THE INFLUENCE OF DUFF DISTRIBUTION IN POST-FIRE VEGETATION RECOVERY PATTERNS IN WESTERN JUNIPER (JUNIPERUS OCCIDENTALIS) WOODLANDS IN SOUTHWESTERN IDAHO

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AUTHORIZATION TO SUBMIT THESIS

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ABSTRACT

Woody plant expansion is a global phenomenon that alters the spatial distribution of nutrients, biomass, and fuels in affected ecosystems. Altered fuel patterns across the landscape influences ecological processes including fire behavior, fire effects, and can impact post-fire plant recovery. The purpose of this study was to determine how accumulations of ground fuels in maturing western juniper (*Juniperus occidentalis* ssp. *occidentalis*) woodlands affect post-fire species response as well as demonstrate new methods in wavelet analysis to quantify landscape scale patterns of fuel loading. Sampling and analysis was conducted across environmental gradients following the Tongue-Crutcher Wildfire Complex in 2007 in order to determine conditions that were most influential in vegetation recovery. Of the multiple environmental gradients analyzed, duff depth and fire severity were determined to be the two most influential factors affecting post-fire vegetation response. Decreasing species diversity was represented along the increasing duff depth gradient as well as the exclusion of some species at certain depths. Species response grouped by fire severity revealed significant presence of cheatgrass (*Bromus tectorum*) in low severity sites and a dominant presence of snowbrush ceanothus (*Ceanothus velutinus)* in higher severity sites. Native perennial bunch grass cover was greater in unburned areas compared to burned areas of the landscape. Landscape scale representations of fuel loading for duff/litter were derived from the recognition of individual crowns using a discrete wavelet transformation. Determining sub-crown surface fuel characteristics on a landscape scale make it possible to predict future patterns and processes as they relate to vegetation recovery and/or fire severity components.

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DEDICATION

This thesis is dedicated to my mother and father, Teresa and George Weiner, for their unwavering support of my education and constant belief that goals can be achieved no matter how high. Your love and passion for my success is unmatched. I also dedicate this to my grandfathers Dr. Dale Wilhelm and the late Dr. Murray Weiner for their lifelong dedication to science and the never-ending pursuit of life's toughest questions. You all are and always will be sources of great inspiration, thank you.

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CHAPTER I – INFLUENCE OF DUFF ON POST-FIRE VEGETATION PATTERNS

Western juniper (*Juniperus occidentalis* ssp. *occidentalis*) woodlands have undergone significant expansion in many areas of the Great Basin during the last century (Burkhardt and Tisdale 1969). The expansion of the woodlands has been attributed to a variety of both anthropogenic and environmental conditions, most notably fire exclusion (Burkhardt and Tisdale 1976, Belsky 1996). The expansion of the juniper woodlands into sagebrush steppe has resulted in a shift in understory species composition of the steppe plant community and the availability and composition of wildfire fuels (Bunting et al. 1999, Yanish 2002).

The expansion and successional maturation of the juniper woodlands may be resulting in historically unnatural accumulations of litter and duff, as has been the case in many mixed-conifer forests experiencing fire exclusion (Parsons and DeBenedetti 1979, Belsky 1996, Keane et al. 2002). In some ecosystems, the consumption of duff under wildfire conditions is known to downwardly heat soil, influencing plant structure or soil stored seeds in the organic and mineral soil horizons (DeBano 1990, Brown et al. 1991, Hungerford et al. 1991). Little is known about the consumption and post-fire influence of western juniper duff under wildfire scenarios, prompting the origins of this research.

The objectives of this study are to 1) Determine the relationship between the pre-fire western juniper litter and duff depth gradient and post-fire vegetation species composition; 2) Determine the relationship between burn severity and post-fire vegetation species composition; 3) Demonstrate the ability of wavelet analysis to spatially represent litter and duff loading on a landscape scale in the GIS environment.

LITERATURE REVIEW

In the last 130 years, western juniper (*Juniperus occidentalis* ssp. *occidentalis*) woodlands have undergone an unprecedented expansion in many areas of the Great Basin, including the Owyhee Mountains in southwestern Idaho (Burkhardt and Tisdale 1969). As of the late 20th century western juniper occupied over 160,000 hectares in Idaho, continuing expansion into present day (Burkhardt and Tisdale 1969, Miller et al. 2000). While western juniper was once historically confined to rocky terrains and generally less productive sites, expansion of juniper to more productive sites in the last 100 years has resulted in over 3.5 million hectares of western juniper in Nevada, Oregon, Idaho and California (Belsky 1996, Miller et al. 2005). An estimated 90% of the juniper woodlands in the western United States have developed in the last 100 years, with the greatest rate of expansion occurring between 1870 and 1920 (Miller and Rose 1999, Miller et al. 2000).

The expansion of western juniper into systems such as the sagebrush steppe (*Artemisia* spp.) is suggested to be a result of both anthropogenic and environmental conditions (Burkhardt and Tisdale 1976, Belsky 1996). Most commonly noted is the cessation of historic fire intervals due to fire suppression, development of fuel barriers (roads, agricultural land, etc) and degradation of fine, fire carrying fuels via livestock introduction and subsequent grazing (Burkhardt and Tisdale 1976, Young and Evans 1981, Belsky 1996, Miller et al. 2000). In addition to the anthropogenic influences of fire suppression and the introduction of livestock, climatic shifts in the last 200 years have also been considered a contributing factor to the expansion of juniper woodlands (Burkhardt and Tisdale 1976, Belsky 1996).

The western juniper is a slow growing, long-lived submonoecious tree; indicating that male and female cones are borne on the same individual tree, with some trees presenting sexual dominance one way or the other (Miller et al. 2005). Post germination, belowground growth is favored in during its youth with above ground crown development advancing age at 45-50 (Miller et al. 2005). Western juniper trees typically range between 4 to 10 m in height with some individuals being recorded over 18 m and having a potential lifespan of over 1000 years in areas void of major disturbance (Tirmenstein 1999, Miller et al. 2005). Crown diameters typically range between 1 and 12 m (Strand et al. 2008). Many of the ecophysiological and morphological properties of the western juniper allow the species to be tolerant to a wide variety of environmental conditions (Miller et al. 2005). Western juniper woodlands are often indicative of a late-seral stage in sagebrush steppe ecosystems (Tirmenstein 1999).

The development of mature juniper woodlands has been notably associated with the decline in herbaceous and shrub components of the sagebrush steppe community

(Bunting et al. 1999). Many of these expanding juniper communities are currently in the transition from an early successional plant community, i.e. shrub steppe with young juniper, to closed canopy juniper woodland (Miller et al. 2000). Miller et al. (2000, 2005) define the successional progression of sagebrush steppe to mature juniper woodlands in four distinguishable stages. The first stage, Phase 1, is characterized by an open but actively expanding tree canopy with less than or equal to 10% of maximum potential and an intact shrub layer. The next stage, Phase 2, is defined by an actively expanding tree canopy with 10-49% of maximum potential and a nearly intact shrub layer. Phase 3 is defined by reduced expansion with 50-80% maximum potential of tree canopy and greater than 75% dead thinning of the shrub layer. The final stage, Mature, is characterized by nearly stable expansion with greater than 80% of maximum potential and greater than 90% dead shrub layer.

Yanish (2002) determined through field sampling and modeling that western juniper encroachment and succession have an effect on fuels and fire behavior of a given landscape. More specifically, changes in fuel loads, species composition, fuel bed depth, and fire behavior ultimately affect the fire size (Yanish 2002). Phase 1 of western juniper encroachment and advancing succession in mountain big sagebrush (*Artemisia tridentata* ssp. *vaseyana*) cover types are highlighted by an increase in 1-, 10-, and 100-hour fuel loading with fuel load values of ≈ 1.5, ≈ 1.0, ≈ 0.5 Mtons/ha, respectively and ≈ 0.5 Mtons/ha of live herbaceous. Phase 2 succession sees a peak of fuel loading in all types prior to the decrease of 1-hour, 10-hour, and live fuels; ≈ 2.0, ≈1.5, ≈1.0, ≈0.6 Mtons/ha respectively. Phase 3 and the mature stage of western juniper encroachment and successional development is characterized by a sharp increase in 100-hour fuels, attributed to downed juniper trees or branches, a continual decrease in 1- and 10- hour fuels, and an almost complete loss of live herbaceous cover (Figure 1) (Yanish 2002). Additionally, Yanish (2002) determined through a modeling study that the percent cover of sagebrush types in mid- or late-successional stage had the strongest influence on fire size.

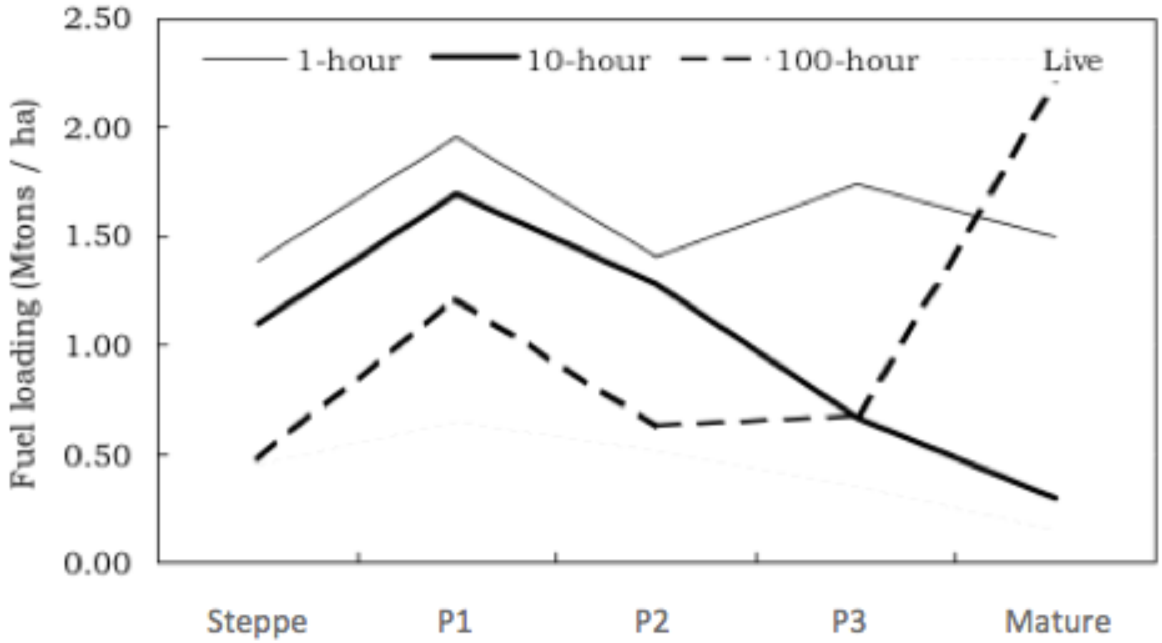


Fig 1. Changes in fuel loading associated with western juniper encroachment and advancing succession in mountain big sagebrush cover types (adapted from Yanish 2002)

Prior to western settlement, western juniper stands were restricted in expansion by fire return intervals of around 40 years (Burkhardt and Tisdale 1969). The fire return interval typically limited the potential range of western juniper to rock outcrops on topographic features (Burkhardt and Tisdale 1969). With the introduction of grazing and fire suppression during the last century, significant expansion in distribution has occurred in addition to an alteration in density and age structure of many juniper woodlands (Young and Evans 1981). The age of plant communities is the most influential factor in the effect of fire on individual western juniper trees (Dealy 1990). Young trees can be more susceptible to fire from cambium heating due to thinner bark structure while older trees with thicker bark structure are less vulnerable and typically contain smaller concentrations of fine, fire-carrying fuels near the stem (Dealy 1990, Tirmenstein 1999). Extreme fire conditions, typically involving crown scorch, are often required to kill taller more mature trees (Tirmenstein 1999).

There is no available literature regarding accumulations of ground fuels such as litter, or the formations of duff, beneath individual western juniper trees, stands, or mature woodlands; however, studies suggest that the exclusion of fire in many mixed-conifer forests has resulted in uncharacteristic accumulations of ground litter and duff (Keane et al. 2002). This historic exclusion of fire has occurred during the same time periods for juniper woodlands as it has for many mixed-conifer forests (Parsons and DeBenedetti 1979, Belsky 1996). Duff accumulation is noted to increase in depth as crown diameter increases and distance from the bole decrease under some coniferous tree species (Ryan and Frandsen 1991). In general, biomass increases with time until a disturbance such as fire is present, or when accumulation and decomposition occur at equal rates (Hungerford et al. 1991).

