

University of Nevada, Reno

**Fuel load and understory community changes associated with  
varying elevation and pinyon-juniper dominance**

A thesis submitted in partial fulfillment of the requirements for the degree of Master of  
Science in Environmental and Natural Resource Science

by

Alicia L. Reiner

Dr. Roger F. Walker/Thesis Advisor

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## Abstract

In response to climatic and anthropogenic factors, plant community distributions change over centuries and decades. Since settlement of the Great Basin by European Americans about 140 years ago, singleleaf pinyon (*Pinus monophylla* [Torr. & Frem.]), and Utah juniper (*Juniperus osteosperma* [Torr.] Little) have increased in area, density, and dominance, encroaching into adjacent sagebrush communities. Increases in pinyon and juniper density and biomass are resulting in the decline of the associated understory plant communities as well as potentially more intense fire behavior as fuel loads contributed by the trees increase. The purpose of this study is to quantify changes in understory plant community biomass and fuel loads associated with variation in both elevation and tree dominance. The weight of understory plant species by fuel timelag size classes as well as biomass by life form (grass, forb and shrub) were estimated in areas of varying pinyon-juniper dominance distributed over an elevation gradient in central Nevada. Regression equations for predicting biomass were derived and tested with a subset of measured and weighed plants. The equations providing the best overall results for calculating fuel loadings and biomass from plant size measurements were determined by using graphical analysis,  $R^2$  and split-sample cross validations. Understory fuel loadings and biomass were analyzed graphically and with Analysis of covariance and ANOVA to determine differences in fuel loadings and understory characteristics with variation in tree dominance and elevation. Both the biomass and the associated fuel loads of shrubs, forbs and grasses were found to be affected more by tree dominance than by elevation.

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## Table of Contents

<b>Abstract</b> .....	i
<b>Acknowledgements</b> .....	ii
<b>List of Tables</b> .....	iv
<b>List of Figures</b> .....	v
<b>Introduction</b> .....	1
<b>Background</b> .....	1
<b>Objectives</b> .....	6
<b>Methods</b> .....	10
<b>Study site description</b> .....	10
<b>Field sampling</b> .....	11
<b>Analysis methods</b> .....	14
<b>Cross validation procedures</b> .....	16
<b>Biomass computation and analysis</b> .....	19
<b>Grass and forb biomass predictions</b> .....	22
<b>Shrub biomass predictions</b> .....	23
<b>Shrub litter</b> .....	26
<b>Treatment analysis</b> .....	26
<b>Results and Discussion</b> .....	28
<b>Community composition overview</b> .....	28
<b>Biomass computations</b> .....	29
<b>Example species: Idaho fescue</b> .....	29
<b>Grass and forb biomass</b> .....	33
<b>Shrub biomass</b> .....	37
<b>Shrub litter</b> .....	43
<b>Treatment analyses</b> .....	44
<b>Understory community trends</b> .....	44
<b>Fuels trends</b> .....	47
<b>Summary</b> .....	51
<b>Conclusions</b> .....	53
<b>Synthesis</b> .....	53
<b>Management implications</b> .....	55
<b>Research needs</b> .....	56
<b>Literature Cited</b> .....	58

