Arar	4%	13%	7%	22%	10%	0%	0%	0%	0%	1%
W2 Artr	7%	4%	11%	13%	16%	0%	0%	19%	0%	2%
W4 Arar	7%	10%	4%	6%	11%	0%	0%	1%	0%	5%
W4 Artr	24%	20%	2%	3%	2%	33%	26%	15%	41%	46%
W5 Arar	9%	14%	4%	7%	4%	4%	3%	18%	7%	12%
W5 Artr	3%	8%	0%	2%	2%	26%	36%	10%	19%	21%
Rock	26%	1%	0%	0%	1%	3%	0%	0%	23%	5%
Early	18%	19%	42%	31%	25%	32%	32%	23%	10%	8%
Mid	13%	27%	48%	50%	56%	1%	0%	33%	0%	3%
Late	80%	59%	11%	19%	21%	99%	96%	45%	100%	93%
Burn area (ha)	32.2	26.5	170	94.5	128	5.62	4.2	6.17	2.39	7.13

	W5 Arar					W5 Artr				
Model	A	B	C	D	E	A	B	C	D	E
Arar Steppe			1		9					
Arar Table										
Artr Steppe										
Artr Steppe										
Artr Steppe	12	2	28		3		2	1		
Aspen									1	1
Meadow	12		12		5		2		1	5
Cele	13	11	1	6	1	1	1		4	11
Meadow										
Mid Shrub	1	1	4	2	7	4	1	1		
W1 Arar			18							
W1 Artr				1						
W2 Arar			37		8					
W2 Artr	8	1	19	1	19		1			1
W4 Arar	8	1	82	3	65		6			
W4 Artr	23	28	23	6	22	8	15	3	5	3
W5 Arar	56	34	99	27	85	2	3	12	4	
W5 Artr	28	41	6	75	10	39	34	31	37	42
Rock				1	3			1		
Rock	17	5		13	8			5		
TOTAL	178	124	330	135	245	54	65	54	52	63
Arar Steppe	0%	0%	0%	0%	4%	0%	0%	0%	0%	0%
Arar Table	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%
Artr Steppe	7%	2%	8%	0%	1%	0%	3%	2%	0%	0%
Aspen	0%	0%	0%	0%	0%	0%	0%	0%	2%	2%
Cele	7%	9%	0%	4%	0%	2%	2%	0%	8%	17%
Meadow	7%	0%	4%	0%	2%	0%	3%	0%	2%	8%
Mid Shrub	1%	1%	1%	1%	3%	7%	2%	2%	0%	0%
W1 Arar	0%	0%	5%	0%	0%	0%	0%	0%	0%	0%
W1 Artr	0%	0%	0%	1%	0%	0%	0%	0%	0%	0%
W2 Arar	0%	0%	11%	0%	3%	0%	0%	0%	0%	0%
W2 Artr	4%	1%	6%	1%	8%	0%	2%	0%	0%	2%
W4 Arar	4%	1%	25%	2%	27%	0%	9%	0%	0%	0%
W4 Artr	13%	23%	7%	4%	9%	15%	23%	6%	10%	5%
W5 Arar	31%	27%	30%	20%	35%	4%	5%	22%	8%	0%
W5 Artr	16%	33%	2%	56%	4%	72%	52%	57%	71%	67%
Rock	10%	4%	0%	10%	4%	0%	0%	11%	0%	0%
Early	21%	11%	14%	6%	10%	9%	9%	4%	10%	25%
Mid	4%	1%	22%	1%	11%	0%	2%	0%	0%	2%
Late	81%	97%	64%	97%	79%	93%	91%	96%	98%	90%
Burn area (ha)	3.22	1.96	7.64	2	6.98	0.18	0.36	0.18	0.14	0.3