The duff layer itself is commonly defined as the decomposing organic matter below the fresh litter layer but above mineral soil (Valette et al. 1994). The duff layer plays a crucial part in forested ecosystems as it protects soils from erosion, retains moisture, releases nutrients, and has a critical impact on post-fire forest regeneration in many ecosystems (Valette et al. 1994, Hille and Stephens 2005). Despite the lack of research in to the accumulations of ground litter and duff directly relating to western juniper, some research has been done on accumulations of litter and duff in mixed-conifer forests. These studies indicate that fire exclusion has resulted in increased litter/duff loading and that smoldering combustion of duff can both stimulate stand development as well as cause varying degrees of vegetation mortality (Parsons and DeBenedetti 1979, Hille and Stephens 2005).

In addition to the lack of literature on the accumulation of western juniper duff, there is no available literature concerning the relationship of western juniper duff and fire. The relationship between litter/duff and fire has, however, been studied in mixed-conifer forests, wetlands, and in mastication scenarios, often under prescribed fire conditions (Valette et al. 1994, Frandsen 1997, Reardon et al. 2007). Under a wide range of fire scenarios it is recognized that smoldering combustion often occurs in the organic soil horizon, or duff, following surface or crown fires in many of ecosystems (Frandsen 1997). The rate of propagation, heat output, and consumption within the duff layer during smoldering combustion is influenced by the moisture content, inorganic content, depth, and duration of the igniting fire (Brown et al. 1991, DeBano 1991, Hungerford et al. 1991, Hille and Stephens 2005). Combustion of this duff layer is recognized to downwardly heat the mineral soil via conduction, convection, and vaporization (DeBano 1990). Studies by Frandsen (1997) and Brown et al. (1991) indicate that both the potential for ignition and total fuel consumption decreases as moisture content increases. Additionally, a study by Valette et al. (1994) determined that duff could act as a significant insulator for mineral soil, especially with higher moisture content, when the duff remained unburned in wild fire scenarios.

Smoldering combustion in the duff layer can exceed temperatures of 500 to 600 °C (Hungerford et al. 1991). While these temperatures are often lower than temperature values during flaming combustion, the long duration of combustion and proximity to mineral soil can result in greater total heating (Hungerford et al. 1991). The soil heating process under wildfire or prescribed fire conditions is recognized to have altering effects on soil properties such as: structure, water-absorbing capacity, soil nutrients, and microbial populations. Hungerford et al. (1991) notes that the ability of given soil to absorb water after a fire scenario is directly related to the amount of organic matter consumed during the process. Additionally, cat-ions are generally increased following burning of organic matter while plant available nitrogen may decrease, affecting site productivity (Hungerford et al. 1991). Severe soil heating in some scenarios may have negative effects on soil productivity; however, the consumption of duff is recognized to play an important factor in post-fire stand recruitment in certain forest types (Brown et al. 1991, Hungerford et al. 1991, Miyanishi and Johnson 2002, Reinhardt et al. 2003).

The degree of influence smoldering combustion has on plant components are determined by the depth and the duration of sub-surface combustion (Stephan et al. 2010). Stephan et al. (2010) note that soil stored seeds and buried regenerative plant structures within duff or organic layers are at high risk from fires due to the direct exposure to smoldering combustion. A study by Varner et al. (2009) recorded duff and mineral soil temperature consistently exceeding the lethal temperature of >60° C in smoldering combustion conditions under longleaf pine (*Pinus palustris)* trees.

The establishment of plant species on post-burn site is dependent on the type and morphology of the species present pre-burn, along with the dynamic characteristics of the fire and post-fire environment (Hungerford et al. 1991).

While sub-surface heating can cause mortality of soil-stored seeds, seed bank germination can also be stimulated by soil heating under the right conditions. This potential response is determined by the heat tolerance of seed species, as well as the magnitude and duration of the soil heating process (Stephan et al. 2010).

One such species, of particular interest to this study, is snowbrush ceanothus (*Ceanothus velutinu).* Snowbrush is often observed in the post-burn areas is known to have botanical characteristics that relate to wildfire conditions. More specifically, snowbrush has soil stored seeds that can stay viable in the soil for up to 200 years and contain a hard impermeable seed coat that must be cracked, abraded or exposed to heat in order to stimulate germination (Anderson 2001). Snowbrush seeds can grow in almost any soil type and are recognized to dominate early seral growth following a “medium or hot” fire (Anderson 2001). Snowbrush is of particular interest to some land managers as dense stands can dominate for many years following fires, creating extensive competition for tree seedling recruitment and providing poor forage value for domestic livestock (Gratkowski 1962, Anderson 2001).

Another species of particular interest to the study is cheatgrass (*Bromus tectorum*), due to its invasive characteristics, fire response and prominence in burned areas . Cheatgrass is an invasive annual grass introduced to North America in the 18th century (Mack 1981). Cheatgrass is recognized to be a persistent invasive species in the sagebrush steppe of the Intermountain West; introduced with the introduction agricultural practices and often playing a role in changes between herbaceous understory and woody over story species composition (Zouhar 2003). Cheatgrass is recognized to be an extremely efficient seed producer particularly under heightened disturbance regimes such as fire. During a wildfire event heat will likely kill most surface cheatgrass seeds within a sagebrush system, though seeds between shrubs or fuels, those buried, or those within cracks of the soil may survive (Zouhar 2003). Additionally, cheatgrass seeds can readily re-establish from transportation into post-fire environment via livestock or wildlife. Cheatgrass often outcompetes native species in post-fire vegetation recovery (Zouhar 2003).

Determining the degree to which a vegetated landscape has changed following a disturbance has become more achievable with the introduction and use of remote sensing techniques. The use of remotely sensed pre- and post-fire data has become a valuable tool in assessing the change in vegetation cover, or severity, following a wildfire event. One of these widely used methods is the normalized burn ratio (NBR);

(Key and Benson 2006), a technique that utilizes LandSat TM/ETM infrared signatures to compare the temporal changes in infrared reflectance following a wildfire. Areas that experience a loss of live vegetation will exhibit a reduction in 0.4–1.3 μm region of the electromagnetic spectrum as well as an increase in the 1.6-2.5 μm region of the spectrum due to the increased exposure of soil and charred vegetation (Lentile et al. 2006). The degree at which the pre- and post-fire NBR values differ is referred to as the differenced normalize burn ratio (dNBR) and is commonly used in the classification of burn severity of remotely sensed wildfires (Key and Benson 2006).

METHODS

Site Description

The Owyhee Plateau in Owyhee County of southwestern Idaho (116 W Long 43 N Lat) is located in an area dominated by western juniper and sagebrush steppe. The occurrence of western juniper in this area is primarily in the form of open savanna woodlands with interspersed rock canyons, small mountains, and riparian areas. Elevations for the study site were between 1756 m and 2015 m with annual precipitation ranging from 330 to 406 mm. Average temperatures range from -6.0°C in winter months to 35°C during the summer. The soil composition of the study area is primarily mountain loam.

The Bureau of Land Management (BLM) manages the majority of land area in Owyhee Plateau region, interspersed by private and State of Idaho ownership. Land uses in the area include: livestock grazing, recreation, hunting, and firewood cutting. The Owyhee Plateau provides forage and habitat for an abundance of wildlife, including large and small games species.

Common tree species in the study area include western juniper, curlleaf mountain-mahogany (*Cerocarpus ledifolius*), and quaking aspen (*Populus tremuloides*). Shrub species include but are not limited to: mountain big sagebrush (*Atemisia tridentata* ssp. *vaseyana*), low sagebrush (*Artmesia arbuscula*), shiny leaf ceanothus (*Ceanothus velutinus*), green rabbitbrush (*Chrysothamnus viscidiflorus*), and antelope bitterbrush (*Purshia tridentata*). Common native perennial grasses include but are not limited to: bluebunch wheatgrass (*Pseudoroegneria spicata*), Idaho fescue (*Festuca idahoensis*), Sandberg bluegrass (*Poa secunda*) and needgrass (*Achnaterum* spp.). A wide variety of perennial and annual forbs are also present across the study area (See Appendix 1 for a species list).

Portions of the field sampling procedures were conducted in areas burned during the Tongue-Crutcher Wildland Fire Complex (TCWFC). The TCWFC was ignited by lighting on July 6th 2007 along the Owyhee River south of Juniper Mountain on Owyhee Plateau of southwestern Idaho, following an unusually dry spring (Fig. 2). At the time of ignition nearby weather stations reported relative humidity of less than 10% with variable winds and gusts exceeding 80 km per hour. In the days following ignition, the wildfire burned intensely and exhibited extreme fire behavior such as crowning, torching and spotting. Suppression efforts began on July 11th 2007 and the fire was deemed mostly contained by July 21st 2007. The TCWFC burned a total of 18,890 hectares prior to containment. Since 2007 the area has not been seeded or treated in any other way, providing a unique opportunity to observe natural post-fire vegetation response along successional gradients in the juniper woodlands.

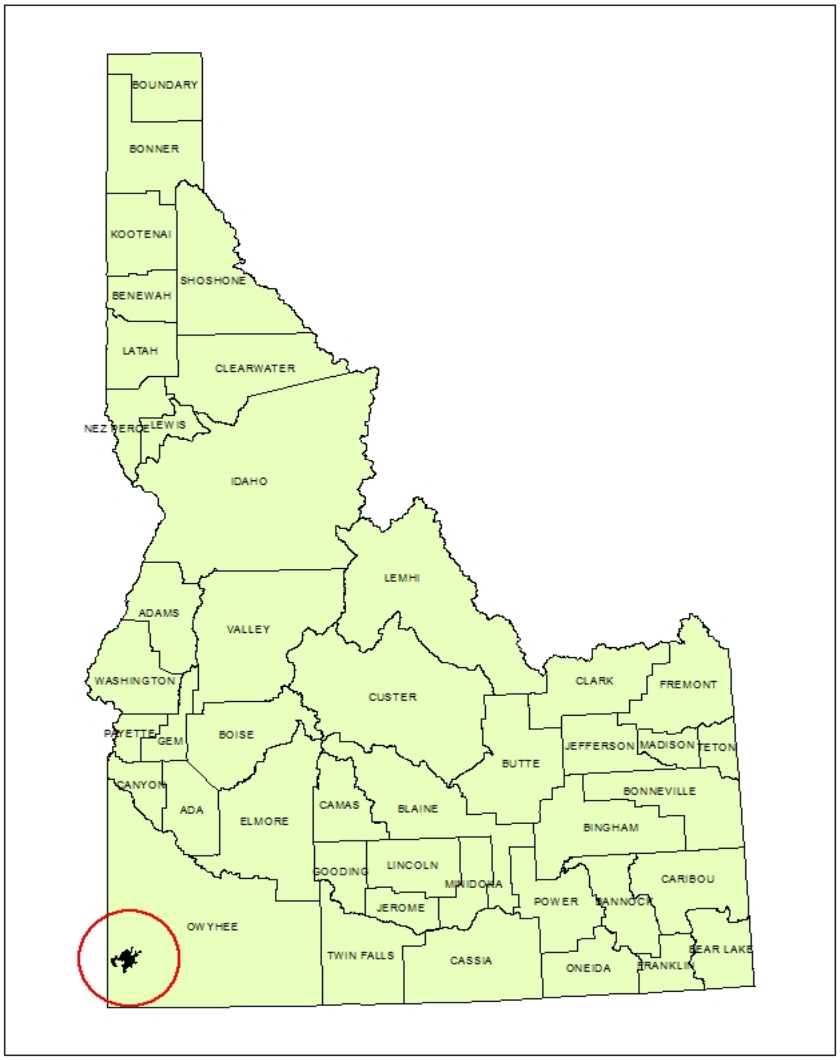


Fig 2. Location of Tongue-Crutcher Complex fire in Owyhee County, Idaho

Burn Severity of Remotely Sensed Data

Following Key and Benson (2006) fire severity for the study area was calculated using raw 30-m multispectral Landsat data to determine pre- and post-fire normalized burn ratio (NBR) and subsequent differential normalized burn ratio (dNBR) for each pixel

(Fig. 3). Pre- and post-fire NBR values were calculated using the following NBR equation where B4 represents Band 4 of the electromagnetic spectrum and B7 represents Band 7 of the electromagnetic spectrum.

$$NBR = (B4 - B7) / (B4 + B7)$$

To determine the magnitude of change between the pre- and post-fire environment, dNBR values were calculated for each pixel using the following equation.

$$dNBR = NBRprefire - NBRpostfire$$

As it is assumed that unburned environments contain similar reflectance signatures between separate sample dates and thus have dNBR values closer to zero, pixels that exhibit greater positive or negative dNBR values correspond with greater environmental changes post-fire. The range of dNBR values were then classified in to five severity categories for the purpose of this study (Table 1).