## List of Tables

Table 1: Number of replicate macroplots for each combination of tree dominance level and elevation (m) sampled in Underdown Canyon.....	12
Table 2: Regression equations used to predict total plant weight (Y) for grasses and forbs from the ellipsoid volume (X) calculated from crown dimensions.....	34
Table 3: Regression equations used to predict total plant weight for grasses and forbs using percent cover and average height.....	35
Table 4: Regression equations used to predict total plant weight for groups of species by generic lifeform in Underdown Canyon.....	36
Table 5: Species grouped to create generic regressions.....	37
Table 6: Regression equations used to predict various subsets of <i>Artemisia tridentata vaseyana</i> weight.....	38
Table 7: Regression equations used to predict various subsets of <i>Artemisia tridentata wyomingensis</i> weight.....	39
Table 8: Regression equations used to predict various subsets of <i>Chrysothamnus viscidiflorus</i> weight.....	39
Table 9: Average percentages of live and dead fuel subparts for <i>Artemisia tridentata wyomingensis</i> by field estimated percent dead category.....	40
Table 10: Average percentages of live and dead fuel subparts for <i>Artemisia tridentata vaseyana</i> by field estimated percent dead category.....	40
Table 11: Average percentages of live and dead fuel subparts for <i>Chrysothamnus viscidiflorus</i> by field estimated percent dead category.....	40
Table 12: Regression equations used to predict various subsets of plant weight for less abundant species of shrubs.....	42
Table 13: Average percentages of live and dead fuel subparts for less abundant shrub species by field estimated percent dead category or measurement method.....	43
Table 14: Regression equations used to predict sagebrush litter by elevation.....	44
Table 15: F-test and significance for comparison of biomass by lifeforms.....	46
Table 16: F-test and significance for comparison of fuels.....	49

## List of Figures

Figure 1: Historical and present distribution of singleleaf pinyon.....	2
Figure 2: Aerial photos from 1961 and 1993 of a mid elevation portion of Underdown Canyon, Nevada.....	4
Figure 3: Topographic map of study area, Underdown Canyon, Shoshone Mountains, Nevada.....	11
Figure 4: Diagram of general macroplot layout.....	13
Figure 5: Error between sum of actual and predicted weights for two rounds of split sample cross validations.....	19
Figure 6: Boxplot of the 16-50% dead category of Wyoming big sagebrush.....	20
Figure 7: Scatter plot of datapoints in the 16-50% dead category of Wyoming big sagebrush along with regression models.....	21
Figure 8: Percent cover of understory, trees and total vegetation for the mid elevation plots.....	28
Figure 9: Boxplots of area and average height for Idaho fescue.....	29
Figure 10: Scatter plot of area versus total weight for Idaho fescue.....	30
Figure 11: Scatter plot of average height versus total weight for Idaho fescue.....	31
Figure 12: Residual plot of $\hat{Y}$ versus $DY$ for the percent cover measured Idaho fescue.....	32
Figure 13: Residual plot of $X$ versus $DY$ for the percent cover measured Idaho fescue.....	33
Figure 14: Percent of plant numbers within each percent dead category by species.....	41
Figure 15: Understory biomass versus tree dominance for the mid elevation plots.....	45
Figure 16: Understory biomass by lifeform versus elevation for the mid tree dominance plots.....	46
Figure 17: Understory fuels versus tree dominance at mid elevation plots.....	48
Figure 18: Understory fuels versus elevation for mid tree density plots.....	49
Figure 19: 1 hour tree and understory fuels versus tree dominance for mid elevation plots.....	50

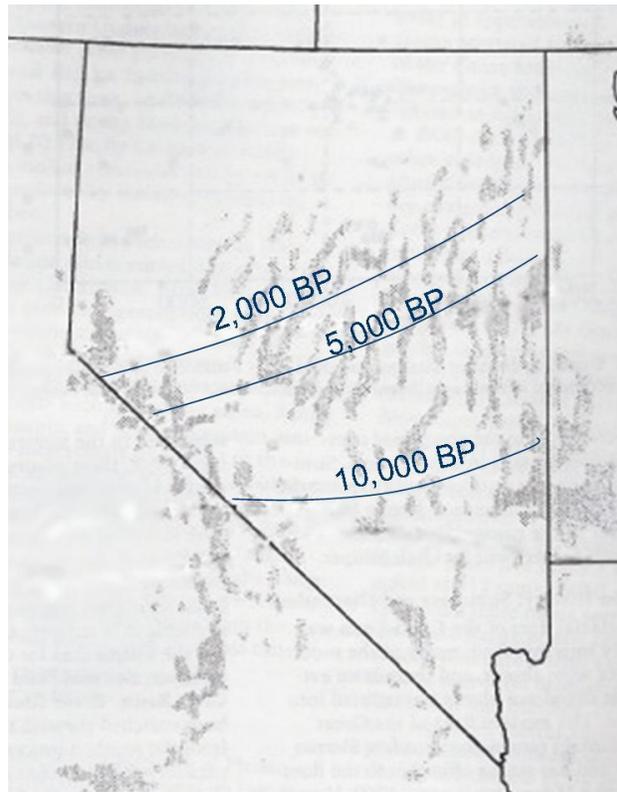
## Introduction

### Background

In response to climatic and anthropogenic factors, plant community distributions change over centuries and decades (Thompson 1990, Miller and Rose 1999, Swetnam et al. 1999, Lyford et al. 2003). Evidence of plant communities trapped in sediment or packrat middens provide a record of historic plant distributions (Swetnam et al. 1999). When multiple types or dense networks of these proxy data are used, the resulting historical account can be greatly improved (Swetnam et al. 1999, Renssen et al. 2001). Although historic climate regimes for the Great Basin are generally inferred from plant distribution shifts read from proxy records, these historic climate changes are also corroborated by evidence from fluvial geomorphology and ice core analyses (Miller and Tausch 2001).

In the Great Basin, species have migrated latitudinally as well as elevationally following climatic changes. Between 10,500 and 5,000 years before present the warmer climate stimulated the northward movement of the northernmost edge of the singleleaf pinyon distribution (Figure 1). Precipitation increased from 5,000 to 3,500 years BP leading into the much cooler and wetter climate of the Neoglacial period 3,500 to 2,600 years BP. Due to the Neoglacial climate, the upper elevation limits of woodlands moved down and woodland expansion occurred at low and mid elevations. A major drop in precipitation between 2,600 and 1,600 years BP, the Post-Neoglacial drought, then followed (Tausch et al. 2004). The lower precipitation of this period led to a decline in woodlands and an increase in desert shrub vegetation. The climate was generally warmer

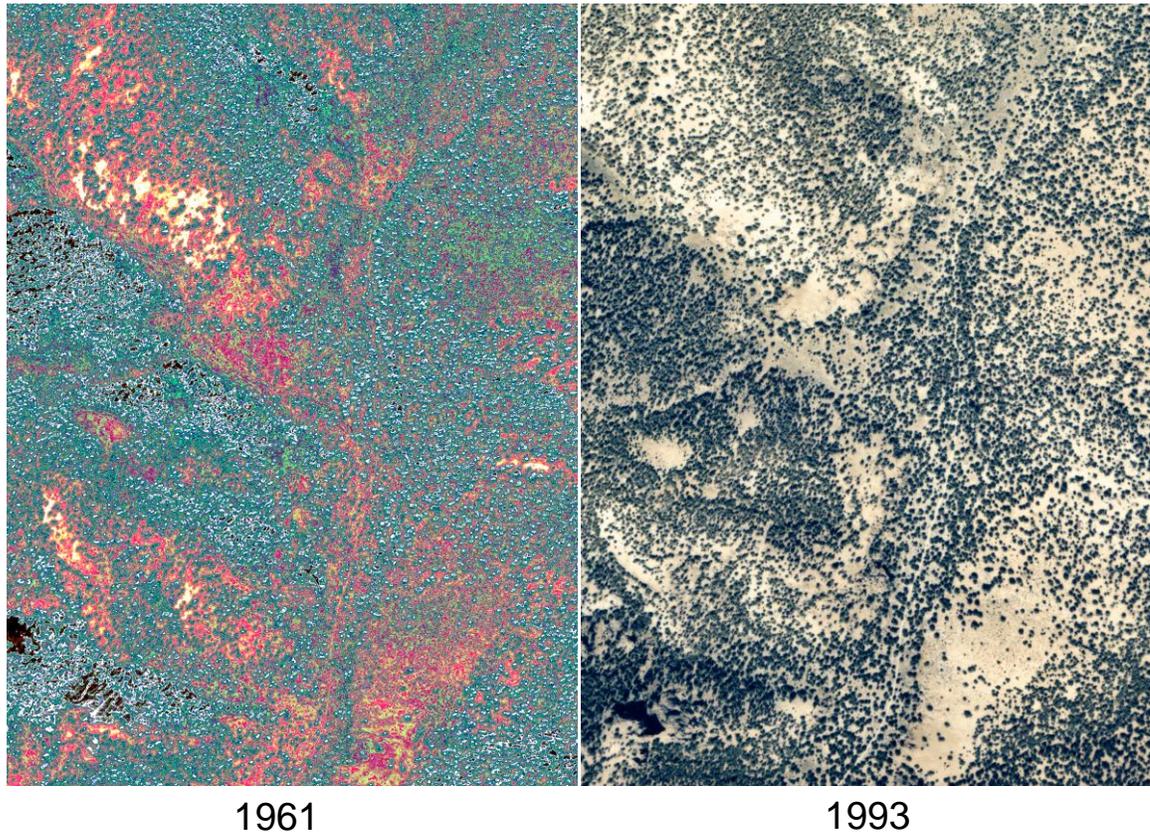
with an increase in summer precipitation from 1,600 to 650 years BP, leading to some re-expansion of woodlands. The time between 650 to 150 years BP is termed the Little Ice Age due to the cooler and somewhat wetter conditions of this era. Woodlands steadily expanded within their range during the Little Ice Age (Tausch et al. 2004). During the past 150 years temperatures have been slowly rising. Current woodland expansion is exceeding previously known expansion rates, and is most likely triggered by factors in addition to climate (Miller and Tausch 2001).