Table 1. Severity levels classified by dNBR range following the method of Key and Benson (2006) (Scaled by 10^3).

SEVERITY LEVEL	dNBR Range
Unburned	-100 to +99
Low	+100 to +269
Moderate-low Severity	+270 to +439
Moderate-high Severity	+440 to +659
High Severity	+660 to +1300

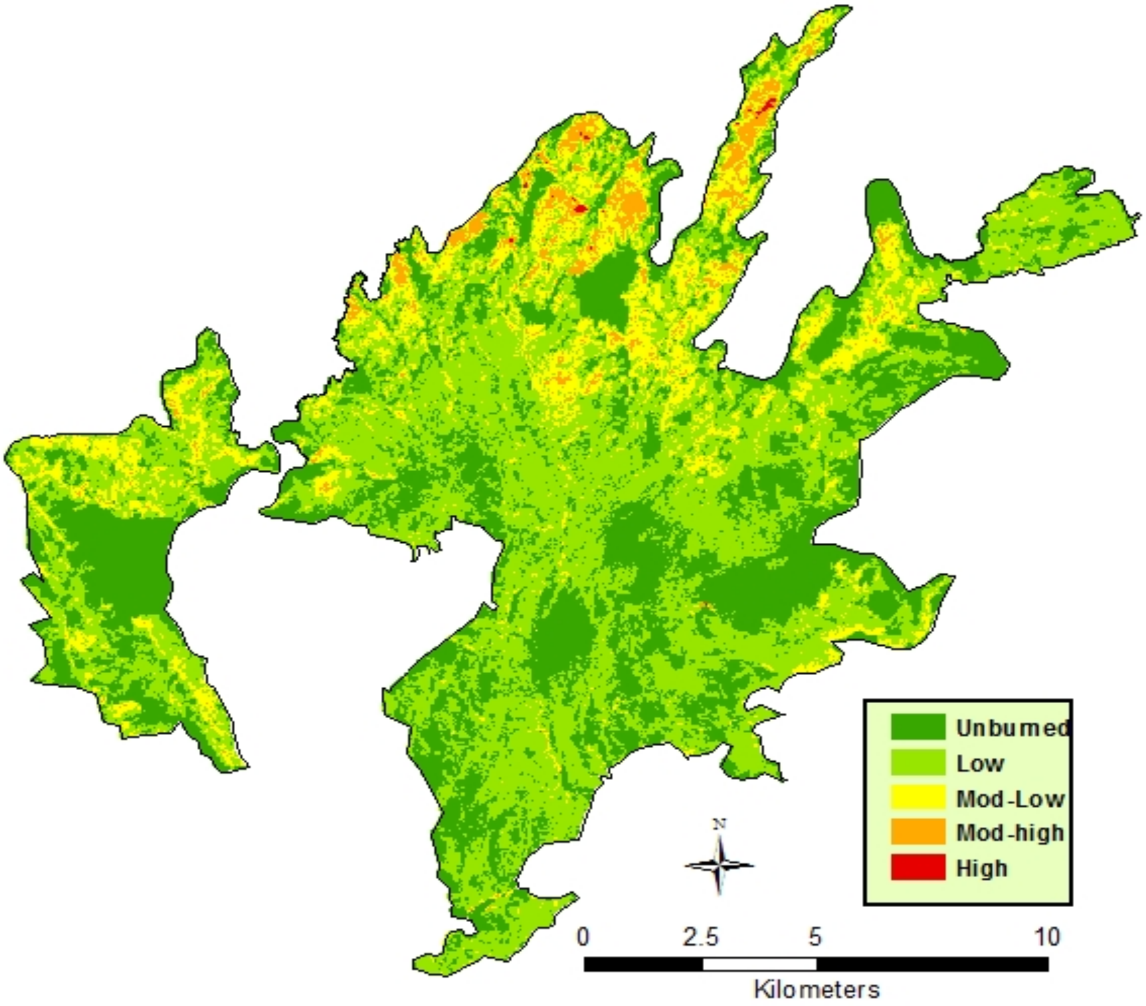


Fig 3. Burn severity map of the Tongue-Crutcher Wildland Fire Complex as determined by the differential normalized burn ratio (dNBR) method.

Sampling Methods

Vegetation data were collected in burned portions of the Tongue-Crutcher Wildland Fire Complex and unburned areas outside or inside of the fire perimeter within the mountain big sagebrush habitat type. Species canopy cover and type were recorded under burned and unburned juniper stems using a line transect and quadrat sampling method. Fifty by fifty cm quadrats were placed at 0.5 m increments on a transect laid from the center of the bole, extending in a random direction outward, to one meter outside of the crown.

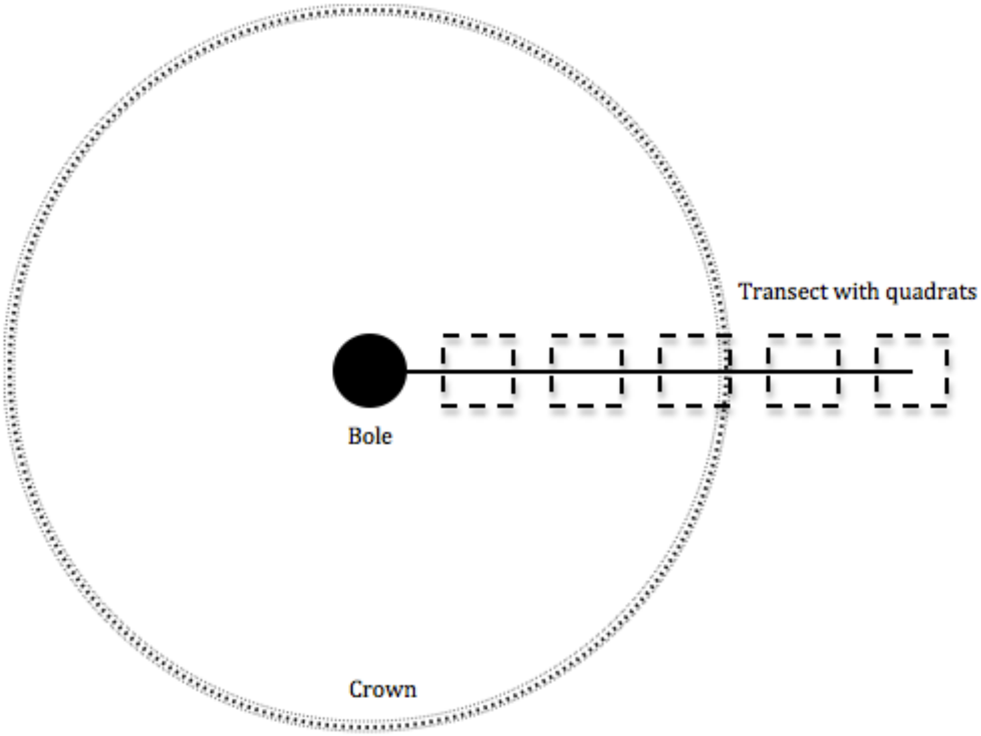


Fig 4. Vegetation sampling design utilized variable-length transects and 50x50-cm quadrats.

A total of 53 randomly selected juniper trees were sampled, 35 burned and 18 unburned. The randomly selected sample plots were stratified to cover the full range of remotely sensed burn severity (unburned, low, moderate, high), successional gradient (Phase 1, 2, 3, and mature), crown diameter (2-11 m) and elevation gradient (1756-2015 m) of the study area. Only juniper trees with a 2-meter or greater crown diameter exhibiting healthy growth were selected for sampling. Trees with less than 2-

meter crown diameters have little to no duff formation underneath the canopy structure are undetectable during wavelet transformation analysis.

Data analysis

Analysis of the vegetation data was conducted using multivariate ordination analysis. Vegetation canopy cover data and environmental conditions (e.g. elevation, burn severity, pre-fire successional phase, duff depth, litter depth) data were compiled in Microsoft Excel and formatted for specific use in the PC-ORD software platform (McCune et al. 2002). Multivariate ordination analysis was chosen among other analysis techniques in order to isolate and identify dominant trends in species composition and individual sample plots in relation to sample plot variables. Species presence and cover represented the primary quantitative matrix, analyzed in coordination with secondary matrix composed of the individual categorical sample plot variables.

Detrended Correspondence Analysis (DCA) ordination technique was chosen over other methods because it is well suited to ecological data sets and terminology based on environmental variables and species (McCune et al. 2002). DCA ordinates both species and sample units simultaneously using an eigenvector ordination technique based on correspondence. The detrending process addresses the arch effect frequent with the parent technique, Reciprocal Averaging (RA). Detrending divides the first Axis into a number of segments prior to the scores on the second Axis being adjusted so that the mean scores within each segment is zero. The rescaling process is designed to address the tendency to compress the Axis relative to the middle, a common problem in RA. The DCA ordinations were performed using relative Euclidean distance in the PC-ORD software as recommended by McCune et al. (2002).

The main study objective test was executed with species cover data as the primary matrix and the isolated duff depth data as the categorical variable in the secondary matrix. Subsequent runs were conducted with the complete species cover matrix and the complete categorical matrix, containing all fields, as well as matrices containing burned plots only. Ordination results were analyzed by suggesting interpretations of the Axis representations, interpreting location of cover types sample stands and agglomerative clustering, and examining software generated groupings. Several 2-dimensional XY graphs and Ordered Main Matrix graphs were generated for analysis and discussion of each of the ordination objectives. Ordered main matrices list species relevant to their location along the Axis and assign a coded weight to the overall cover of that species in a given stand.

Landscape Analysis

Wavelet analysis was used to identify the location and crown diameter of individual trees. Wavelet analysis is an effective image processing technique that has the capability to automatically represent ecological patterns from aerial photography at a variety of spatial scales (Strand et al. 2006). Following Strand et al. (2006), a discrete wavelet transformation was used to identify individual features, juniper trees, within high spatial resolution (<1 meter) panchromatic aerial photography. Discrete wavelet transformation uses convolving ever-increasing sizes (i.e. dilation scales) of wavelet shape within the imagery.

Further following Strand et al. (2006), the ‘Mexican hat’ wavelet equation was used for identifying the location and crown diameter of individual juniper trees due to its smooth edges and spherical shape, generally representing the appearance of a juniper crown in aerial photography. The Mexican hat equation convolves the range of dilation scales likely to match the crown diameters of individual juniper trees (1 to 12meters, incremented at .1 meters). The output of the wavelet transformation contains data on individual trees that is used to create the visualization in the GIS environment by overlaying the information onto the aerial photograph of the study area.

The individual tree data produced during the wavelet transformation allows for the opportunity to develop additional parameters to quantify ecologically relevant patterns in the juniper sagebrush steppe environment. The following empirical equations, developed from field sampling in the Owyhee Mountains, utilize the crown diameter output values for individual juniper trees produced during the wavelet transformation to estimate the duff and litter depths under the canopy of juniper trees across the landscape.

$$Y = -0.829 - 1.803 * D + 1.044 * C$$

Y = Predicted duff depth (cm)
D = Distance from center of stem (m)
C = Crown diameter of juniper tree (m)

Equation 1. Duff depth equation utilizing crown diameter output from wavelet transformation (n=83, $p < 0.0001$, $R^2 = 0.80$).

$$Y = 0.0702 - 1.567 * D + 0.867 * C$$

Y = Predicted litter depth (cm)
D = Distance from center of stem (m)
C = Crown diameter of juniper tree (m)

Equation 2. Litter depth equation utilizing crown diameter output from wavelet transformation (n=83, $p < 0.0001$, $R^2 = 0.74$).

Following the wavelet identification of individual tree crown diameters and utilization of Equations 2 & 3, the total accumulated duff/litter load beneath each tree was calculated using the mean bulk density value (0.23 g/cm^3) from field collected samples (Chapter II). To determine the total load of duff/litter beneath each tree (Table 2), the sum of concentric 1-m rings from the bole to the edge of the crown was calculated using distance from the bole, combined duff/litter depths, and bulk density.

Table 2 represents the duff/litter weight beneath trees with crown diameters of 1 to 20 m. A landscape scale representation of duff/litter fuel loading could then be created in the GIS environment by replacing wavelet recognized crown diameters with corresponding duff/litter weight values. The loads were summarized for trees within 30-m pixels.

Table 2. Duff/litter fuel loading beneath juniper crowns

Crown Diameter (m)	Duff/Litter (Kg)
12	2160
11	1652
10	1233
9	890
8	620
7	409
6	254
5	170
4	73
3	29
2	9
1	2

RESULTS

Mean vegetation cover and standard deviation was calculated from raw data for all species present in burned and unburned sample plots (Table 3). Juniper litter and bare ground composed the highest mean cover values for unburned plots with the highest vegetative cover represented in native perennial bunch grass species: FEID, PSSP, ACOCNE, POSE. In burned plots, bare ground exhibited the highest mean cover followed by snowbrush and cheatgrass. Snowbrush was recorded on a total of 64 burned plots, 14 of which contained additional species, representing a <24% cohabitation rate of snowbrush and any other species. Cheatgrass had the highest cover in 79% of burned plots in which it was present.

Table 3. Mean percent cover and standard deviation for all species found in burned and unburned sample plots

Mean (Unburned)	St. Dev. (Unburned)	Mean (Burned)	St. Dev . (Burned)	Cover Type
28.12	37	47.14	38	Bare Ground
0.00	0	21.82	40	CEVE
0.93	6	9.17	22	BRTE
1.81	7	5.25	18	Rock
0.58	3	1.92	5	CRAC
0.34	<1	1.26	3	EPPA
0.02	<1	1.18	7	GABO
0.41	<1	1.12	3	STME
1.21	3	1.09	5	LUSE
1.83	4	1.08	6	PSSP
1.83	6	0.79	4	ACOCNE
1.05	4	0.77	3	POSE
0.63	2	0.77	4	ELEL
0.65	5	0.76	7	BASA
0.20	<1	0.72	2	AGOS
0.18	<1	0.29	1	COLI
0.00	0	0.28	3	TRDU
0.93	3	0.27	1	COPA
0.46	1	0.20	1	PHLO
11.69	28	0.20	3	FEID
0.10	<1	0.11	1	CRYPT
0.00	0	0.10	1	ALAC
0.14	<1	0.03	<1	VIAD
0.12	<1	0.02	<1	POPR
0.06	<1	0.01	<1	POBU
45.95	41	0	0	Litter

For the primary ordination focusing on the relationship between duff depth and species composition, the duff depth gradient was categorized into five separate classes. Class 0 strictly represents sample plots without pre-fire duff accumulation. The Class 0.5 represents all sample plots that had a pre-fire duff depth greater than zero but less than 1 cm (0 cm < Class 1 < 1 cm). Class 1 represents duff pre-fire depths greater than 1 cm but less than 4 cm (< 1cm Class 2 < 4 cm); Class 2 represents pre-fire duff depths greater than 4cm but less than 6 cm (< 4 cm Class 3 < 7 cm); and Class 3 represents all pre-fire duff values greater than 7 cm (Class 4 > 7 cm). Ordination Axis 1 explains 61.4% of the variation, Axis 2 explains 22.7% of the variation, and Axis 3 explains 1.7% of the variation (Fig. 5). Ordination clearly shows that high pre-fire duff depth results in lower species richness 6 years post-fire and that the pre-fire duff depth affects the plant community composition. Raw data indicates a total of 20 species were recorded in Class 0 sites, 21 in Class 1, 20 in Class 2, 15 in Class 3, and 14 in Class 3. We interpreted that for the post-fire ordination (Fig. 5) that Axis 1 represents the burn severity gradient, where the low value on Axis 1 represents the lowest burn severity designation. Axis 2 is the pre-fire successional gradient, with the low value on the Axis 2 representing the most mature successional status pre-fire. No axes were interpreted beyond Axis 1 and 2. Species codes are listed in Appendix I.

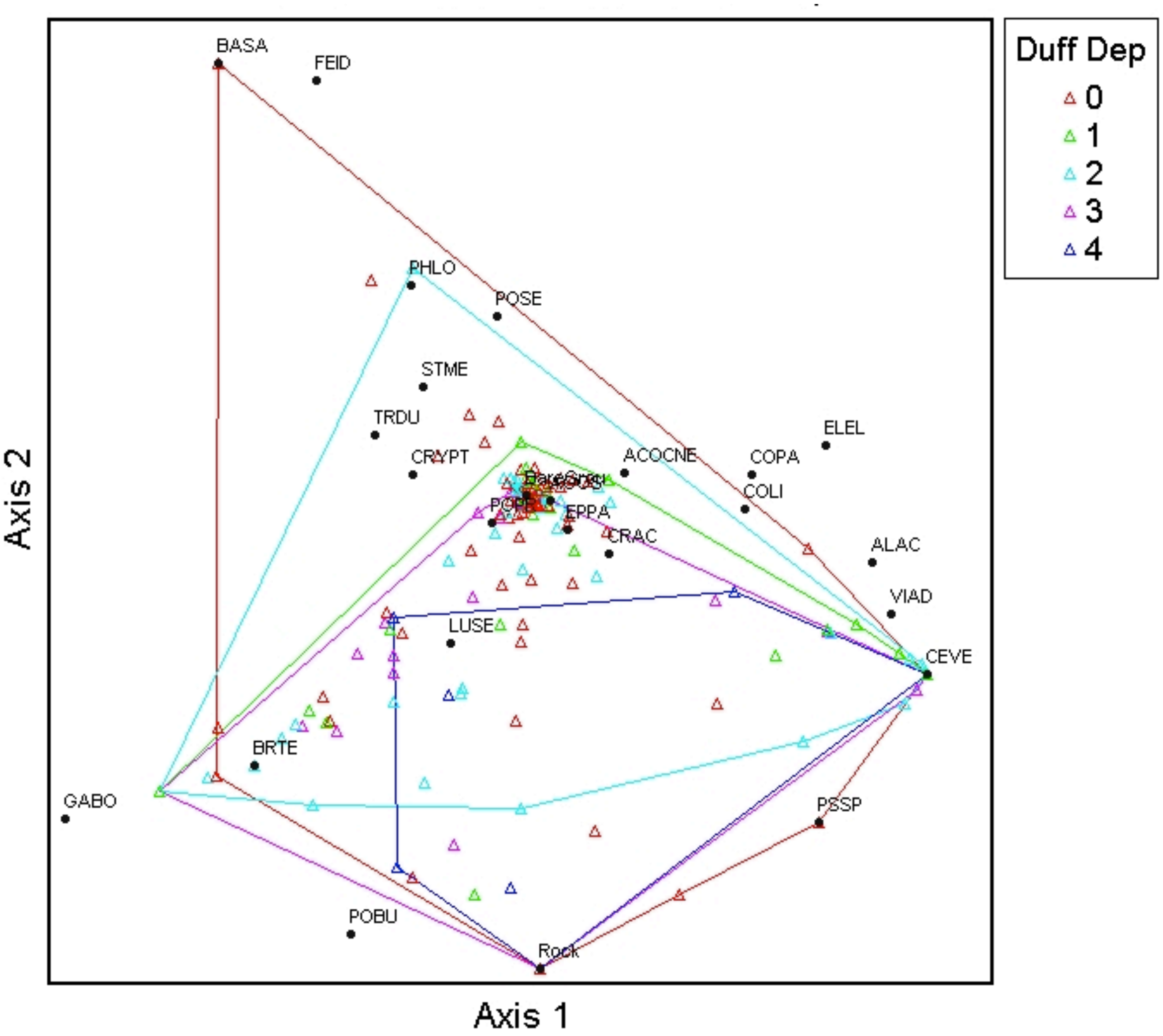


Fig 5. Ordination output using species cover 6-years post-fire and pre-fire duff depth (cm) grouping for burned plots only. Axis 1 represents the burn severity gradient, with increasing severity from left to right. Axis 2 is the pre-fire successional gradient, with decreasing maturity from bottom to top.

Vegetation data classified by duff depth is represented in an ordered main matrix in Figure 6. Species are ordered from left to right in the order in which they occur on Axis 1 of Figure 5. Each quadrat is labeled with stand number and color identification for the duff depth calculated for that sample plot. The shading for each cell is the determined by the percent cover; darker shades represent a higher percentage of cover. Snowbrush exhibits dominant cover in duff depths greater than 1 cm at a rate nearly 3 times that of duff depths less than 1 cm.

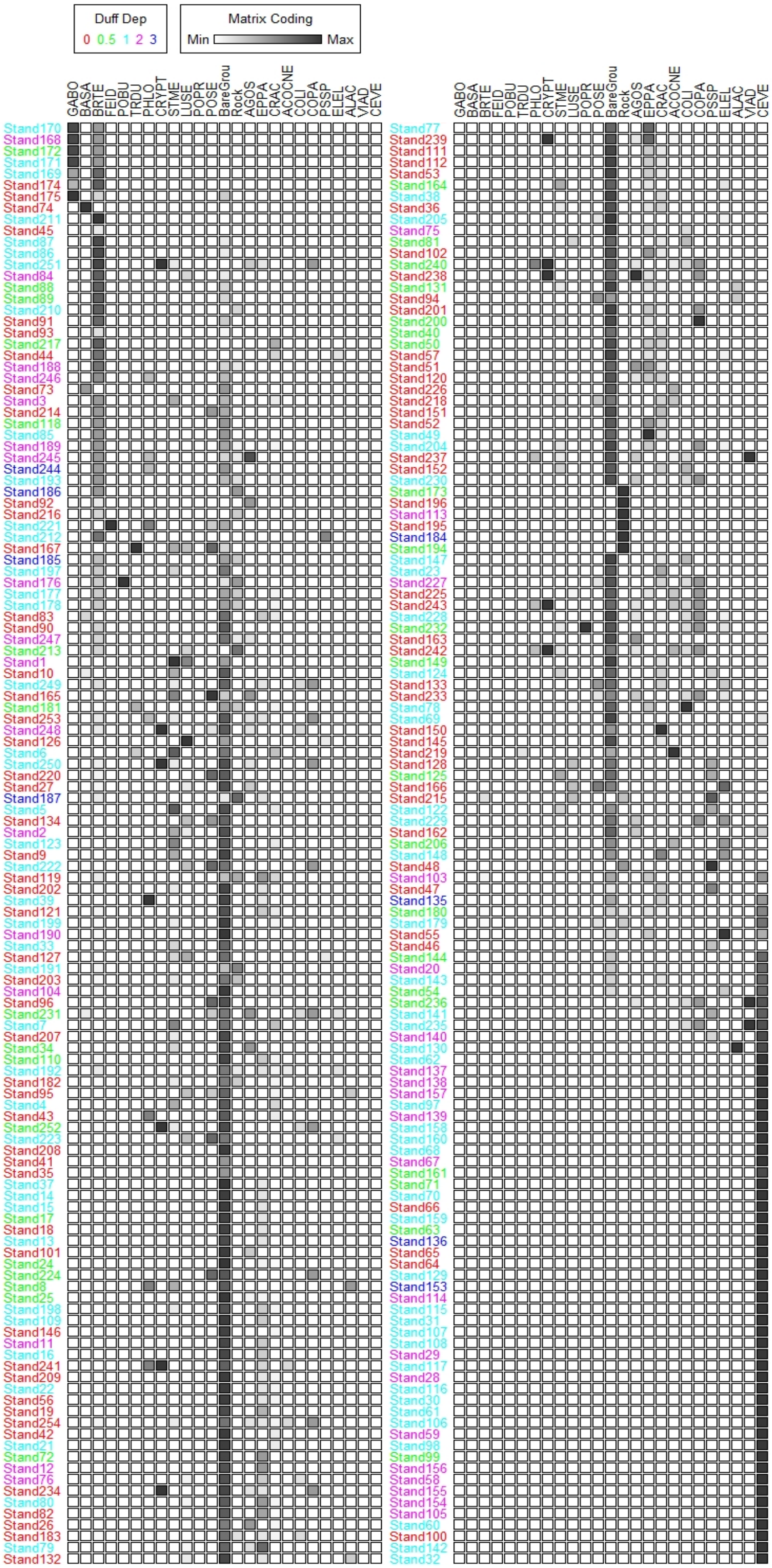


Fig. 6 Ordered main matrix for pre-fire duff depth gradient - vegetation analysis. Species ordered left to right as they appear on Axis 1 of Fig. 5.

The second ordination test utilized data containing the vegetation and categorical data for burned plots (Fig. 7). Axis 1 explains 61.4% of the variation, Axis 2 explains 22.7% of the variation, and Axis 3 explains 1.7% of the variation. A suggested interpretation of this data is that Axis 1 represents the burn severity gradient, where the low value on Axis 1 represents the lowest burn severity designation. The suggested interpretation of Axis 2 is the successional gradient, with the low value on the Axis 2 representing the least mature successional stage. In Figure 7, severity 1 represents low burn severity plots; severity 2 represents moderate-low burn severity plots; Severity 3 represents moderate-high burn severity plots according to the dNBR classification in Table 2. Software generated output created a dominant grouping based on the burn severity (Fig. 7). No Axis beyond Axis 1 and Axis 2 were interpreted.