**Figure 1.** Historical and present distribution of singleleaf pinyon. Mottled gray areas indicate current distribution and lines indicate northern extent of historic distribution two, five and ten thousand years before present. This image was adapted from Thompson (1990) and Nowak et al. (1994).

Pinyon and juniper species currently occupy over 30 million hectares in the American West (West 1999), but are estimated to have covered less than 3 million hectares before European settlement (Gedney et al. 1999, Miller et al. 1999). It is estimated that 90% of the western juniper, *Juniperus occidentalis* (Hook.), woodlands present today have arisen in only the past 100 years (Miller et al. 2000). Increases in pinyon and juniper density in just the past few decades are noticeable in portions of aerial photos of the study site, Underdown Canyon (Figure 2).

Recent increases in the range and density of pinyon and juniper are often attributed to fire suppression and domestic livestock grazing as well as changes in climate (Tausch et al. 1981, Miller and Wigand 1994) and increasing atmospheric CO<sub>2</sub> concentrations (Johnson et al. 1990). The cooler and wetter period of the Little Ice Age enhanced tree as well as herbaceous species growth. An abundance of fine fuels from herbaceous plants during this era probably led to higher fire frequencies, thus limiting woodland expansion. Fire frequencies have purportedly declined since the end of the Little Ice Age because of a reduction of fine fuels due to a period of heavy grazing from 1880 to 1930. This fine fuel reduction, in conjunction with more effective fire suppression efforts beginning in the early to mid 1900's, lengthened fire return intervals in the Great Basin. The reduction of the role of fire has allowed woodlands to expand in area and increase in density (Miller et al. 2000, Miller and Tausch 2001). Carbon dioxide has been shown to increase growth rates of western juniper, even during periods of drought stress (Knapp et al. 2001), and therefore may play a role in the recent expansion of woodlands.



**Figure 2.** Aerial photos from 1961 and 1993 of a mid elevation portion of Underdown Canyon, Nevada.

Understory species diversity and coverage are reduced as pinyon and juniper come to dominate the affected sagebrush/grassland communities (Bunting et al. 1999), which can result in losses in forage production and wildlife habitat (Miller and Tausch 2001). As pinyon and juniper densities increase on a site, a threshold may be crossed that can prevent reversion to a sagebrush/grassland dominated community following tree removal by disturbance (Miller et al. 2000). An example is the increasing density of pinyon and juniper trees creating fuel beds more conducive to high intensity crown fires (Neary et al.