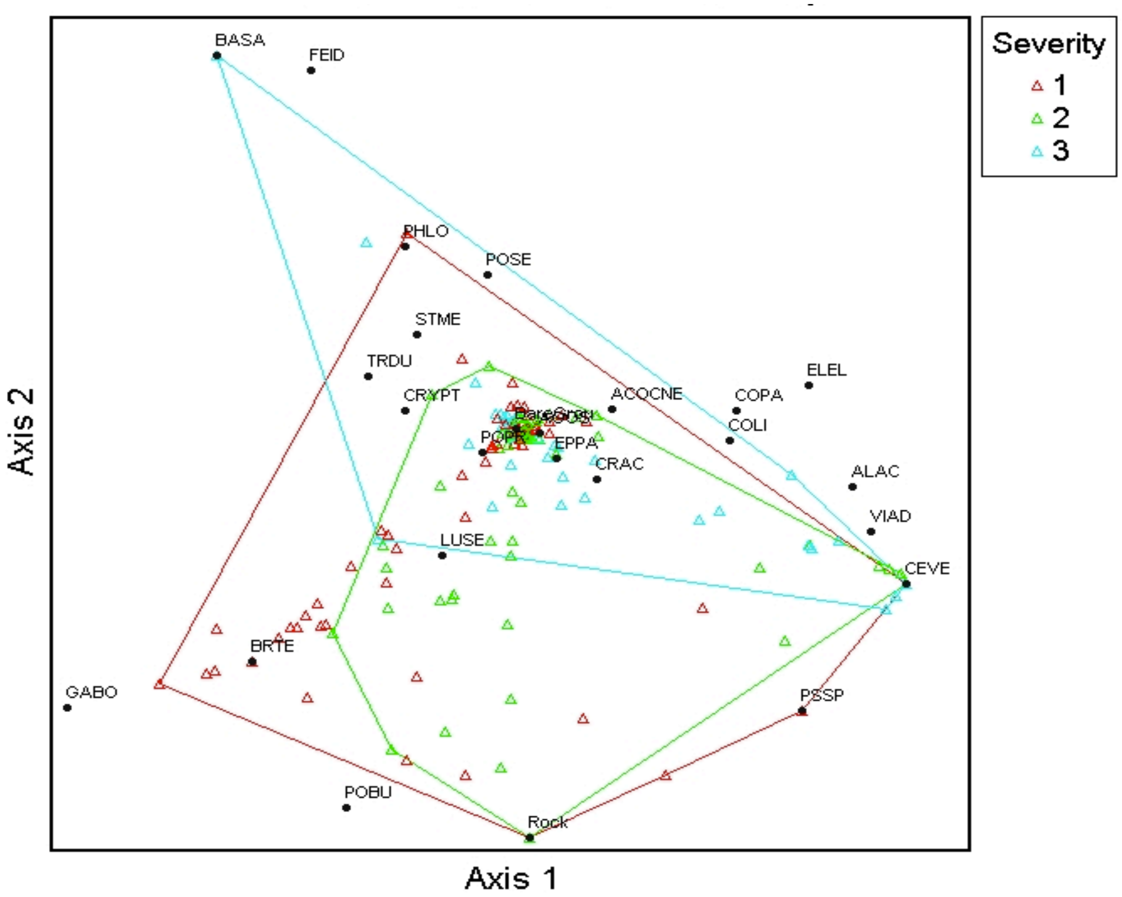


Fig 7. Ordination using burned plots only. Severity class is shown as dominant software generated grouping variable. Axis 1 represents the burn severity gradient, with increasing severity from left to right. Axis 2 is the pre-fire successional gradient, with decreasing maturity from bottom to top.

Vegetation data classified by severity is represented in an ordered main matrix in Figure 8. Species are ordered from left to right in the order in which they occur on Axis 1 of Figure 7. Each sample plot is labeled with stand number and color identification for the burn severity of that sample site. The shading for each cell is the determined by the matrix coding, or percent cover; darker shades represent a higher percentage of cover.

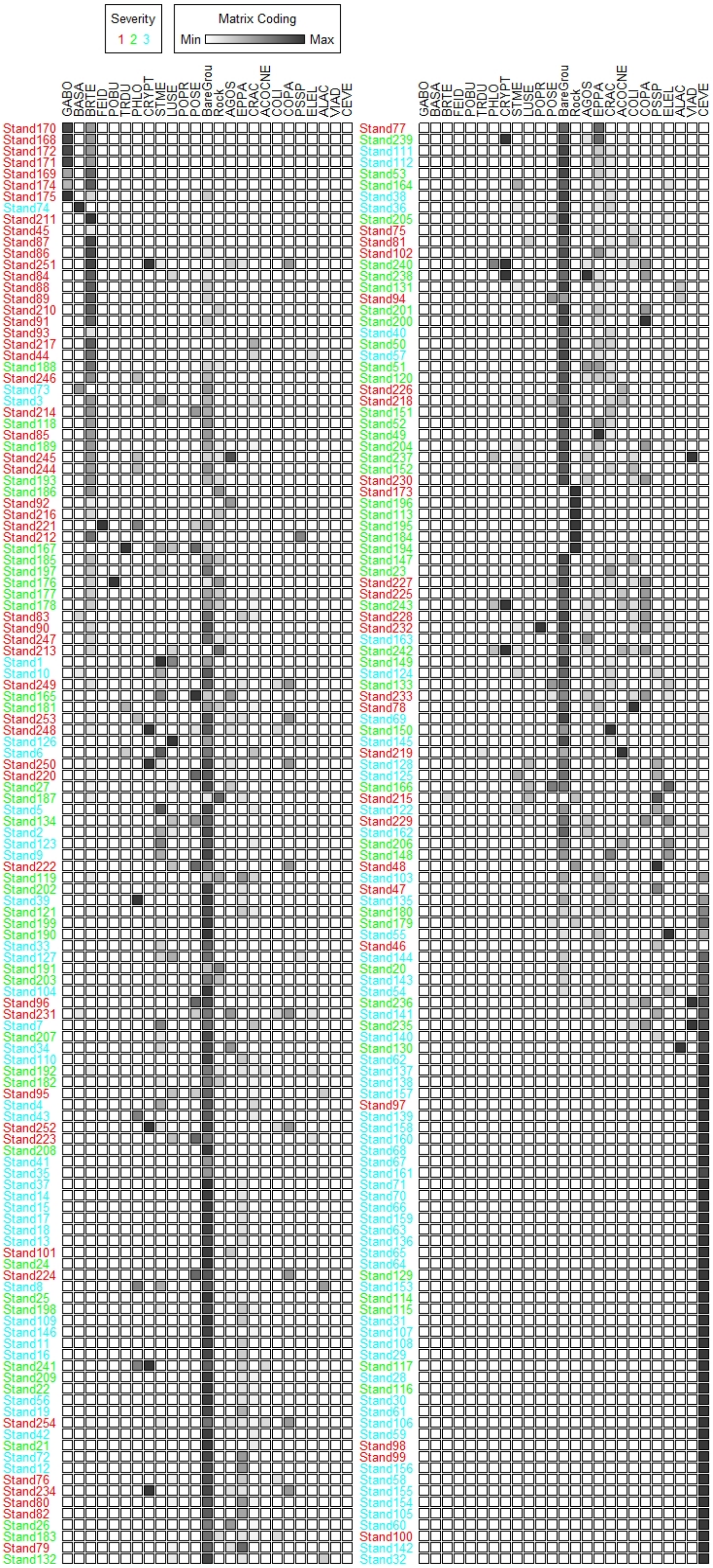


Fig. 8 Ordered main matrix for burn severity - vegetation analysis. Species ordered left to right as they appear on Axis 1 of Fig. 7.

Landscape scale analysis of ground fuel loading using wavelet techniques is demonstrated in Figure 9. Arranged side by side with a 2004 aerial image at the same spatial scale, the wavelet imagery represents the pre-fire duff & litter fuel loading in 30x30m pixels of an area partially burned during the Tongue-Crutcher Wildfire Complex.

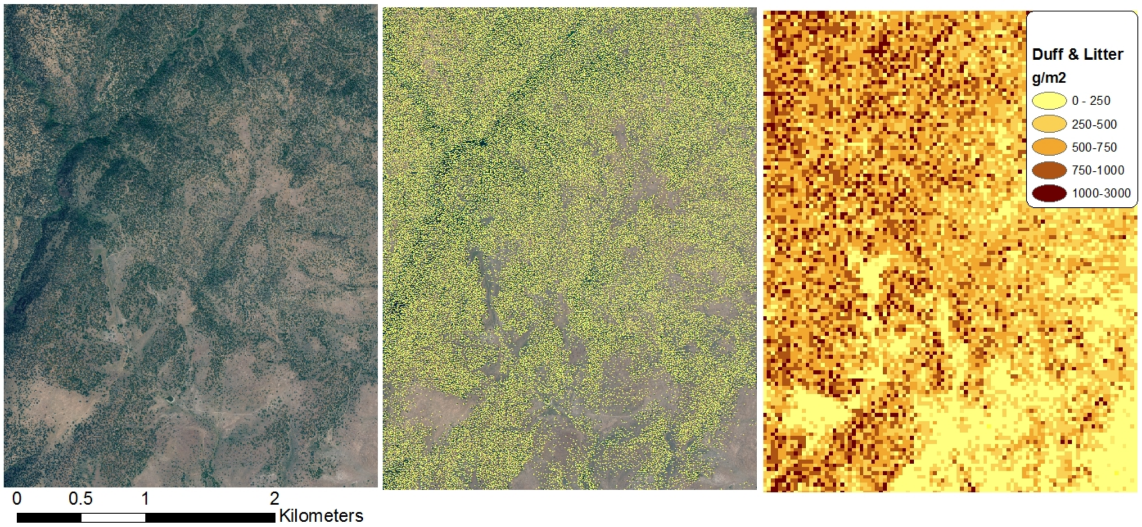


Fig. 9 Pre-fire aerial photograph, wavelet crown recognition and duff/litter loading map of the study area (Left to right)

DISCUSSION

Duff depth and post-fire species composition

The main objective of this study was to determine the relationship between pre-fire duff depth gradient and post-fire vegetation species cover and composition. The results from the ordination test designed for this objective reveal the groups of depth classes reducing in size as the duff depth increased (Fig. 5). Concurrently, as the depth class groupings decreased in relative size within the ordination space, a greater number of species points became excluded from the groupings. This trend reveals an overall species richness dynamic that it is defined by a decrease in total species richness, at least up to 6 years post-fire, as the pre-fire depth duff increases.

This decreasing species richness along the increasing duff depth gradient may be explained by the influence of smoldering combustion of the duff layer during the wildfire event. The presence of deeper duff along the gradient from the bole represents a greater amount of fuel available for ignition and combustion. The increasing duff depth gradient, or increase in fuel load from the bole, is likely to exhibit a greater duration of smoldering combustion. Prolonged smoldering combustion of duff layers will ultimately result in increased soil heating, putting soil or duff stored seeds at increased risk for mortality (Stephan et al. 2010). As deeper duff depths are positively associated with larger trees or mature stands, the decrease in species richness along duff depth gradient is more pronounced in mature stands. This trend is represented on Axis 2 (Fig.5) where fewer species points are present at the lower ends of the Axis, defined as the mature end of the successional gradient.

Initial evaluation of Axis 1 and Axis 2 reveals little indication that there is a significant influence of the duff depth gradient on any one particular species. However, upon detailed review of the ordered main matrix (Fig. 6), the snowbrush cover type exhibits dominant cover in duff depths greater than 1 cm and has a low association rate (< 24%) with other species. The abundance of snowbrush cover on areas with duff depths greater than 1 cm suggests a relationship between germination and presence of a combustible fuel bed. Duff and litter beds deeper than 1 cm may be required in order to create enough heat to insure proper germination of soil stored snowbrush seeds and subsequent site domination. Beyond the relationship between snowbrush cover and duff depth, no other specific species-depth relationship could be drawn from the data. Additionally, there was no indication that perennial and annual species responded differently along the post-fire duff depth gradient.

Burn Severity and post-fire species composition

The second ordination utilized vegetation data of burned plots only, resulting in a dominant grouping trend based on the burn severity classes (Fig. 7). This analysis resulted in a major cluster of plots around the bare ground cover type (Fig. 7) at the relative center of both axes, an expected result given presence bare ground after a wildfire event. The distance and severity class of sample plots not present in the 'Bare Ground' cluster at the center of the XY graph reveal a potential relationship between lack of vegetation cover and burn severity. A trend of increasing proximity to the bare ground cover type occurs with higher burn severity. Sample plots designated as 'low' burn severity or severity Class 1 are notably more distant from the bare ground cover type than those of severity Class 2 and Class 3. Concurrently, sample plots with severity Class 2 and Class 3 designations show increasing proximity to the bare ground cover type. This trend suggests a relationship between overall vegetation cover, and presence of bare ground, as it relates to the burn severity of a location. This may be a result of a decrease in perennial herbaceous vegetation and an increase in annual forbs along the increasing burn severity gradient of Axis 1 (Fig. 7).

Higher severity fires are recognized to inflict greater bud mortality on some perennial bunch grass species thus allowing for an annual forbs dominance stage in the early years following high severity site (Stephan et al. 2010). Idaho fescue located is associated with low severity on Axis 1 (Fig. 5 & 7), is adapted to survive low severity fires but is often killed by more severe fires. Accumulation of fine dead materials at the base of the plant produces long duration combustion capable of lethal temperatures and killing the sensitive root crown structure (Zouhar 2000). Other perennial bunch grasses such as bluebunch wheatgrass and bottlebrush squirreltail (*Elymus elymoides*) are recognized to be more fire tolerant and are located at the high end of the fire severity gradient in the ordination tests (Fig. 7). Bluebunch wheatgrass is generally well protected from fire due to coarse stems that produce short quick burns, transferring little heat to sensitive structure. Even when most above ground herbaceous material is removed bluebunch wheatgrass has a high survival rate, particularly in later months of the season (Zlatnik 1999). Bottlebrush squirrel tail exhibits similar traits in that low-density coarse stems produce short-lived flame residency allowing for little downward transfer of heat to the sensitive below ground growth structure (Simonin 2001). The fire persistence traits of these perennial bunchgrass species are apparent in the results and may provide valuable management implications for the sagebrush steppe.

Cheatgrass and Snowbrush

Cheatgrass and snowbrush represent the two species with the highest mean cover across all burned sample sites (Table 3). The ordination of burned plots (Fig. 7) reveals potential relationships between specific species cover and burn severity class. Cheatgrass and snowbrush exhibit particularly notable behavior in relation to burn severity and species cover. Cheatgrass is located well outside of both the Class 2 and Class 3 burn severity groupings, as well as exhibiting a notable cluster of Class 1 burn severity sample plots within close proximity to Cheatgrass in the ordination space (Fig. 7).

The location of the cheatgrass in relation to numerous low burn severity sample plots, as well the placement on Axis 1 (Fig. 7), defined as burn severity gradient, suggests that cheatgrass is most prevalent in low burn severity areas of the study site. The Axis 1 ordered main matrix (Fig. 8) further indicates that cheatgrass occurs almost exclusively in Class 1 burn severity sites. Additional behavior exhibited by the cheatgrass is the relative isolation from other species cover types in ordination space. This suggests there is a limited association of cheatgrass cover and the presence of other species. Review of the raw vegetation data indicates that only 4% of plots with cheatgrass cover of 50% or greater contained more than two other species. The ordered main matrix for this ordination (Fig. 8) solidifies this finding, showing few, if any, species present when cheatgrass is dominant.

The increased prevalence of cheatgrass in the low severity burn sites may be explained the patchy or incomplete consumption of fuels in that particular area. Unburned patches within the burn perimeter offer ideal edges for the transportation, establishment, and propagation of cheatgrass seeds in newly disturbed areas.

Contrarily, more severely burned areas would offer less edge with more complete combustion of surrounding fuels, including cheatgrass seed sources and soil-stored seeds. The disassociation of cheatgrass from other species in these sites may easily be explained by the invasive, competitive, and dominant characteristics of cheatgrass particularly on newly disturbed sites (Zouhar 2003). The results from this study suggest that while cheatgrass does not exist extensively in pre-fire stands (Table 3), the disturbance regime presented by low severity burn sites provide an ideal location for transportation and propagation of nearby seed sources. With few, if any, other annual grasses exhibiting similar growth behavior, cheatgrass is able to readily compete and compose a significant portion of total vegetation cover on newly disturbed sites.

Snowbrush also exhibits revealing behavior about species cover as it relates to burn severity in the study area. While snowbrush acts as a grouping point for all of the burn classes, the proximity of Class 2 and Class 3 sample plots in ordination space are much closer than those of Class 1 burn severity. Additionally, snowbrush is located on the far high severity end of Axis 1 in Figure 5 and 7, defined as the burn severity gradient. Further examination of this trend in the Axis 1 ordered main matrix from Figure 9 offers the same conclusion, as heavy snowbrush cover is represented primarily in Class 3 stands and minimal presence in other severity classes. The heat requirement of snowbrush seed germination makes it an ideal candidate for the environmental conditions following a moderate to severe wildfire in the sagebrush steppe ecosystem (Anderson 2001). Additionally, moderate to severe fire conditions would increase the amount of litter and duff removed from the soil surface, allowing for greater exposure of soil-stored seeds beneath the organic layers (Anderson 2001). The results of this study indicate snowbrush as an extremely prevalent, if not exclusively dominant, cover type in moderate-severely burned areas of the juniper woodlands post-fire.

Landscape analysis

Results from the wavelet analysis and duff loading calculations demonstrate that the use of discrete wavelet transformations can be an accurate and effective method in mapping sub-crown properties derived from individual stems on the landscape level. Side-by-side comparison of aerial imagery and duff loading outputs (Fig. 9) allows for an enhanced visualization of the extent and distribution of potential surface fuels, more specifically duff/litter, on a scale not previously available. The development and exemplification of these methods can easily be adapted to a wide range of ecological scenarios in which crown dynamics play an important role in calculable sub-crown properties. The use of these techniques provides an effective and valuable tool for researchers and managers with the intent of mapping fine scale ecologic properties on a larger spatial scale. Spatially explicit layers of ground and surface fuels can be used customized inputs to fire effects prediction systems such as the Wildland Fire Assessment Tool (Hamilton et al. 2012) to predict fuel consumption, emissions, soil heating and tree mortality at scales relevant to fire management.

MANAGEMENT IMPLICATIONS

The findings of this study reveal additional challenges for land managers attempting to reduce the invasion of juniper woodlands in to the sagebrush steppe and/or revert these woodlands back to sagebrush ecosystems. The decline in species richness along the duff depth gradient and dominant species cover at varying severities suggests that wildfire or fire use in developed juniper woodlands may result in lengthier recovery times for species biodiversity. The utilization of fire as a management tool may not be ideal if post-fire species diversity or promotion of native perennial bunch grasses is a management objective. The decrease in these bunch grass species in burned areas in combination with the extensive prevalence of species such as cheatgrass or snowbrush are likely to have significant implications on management and potential land use options.

Dense canopies of snowbrush can persist for in excess of 40 years without dominant tree cover and are recognized to deter domestic livestock forage (Anderson 2001). It is expected that snowbrush cover will remain dominant in many areas of the Tongue-Crutcher fire perimeter until significant juniper shading is present. This will likely result in minimal growth of other sagebrush steppe species and provide limited domestic grazing opportunities for these moderately to severely burned areas with heavy snowbrush cover. Additionally, areas of prevalent cheatgrass cover have the ability to persist for decades, competing with native species for post-disturbance resources. Wide spread cheatgrass cover has the potential to alter future fire regimes and affect future seasonal grazing opportunities (Zouhar 2003). The high fire severity tolerances exhibited by specific bunch grass species such as bluebunch wheatgrass and bottlebrush squirrel tail indicate the value of these species when areas exposed to relatively severe fires in the future. Ultimately, the results of the species cover analysis in this study will contribute to a better management understanding of the varying environmental gradients and disturbance conditions that have the potential to alter post-fire vegetation recovery.

The use of discrete wavelet transformations to determine surface loading characteristics is a valuable tool for managers attempting to better understand fine scale ecologic processes on a larger scale. The framework and methods developed in this study provide valuable information for determining pre-fire fuel loading values that may be related to processes such as: vegetation presence, fire potential, potential fire severity and fuels recovery. The ability to determine sub-crown surface characteristics via simple algorithms provides significant opportunity for future research and management options on the landscape scale. The use of the wavelet methods similar to those provided in this study may reduce the need for costly and time-consuming field sampling as well reduce the need for reoccurring sampling methods. In addition, the wavelet analysis yields spatially explicit layers that can be used to customize inputs in spatial fire effects prediction models (e.g. WFAT, Hamilton et al. 2012).

CONCLUSION

The results and conclusions of this study indicate that the duff depth gradient in expanding western juniper woodlands will have multiple influences on vegetation recovery in areas affected by wildfire. Deeper duff depths associated with larger more mature stands may result in an overall decline of species cover in the post-fire community and have the potential to favor individual species, such as snowbrush, at specific pre-fire duff depths. Of stronger influence is the species response following varying levels of burn severity. Conditions favorable to low or high severity fires have the potential to promote the prevalence of species other than native perennial grasses, such as cheatgrass or snowbrush, for extended periods of time following a wildfire event, regardless of duff depth. Single species prevalence and the reduction of native perennial bunch grass species in the post-fire landscape will inherently affect the ecologic conditions of an area for an unknown period of time and influence the productivity of grazing opportunities and alternative land uses. The utilization of wavelet analysis techniques presented by this study represent an effective and valuable tool for determining landscape scale fuel loading from individual crown characteristics. These techniques are an objective and repeatable method for additional research applications in which expanding the spatial representation of a fine scale process is of interest. The methods, management implications, and conclusions of this study give a framework for additional research regarding the patterns and processes associated with the duff depth characteristics in the continuing expansion and maturation of western juniper woodlands

CHAPTER II – EXPLORATORY DUFF/LITTER COMBUSTION AND CONSUMPTION ANALYSIS

The expansion and successional maturation of the juniper woodlands in (*Juniperus* spp.) the Great Basin and on the Columbia Plateau may be resulting in historically unnatural accumulations of litter and duff, as has been the case in many mixed-conifer forests experiencing fire exclusion (Parsons and DeBenedetti 1979, Belsky 1996, Keane et al. 2002). The duff layer plays a crucial part in forested ecosystems as it protects soils from erosion, retains moisture, releases nutrients, and can influence post-fire forest regeneration as well as vegetation mortality (Valette et al. 1994, Hille and Stephens 2005). In some ecosystems, the consumption of duff under wildfire conditions is known to downwardly heat soil, influencing plant structure or soil stored seeds in the organic and mineral soil horizons (DeBano 1990, Brown et al. 1991, Hungerford et al. 1991).

The degree of influence smoldering combustion has on plant components are determined by the depth and the duration of sub-surface combustion (Stephan et al. 2010). Smoldering duff is recognized to exhibit temperatures between 500 and 600˚ C, well above the lethal temperature of 60˚ C for live plant tissue (Reinhardt et al. 1991). Soil stored seeds and live plant structure located in the organic layers are often at higher risk from fire due to the direct exposure to smoldering combustion processes (Stephan et al. 2010). Consumption of the duff layer by a wildfire can also stimulate seed growth in certain species, such as snowbrush ceanothus (*Ceanothus velutinu*), and foster plant regeneration (Hungerford et al. 1991, Anderson 2001). Removal of a thick duff layer during a wildfire scenario can allow for increased solar radiation and exposure to moisture in the post-fire environment, providing a more productive site for germination certain seed bank species (Hungerford et al. 1991).

The soil heating process that can result from the smoldering combustion of a duff profile is recognized to have altering effects on soil properties such as: structure, water-absorbing capacity, soil nutrients, and microbial populations. The ability of a given soil to absorb water after a fire event is directly related to the amount of organic matter consumed during the process (Hungerford et al 1991). Cations are generally increased following burning of organic matter while nitrogen may exhibit decreased productivity when tied up in the surface fuels and duff (Hungerford et al. 1991). Widely used fire effects models such as FOFEM 5.0 (First Order Fire Effects Model) utilize inputs of duff characteristics to predict potential soil heating at in varying soil types, depths and time intervals. Duff consumption values within the model are calculated using a physical model of heat transfer and burning rate of woody fuel particles contained within the duff layer. Total consumption of duff is determined by the cover type, depth, and duff moisture. Consumption rates are assumed to be constant and the duration of consumption is computed from total consumption and consumption rate (Reinhardt 2003). FOFEM further utilizes the total heat production rate and duration of duff consumption in predicting potential soil heating. Soil characteristics such as moisture, density and mineralogy can be input to further investigate the implications of duff consumption on soil heating.