1999), after which a woodland community may cross a threshold to an annual grass dominated community (Tausch 1999).

Managing Great Basin ecosystems properly is of great interest in order to conserve values associated with this vast ecoregion. Due to climate changes and human modification of landscapes, ecosystems of the Great Basin will likely continue changing into the future (Neary et al. 1999). Because fire can be the most important factor in maintaining a shrub/grass, rather than a tree, dominated community (West 1999), pinyon-juniper expansion into sagebrush steppe is often referenced from the perspective of post-fire succession (Barney and Frischknecht 1974, Tress and Klopatek 1987).

Fire may be used as a management tool in Great Basin ecosystems to reduce the potential of catastrophic wildfires in dense pinyon-juniper stands (Everett and Ward 1984, Miller and Tausch 2001). Prescribed fire and naturally ignited fires occurring in designated Wildland Fire Use areas are two scenarios in which land management agencies may use fire to effect change in ecosystems. Fire behavior and effects models can allow land managers to easily compare the results of potential fuels treatments and hypothetical weather conditions on mock fire scenarios before encountering them on the ground. Fire behavior models are also used to help create prescriptions for prescribed fire and to predict the potential spread rates and intensities of wildfires (Brown 1982, Andrews and Queen 2001). Reasonably accurate information on the loads and characteristics of the fuels are necessary for effective use of fire behavior and effects models (Sandberg et al. 2001). Data on how the fuel loads and their characteristics change over the successional gradient from sagebrush steppe to dominance by pinyon-

juniper woodland would aid in both more accurately portraying these fuels types in models and in subsequent management decisions. Information on how the outcome of disturbance could change as the community changes with increasing tree dominance would provide better understanding of how post-fire rehabilitation needs would change along this gradient (Miller and Tausch 2001).

### **Objectives**

Numerous studies across the Great Basin have documented the pattern of a decline in understory coverage as tree coverage on a site increases. (Blackburn and Tueller 1970, Barney and Frischknecht 1974, Tausch and Tueller 1990, Tausch and West 1995, Bunting et al. 1999, Poulsen et al. 1999, Miller et al. 2000). Plant species composition of the understory community and the total amount of vegetative cover have been shown to generally change with elevation (Tueller et al. 1979, Martens et al. 2001). Several studies have used regression equations involving shrub crown measurements to describe all or part of the sagebrush biomass on a site (Harniss and Murray 1976, Rittenhouse and Sneva 1977, Uresk et al. 1977). However, empirical studies correlating shrub crown measurements with the amounts of fuels by timelag category are rare, especially for sagebrush communities (Brown 1982, Frandsen 1983). Timelag categories are conventionally defined as the time required for fuels of  $< \frac{1}{4}$ " ,  $\frac{1}{4}$ " to 1" and 1" to 3" diameter size classes, called 1, 10 and 100 hour fuels respectively, to equilibrate by 63% with ambient moisture (Pyne et al. 1996). Also, few studies test regression equations

used to predict biomass on a subset or a reserved part of the data to evaluate predictive capabilities of the regression equations.

### **Information needs**

The two major information needs on which this study focuses along with ways resultant information could be used are outlined below.

- 1) Quantification of the decline of the understory plant community with increasing pinyon-juniper dominance

Aids in:

- Classifying potential susceptibility to cheatgrass invasion
- Predicting potential post-fire rehabilitation
- Defining areas where prescribed burn treatments are desirable

- 2) Quantification of fuel loads in sagebrush-steppe/pinyon-juniper

Aids in:

- Predicting wildland fire behavior
- Predicting potential fire effects
- Creating fire prescriptions
- Predicting smoke amounts
- Creating carbon and nitrogen budgets

The purpose of this study is to first develop regression equations that can effectively predict the biomass and fuels by timelag classes for plant species commonly found in central Nevada sagebrush communities associated with woodlands. Then, these equations will be used to provide quantification on a plot basis of both understory plant community biomass by species and associated fuel loads. Changes in the understory community and fuel were only compared across three levels of both pinyon-juniper dominance and elevation. The changes in tree dominance were only studied at the mid elevation, and the elevation effect was only studied at the mid tree dominance level. Objectives are summarized below.

- Identify regression equations that can effectively predict the biomass and fuels by timelag categories for plant species commonly found in central Nevada woodlands
- Determine the understory community changes associated with increasing tree dominance or elevation
- Determine the understory fuel load changes associated with increasing tree dominance or elevation

## Null Hypotheses

### Lifeform comparisons

H<sub>0</sub>1: The current year's forb, grass, and shrub biomass, do not differ between low, mid and high tree dominance treatments.

H<sub>0</sub>2: The current year's forb, grass, and shrub biomass, do not differ between low, mid and high elevation treatments.

### Understory fuel comparisons

H<sub>0</sub>3: Aerial 1, 10, and 100 hour dead fuels, do not differ between low, mid and high tree dominance treatments.

H<sub>0</sub>4: Total live fuels do not differ between low, mid and high tree dominance treatments.

H<sub>0</sub>5: Total downed woody fuels do not differ between low, mid and high tree dominance treatments.

H<sub>0</sub>6: Shrub litter fuels do not differ between low, mid and high tree dominance treatments.

H<sub>0</sub>7: Aerial 1, 10 and 100 hour dead fuels, do not differ between low, mid and high elevation treatments.

H<sub>0</sub>8: Total live fuels do not differ between low, mid and high elevation treatments.

H<sub>0</sub>9: Total downed woody fuels do not differ between low, mid and high elevation treatments.

H<sub>0</sub>10: Shrub litter fuels do not differ between low, mid and high elevation treatments.

## Methods

### Study site description

The study area is located in the Shoshone Mountain Range on the Humboldt-Toiyabe National Forest, Austin Ranger District, and the Battle Mountain District of the Bureau of Land Management in central Nevada (38° 10' N, 117° 25' E). Study plots are located in Underdown Canyon (Figure 3), which is typical of much of the woodland dominated areas of the central Great Basin. The geology is dominated by volcanic tuff and an intermittent stream runs down the canyon. The study plots are located along the elevation and tree dominance gradients of the canyon on side-valley alluvial fans. They are also positioned to keep topographic conditions as uniform as possible. Average yearly precipitation ranges from 23 cm at lower elevations to 50 cm at higher elevations, with most precipitation arriving in the winter and spring.

Within the canyon, the woodlands are characterized primarily by singleleaf pinyon. There are scattered Utah juniper, and occasionally hybrids of Utah and western juniper (Terry et al. 2000). At the lower elevations, understory plant communities are dominated by Wyoming big sagebrush (*Artemisia tridentata wyomingensis* Beetle & A. Young), Sandberg's bluegrass (*Poa secunda* J.S. Presl) and bottlebrush squirreltail (*Elymus elymoides* [Raf.]Swezey). At higher elevations Mountain big sagebrush (*Artemisia tridentata vaseyana* [Rydb. Beetle]), occasional low sagebrush (*Artemisia arbuscula* Nutt.) and Idaho fescue (*Festuca idahoensis* Elmer) dominate the understory.