Although variable duff properties have been utilized in fire effects modeling of soil heating, few methods and data collection procedures have been specifically developed for evaluating the consumption and combustion properties of western juniper litter and duff. The objectives of this study are to 1) Develop methods for collection and combustion of western juniper duff/litter samples, 2) Gather exploratory data on thermal properties of western juniper duff combustion, 3) Collect exploratory data on the consumption properties of western juniper duff.

METHODS

Duff Collection

Duff samples were collected on Juniper Mountain in Owyhee County of southwestern Idaho (116 W Long 43 N Lat), located in an area characterized by western juniper (Juniperus occidentalis ssp. *occidentalis*) in a sagebrush steppe (*Artemisia* spp.). The occurrence of western juniper in this area is primarily in the form of open savanna woodlands with interspersed rock canyons, small mountains, and riparian areas. Elevations for the study site were between 1756 and 2015 m with precipitation ranging from 330 to 406 mm. Average temperatures range from -6.0° C in winter months to 35° C during the summer. The soil composition of the study area is primarily mountain loam in an ecological site dominated by mountain big sagebrush (*Artemisia tridentata* ssp. *vaseyana*), bluebunch wheatgrass (*Pseudoroegneria spicata*) and Idaho fescue (*Festuca idahoensis*) (http://websoilsurvey.sc.egov.usda.gov). Juniper woodlands currently dominate the majority of the area in various developmental stages ranging from sagebrush with juniper seedlings to mature woodlands. All developmental phases (phase 1-3 and mature) described by Miller et al. (2005) are present in the area.

Duff samples were collected using 20 x 20 centimeter steel frame pressed (Figure 10) in to the litter/duff layer and removed in a block form. Samples were collected under the crowns of trees exhibiting 2-m or greater crown diameter presenting normal healthy growth consistent of what is typical in the area. Core samples were extracted in a manner in which any stratification or horizons within the duff remained as intact as possible during removal and transportation. Rigid packaging containers were prefabricated to match the size of the segments to insure that disturbance of the sample is minimized during transportation. Litter or lightly decomposed material remained on the upper most strata of each sample, keeping the representation of surface fuels consistent of those that would be present at that stage of tree growth.

Figure 10 20x20 cm steel frame used to extract duff samples for lab experimentation

A total of 40 samples were collected from the study site for combustion and consumption analysis. Samples covered a full range of environmental gradients (Chapter I) and were represntative of the expected duff/litter depths for the landscape. In addition to the collection of duff cores, small duff samples were collected and weighed in the field in order to determine moisture content at varying depths. Samples were then dried in a forced air drying oven at 60 ° C to remove moisture, reweighed, and moisture content was recorded.

Lab experimentation

All sample preparations and lab experimentations were conducted in the University of Idaho's IFIRE combustion laboratory. In order to keep moisture properties consistent, all samples were dried in a drying oven for a minimum of 72 hours or until moisture weight loss was no longer measurable. While it is recognized that consistent moisture content throughout a sample does not accurately represent the real-world duff moisture gradient, consistently dry samples were determined to be the most effective for exploratory method design and consumption/combustion data collection. All samples were weighed prior to combustion testing in order to establish a pre- and post-ignition standard for consumption percentages and bulk density.

Preliminary combustion boxes were designed to fit the exact dimensions, 20 x 20 cm, of duff core samples with four sides, a base and an open top. Boxes were constructed from plywood material and the bottom was lined with sand to prevent burning through the base. Initial testing revealed that the enclosed structure of the combustion box would not facilitate sufficient ignition and propagation through the duff sample despite multiple ignition methods including: hot coals, accelerants, direct propane torch, and excelsior. Due to questions about how conductive properties of the plywood material might affect thermal sampling and the inability to induce propagation in the sample, this combustion design was deemed ineffective.

A subsequent combustion box design was developed with a sand lined wooden base, coarse aluminum mesh sides, and an open top. This design was constructed to maximize convective airflow through the sample and facilitate unassisted propagation through the sample. Testing again revealed that ignitions methods were ineffective in starting uninhibited propagation through the sample. In a final effort to facilitate unassisted propagation through the sample, a steel fan was placed approximately 30 cm from the sample at a height that provided airflow across the surface of the sample (Figure 11).

Figure 11 Final combustion/consumption container and fan setup for lab experimentation

The fan was run at the lowest power setting providing a simulated 11 to 13 km per hour wind across the surface of the sample. The addition of an external air sourced proved to solve the ongoing complications of facilitating propagation and was added to the experimental design for further testing. Furthermore, it was determined that sample ignitions would be from exposure of a propane flame to the 'windward' side of the sample for a period of 5 seconds, successfully igniting the front edge of the sample.

Following the successful development of combustion design, uniform testing procedures were developed for thermal and consumption data collection.

Prior to the ignition of samples, two Type-K thermocouples were placed in the sample to record the thermal signatures as combustion occurred. One thermocouple was placed in the center of the litter strata and the other at the base of the sample where mineral soil would begin. A Pico TC-08 thermocouple logger recorded continuous real-time data at an interval of 45 seconds until both the uppermost and lowermost thermocouples recorded temperatures values of less than 60 ° C. All duff core samples were allowed adequate time to complete potential consumption prior to being weighed for final calculations. Following combustion, unconsumed material was taken from each duff core, weighed, and burned in a muffle furnace for 24-hours at 500 ° C to determine mineral content. Finally, duff properties and temperatures observed in the laboratory experiments were entered into the FOFEM model to estimate the temperature profile in the soil.

RESULTS

The following graphs (Fig. 12 – 14) represent a sample of the continuous real-time thermal data collected from the combustion of the litter and duff samples. A general trend in thermal curves was observed through many of the samples, highlighted by a sharp increase in temperature litter strata followed by a more gradual increase at the soil surface. Temperatures tended to remain higher at the soil surface for a longer period of time and experience a more gradual cooling than that of the litter strata. Temperatures near or in excess of 500 degrees Celsius were consistently observed through many of the samples with the duration of lethal temperature of 60 degrees Celsius varying between 1.5 and 6+ hours.

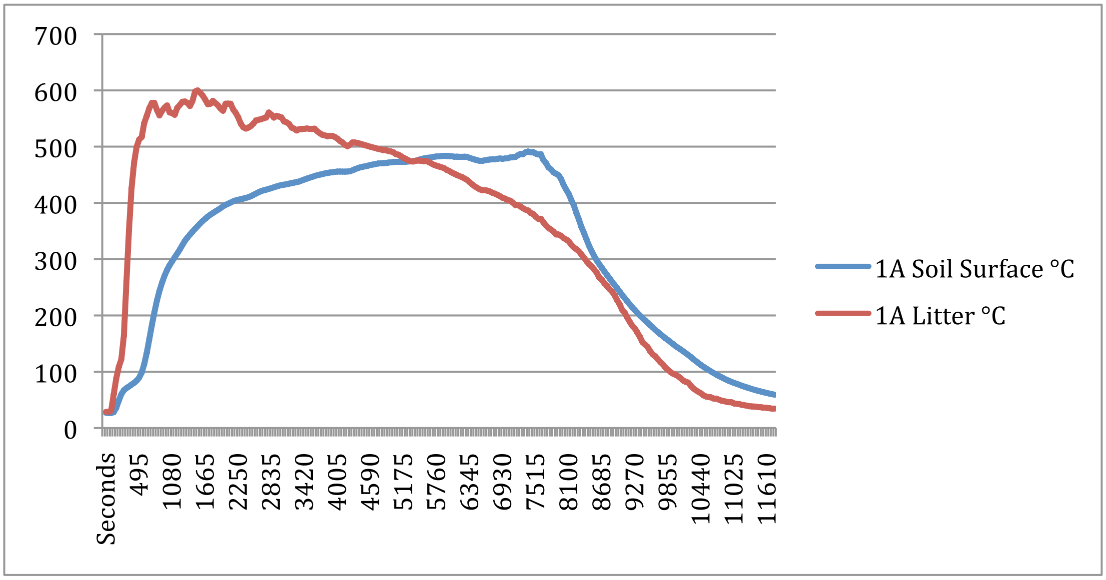


Fig. 12 Time-Temperature graph for combustion of sample 1A (4.5 cm depth)

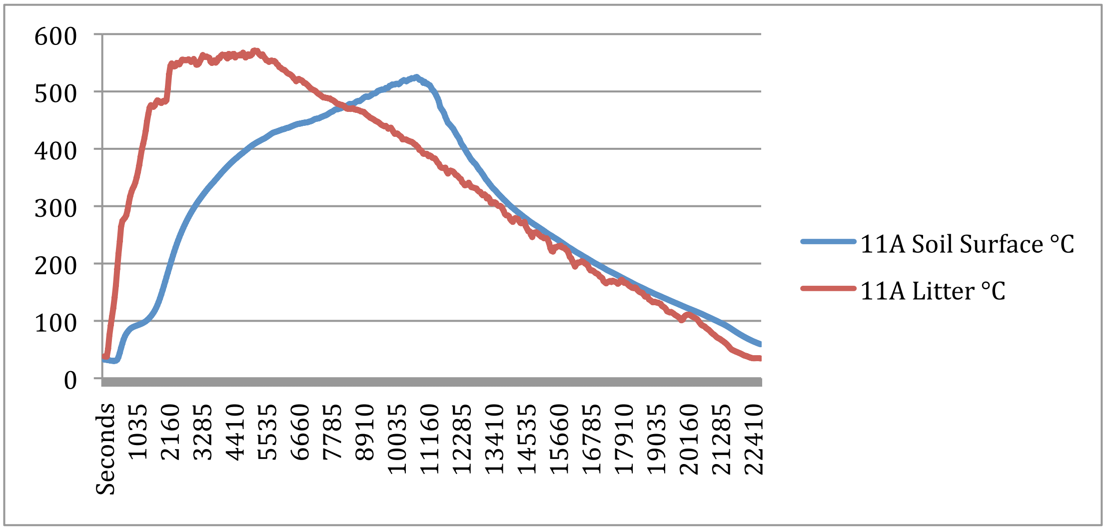


Fig. 13 Time-Temperature graph for combustion of sample 11A (6 cm depth)

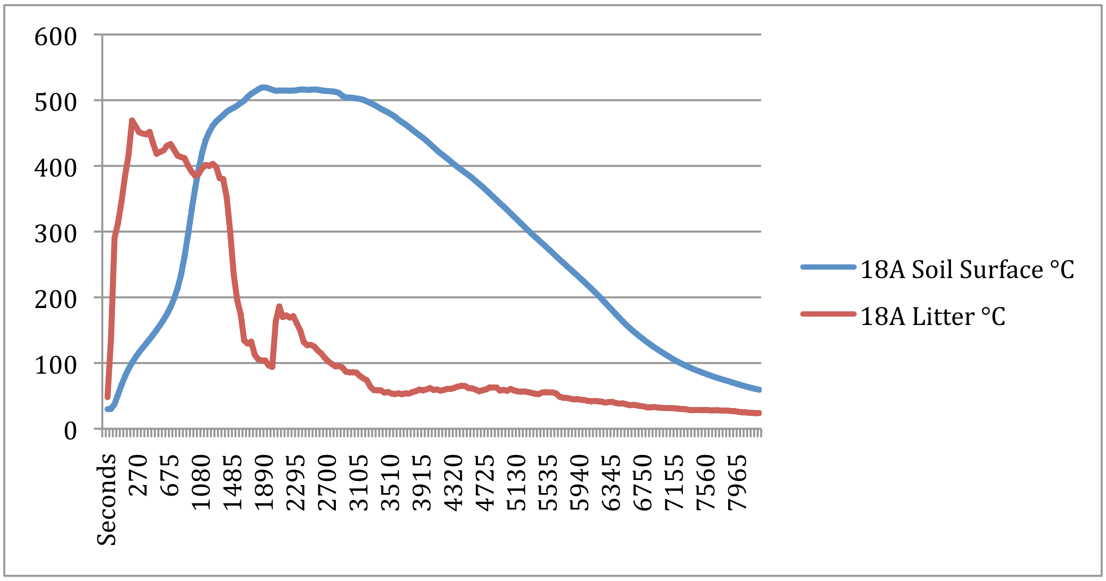


Fig. 14 Time-Temperature graph for combustion of sample 18A (4 cm depth)