**Figure 3.** Topographic map of study area, Underdown Canyon, Shoshone Mountains, Nevada.

### Field sampling

Prior to sampling, alluvial fans on the north facing slopes of the study area were stratified into polygons representing low, mid and high tree dominance categories based on the relative cover of tree versus understory. Macroplots were centered in polygons of each tree dominance level at each site that had sufficient area to contain the plots plus a buffer zone around them. Only the mid tree dominance polygons had adequate area for a sufficient number of macroplots to be located at all the different elevations sampled. At the two mid elevation alluvial fans, polygons for all three levels of tree dominance (low, mid and high) were of a sufficient size to locate macroplots. Macroplots sampled at the

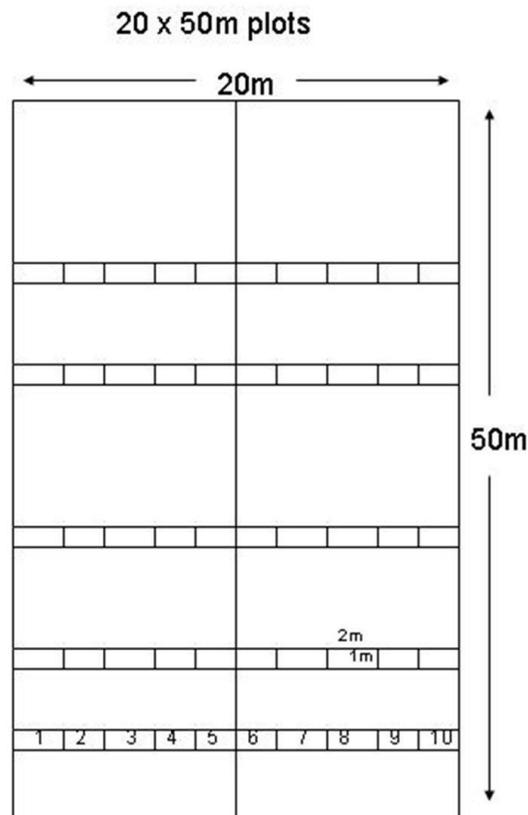
mid tree dominance level were grouped into three different elevation intervals for analysis. This provided six replicate plots for each interval. A total of 30 macroplots were sampled over tree dominance and elevation gradients (Table 1). Tree data were gathered in the summer of 2000 and understory data in the summer of 2001. Some clipped plant data gathered during the summer of 2002 for post-fire effects information were used to increase sample sizes when appropriate.

**Table 1.** Number of replicate macroplots for each combination of tree dominance level and elevation (ft) sampled in Underdown Canyon.

Tree dominance			Elevation
Low	Mid	High	
	6		6800' - 6900'
6	6	6	7200' - 7300'
	6		7700'

Understory vegetation in each macroplot was sampled in fifty 1 x 2m subsampling microplots located contiguously along belt transects that were positioned perpendicular to the long axis of the plot (Figure 4). The belt transects were located in a stratified random manner along the length of the plot and spanned the width of the plot. All shrubs rooted in the microplots were measured by species for the longest crown diameter, the crown diameter perpendicular to the longest, total plant height, the crown height of live foliage and the basal diameter (stem diameter just above ground level). The percent of dead material comprising the crown of each shrub was also estimated. Perennial forbs were measured for two crown diameters and the total height. Perennial grasses were measured for two basal diameters and the total height. To facilitate the measuring process when herbaceous plants were small and abundant, grasses and forbs were sampled by species in

each microplot by estimating their percent cover plus a measurement of average height. For each shrub measured as well as for each grass or forb where crown dimensions were measured on a transect, an individual of that species was randomly located off the end of the transect outside the macroplot and then clipped to ground level. One subsampling microplot on each transect was randomly selected and clipped to obtain the biomass for the species for which the percent cover was determined. The shrubs were separated into live and dead categories of 1, 10 and 100 hour fuels. Herbaceous species were also separated into live and dead portions prior to weighing when sufficient amounts of dead material were present. The samples were oven dried and weighed in the lab.



**Figure 4.** Diagram of general macroplot layout. Subsampling microplots are depicted in the belt transects running from left to right.