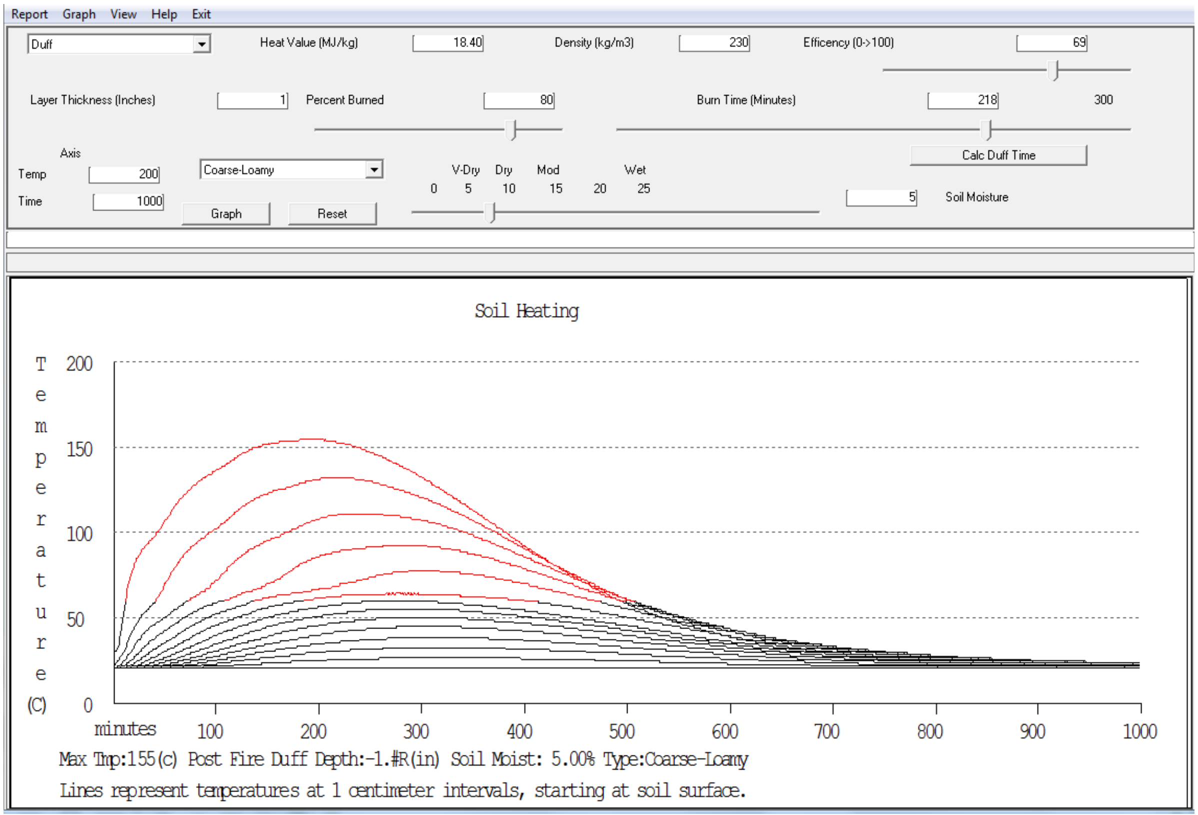
The percent of duff/litter consumed (by weight) during combustion ranged from 27% to 95% with an average of 69% (Table 4). Unburned material, or remnant duff, was composed of 83% to 98% mineral content with an average of 92% (Table 4). Bulk density calculations made prior to combustion determined that densities varied between .11 g/cm^3 and .53 g/cm^3 with an average density of .23 g/cm^3 (Table 4).

Table 4 Combustion characteristics of samples, by depth

Depth (cm)	Consumption (%)	Mineral Content (%)	Bulk Density (g/cm^3)
4	62	95	0.21
8	65	98	0.22
4.5	85	95	0.18
7	N/A	97	0.25
4.5	86	89	0.18
3.5	25	94	0.39
3.5	59	95	0.25
6	82	93	0.15
7.5	N/A	N/A	0.2
5.5	91	93	0.16
7	81	92	0.16

5	64	95	0.21
6.5	76	93	0.14
6	77	87	0.22
6	95	96	0.16
5	84	90	0.15
7.5	73	95	0.11
5.5	78	91	0.13
5	83	96	0.17
4	76	82	0.21
6.5	70	92	0.23
4.5	67	91	0.24
3.5	31	87	0.31
4	75	89	0.23
5	80	95	0.19
2	38	86	0.52
2	27	83	0.53
2.5	66	89	0.32
Mean	69	92	0.23

An example of the soil heating output by the FOFEM model using multiple duff variables is included in Figure 15. The variable duff values input for this example were derived from the properties present in western juniper duff samples collected for this study. At a 2.5 cm (1 inch) duff depth, this model predicts temperatures at multiple depths exceed the necessary ~80 ° C needed for germination of snowbrush ceanothus seeds (Gratkowski 1962). Temperatures lethal to plant tissue (60 ° C) is modeled down to 6 cm below mineral soil with a 2.5 cm duff depth. Near the surface, temperatures necessary to damage ceanothus seed, 120 ° C (Gratkowski 1962) is observed.



Duff

Heat Value (MJ/kg) 18.40

Density (kg/m3) 230

Efficency (0->100) 69

Layer Thickness (Inches) 1

Percent Burned 80

Burn Time (Minutes) 218 300

Temp 200

Time 1000

Coarse-Loamy

5 Soil Moisture

Max Tmp:155(c) Post Fire Duff Depth:-1.#R(in) Soil Moist: 5.00% Type:Coarse-Loamy

Lines represent temperatures at 1 centimeter intervals, starting at soil surface.

Fig. 15 Example output of soil heating predictions using FOFEM modeling and western juniper duff properties at 2.5 cm duff depth.

DISCUSSION

The exploratory designs of this study reveal valuable information about smoldering western juniper litter/duff characteristics and development of laboratory experimentation methods for duff analysis. The trial and error phase of developing effective laboratory combustion methods for this study indicate that the availability of oxygen plays a critical role in the successful ignition and propagation of smoldering fires in juniper litter/duff in even the driest of conditions. The complete inability of dry samples to successfully ignite and propagate in limited airflow lab tests suggests similar characteristics may play an important role in real-world wildfire scenarios.

The wind event during the ignition time and spread of the Tongue-Crutcher Complex fire may have been a key factor in not only the spread of surface fire but also the extent and scale of smoldering combustion beneath the crowns of juniper trees. Studies that aim to further analyze the characteristics of western juniper litter/duff ignition and propagation or require the development of laboratory experimentation should take the role of oxygen availability in to specific consideration.

Thermocouple data revealed that all samples exhibited litter and soil surface temperatures in excess of 400 ° C (Fig. 10-12) and often over 500 ° C, well above the lethal temperature for live plant tissue. Smoldering duff is recognized to yield temperatures between 500 and 600 ° C while temperatures for flaming combustion are between 1000 and 1500 ° C (Reinhardt et al. 1991). A trend among many of the thermal curves is an initial spike in duff temperature followed by a gradual increase in soil surface temperature (Fig. 10, 11, 12). Time at lethal temperature ranged among the experiments from 1.5 hours, to 6+ hours for these 20x20 cm samples. Samples with deeper duff depths tended to burn longer, as was expected with a higher volume of combustible material. Overall, the curvature of thermal signatures varied between samples. Some examples exhibited longer more gradual decrease in lethal temperatures at the soil surface while others exhibited parallel cooling in both the litter strata and soil surface. This variation among samples suggests factors other than moisture, such as compaction or mineral content, may have been influential in the duration and extent of smoldering. The results from thermal testing demonstrate effective methods for monitoring in-material combustion temperatures/time as well as reveal the range of potential heating under the driest of conditions.

Consumption analysis determined a range of variability from 25 to 91% consumption (Table 4). This range may indicate an influence of compaction and mineral content among depths on potential consumption values. Further analysis of unburned material located at the lower most portions of the duff layer indicated that propagation and combustion continued through the majority of samples, only failing to consume material with a high mineral content, 92% on average (Table 4). Visual observations prior to ignition, and post-ignition, revealed that mineral content among samples is highly variable in both particle size and distribution. Rocks and pebbles up to 1 cm in diameter were often found within the ash following the consumption of samples. Bulk density calculations revealed a wide range of values across duff depths (Table 4), suggesting variable degrees of compaction and mineral distribution. Additional research in to the compaction and mineral content characteristics of western juniper duff is necessary to fully understand their role in the combustion and consumption process.

Using the duff characteristics from samples collected at the study site, the FOFEM soil heating model determined that soil heating at multiple depths would be sufficient in providing the appropriate temperature range for the germination of snowbrush, ~80 ° C (Fig. 13). These results are particularly relevant as they pertain to the findings of Chapter I and the significant presence of snowbrush in burned areas of the Tongue-

Crutcher Wildfire Complex. The results of this exploratory study and the utilization of existing modeling techniques suggest that the presence of a duff horizon may play a critical role in providing the necessary conditions for snowbush germination following a wildfire event in juniper woodlands.

CONCLUSION

The primary objectives of this study were to develop exploratory methods for the analysis of the previously unstudied combustion and consumption characteristics of western juniper duff. Multiple attempts at constructing an effective laboratory combustion enclosure revealed that airflow across duff layer and sufficient oxygen supply plays a crucial role in the ignition and propagation of smoldering combustion. Analysis of combustion and consumption characteristics revealed that smoldering temperatures have the potential to create lethal temperatures in duff and soil for extended periods of time and can consume significant portions of the organic material present. Additional factors that have the potential to play a large role in consumption characteristics is the size and distribution on mineral content within the duff/litter layer, as well as variable degrees of compaction. A better understanding of these properties will add to the usefulness of existing models such as FOFEM and the ability of these models to predict soil heating. Furthermore, FOFEM is demonstrated to be an effective tool in predicting characteristics smoldering combustion as it relates to sub-surface lethality and germination of soil-stored seeds such as snowbrush. Further detailed research will be necessary to fully understand the how varying characteristics interact during the combustion and consumption process in western juniper duff. The results and methods of this study provide a foundation and groundwork for areas of particular focus in future studies that aim to analyze the combustion dynamics of western juniper duff and litter

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APPENDIX I

Species lists for all species found during data collection.

APPENDIX I

Code	Scientific Name	Common name
ACOC	*Achnatherum occidentale*	Western needlegrass
ACOCNE	*Achnatherum nelsonii*	Columbia needlegrass
AGOS	*Agoseris* spp.	Agoseris
ALAC	*Allium acuminatum*	Tapertip onion
ANRA	*Antennaria racemosa*	Raceme pussytoes
ARAR	*Artemisia arbuscula*	Little sagebrush
ARCA	*Arenaria capillaris*	Slender mountain sandwort
ARCO	*Arenaria congesta*	Ballhead sandwort
ASAT	*Astragalus atratus*	Mourning milkvetch
BASA	*Balsamorhiza sagittata*	Arrowleaf balsamroot
BRTE	*Bromus tectorum*	Cheatgrass
CALI	*Castillegja linariifolia*	Indian paintbrush
CARU	*Calamagrostis rebescens*	Pinegrass
CEVE	*Ceanothus velutinus*	Snowbrush ceanothus
COLI	*Colomia linearis*	Tiny trumpet
COPA	Collinsia parviflora	Blue eyed-mary
CRAC	*Crepis acuminata*	Tapertip hawksbeard
CRYPT	*Cryptantha* spp.	Cryptantha
ELEL	Elymus elymoides	Squirreltail bottlebrush
EPPA	*Epilobium paniculatum*	Tall annual willowherb
ERHE	*Eriogonum heermannii*	Buckwheat
FEID	*Festuca Idahoensis*	Idaho fescue
GABO	*Galium boreale*	Northern bedstraw
LASE	*Lactuca serriola*	Prickly lettuce
LUSE	*Lupinus sericeus*	Silky lupine
PHHE	*Phacelia heterophylla*	Varileaf phacelia
PHLO	*Phlox longifolia*	Longleaf phlox
POBU	*Poa bulbosa*	Bulbous bluegrass
POPR	*Poa pratensis*	Kentucky bluegrass
POSE	*Poa secunda*	Sandberg bluegrass
PSSP	*Pseudoroegneria spicata*	Bluebunch wheatgrass
PUTR	*Purshia tridentata*	Antelope bitterbrush
SIAL	*Sisymbrium altissimum*	Tumble mustard
SIDO	*Sisyrinchium douglasii*	Douglas' grasswidow
SPCR	*Sporobolus crypthandrus*	Sand dropseed
STME	*Stellaria media*	Common chickweed
TRDU	*Tragopogon dubius*	Yellow salsify
VIAD	*Viola adunca*	Hookedspur violet