Intercepted downed woody fuels were counted along a line intercept placed on one side of each microplot belt transect to estimate downed woody biomass (Brown 1974). Shrub litter mats were sampled in the summer of 2003 under 18 rabbitbrush, *Chrysothamnus viscidiflorus* Hook. (Nutt.), and 36 sagebrush (a combination of Mountain big sagebrush and Wyoming big sagebrush) plants. Shrub litter was sampled across the elevation gradient of the study area under interspace shrubs to avoid sampling tree litter mats. A 10 X 10 cm square frame was placed approximately halfway between the stem and the outer edge of the litter mat of each shrub in order to gather samples representative of the entire litter mat (Brown 1982). The litter in each frame was collected from the Oi and Oe horizons. Full crown and litter mat dimensions were also taken for each shrub by measuring the longest diameter and the diameter perpendicular to the longest. Each litter sample was floated to remove rocks, then dried and weighed.

### **Analysis methods**

Biomass estimates are needed in order to assess fuels, primary productivity, nutrient cycling, food abundance, treatment effects, competition within plant communities and effects of different fire regimes (Murray and Jacobson 1982, Tausch and Tueller 1988, Hierro et al. 2000). Regression analysis is the method most often used to predict the weight of both the entire plant and selected sub-parts from crown or basal measurements and aerial cover estimates (Tefler 1969, Ludwig et al. 1975, Brown 1976, Roussopoulos and Loomis 1979, Thomson et al. 1998). Many three-dimensional shapes describing the crown volume of plants can be calculated from crown measurements

(Mawson et al. 1976, Murray and Jacobson 1982). In situations where plant density and small size cause measuring individual plant crowns to be too time consuming, estimates of percent cover and average height in sample plots can be used to predict plant biomass (Alaback 1986).

In biomass prediction, log-log regression, in the form  $\ln(y) = \ln a + b \ln(x)$ , is commonly used in cases involving non-normal error distributions (Draper and Smith 1998). However, logarithmic equations tend to result in bias of the estimates of biomass (Baskerville 1972). Also, because the coefficient of determination ( $R^2$ ) is computed from the logarithmically transformed values in a log-log regression, it applies only to the logarithmically transformed data, not the original, untransformed data (Tausch and Tueller 1988). The Ordinary Least Squares (OLS) method of calculating regression equations has been used quite prominently (Draper and Smith 1998), but since the advent of modern computers several iterative methods utilizing robust analyses, which are less sensitive to outliers and non-normal error distributions, can be employed as well. These robust methods work by minimizing the sum of absolute deviations, as in Least Absolute Deviations (Gentle 1977), or by down weighting the more deviant points, as in Andrew's Sine or Tukey's biweight (Press et al. 1986, Mielke and Berry 2001).

In regression analysis, the coefficient of determination ( $R^2$ ) measures the distance from the data points to the regression line in the Y direction in relationship to the range of the data, giving an estimate of the precision of the equation (Hoshmand 1988). Many studies involving biomass estimation using regression analysis employ  $R^2$  as the main factor determining how well particular regression models predict biomass. The accuracy

of the Y intercept and slope of the regression equation are not directly quantified by  $R^2$ . Also,  $R^2$  should not be used to compare regression equations using different sets of independent variables or different transformations of response variables (Draper and Smith 1998). Methods involving cross validation hold promise for comparing the accuracy of regression equations and therefore their predictive capabilities (Snee 1977). In this study, split-sample cross validation analysis was used to aid in choosing the most accurate regression models for the data.

### **Cross validation procedures**

Cross validations of several commonly used regression equations and methods for three species were performed in order to choose the models and methods yielding the most accurate biomass predictions. The three data sets used for cross validation analyses, Mountain big sagebrush; rabbitbrush; and tailcup lupine, *Lupinus caudatus* Kellog, had 126, 148 and 54 samples respectively. Regression analyses were performed using the 2001 version of NCSS statistical software. Simple, multiple and transformed regression models were formulated as outlined below (Draper and Smith 1998). The dependent variable for cross validation tests was the total weight of the plant. The independent variables used in the multiple regressions in this study were the height and the two crown diameters, although several different plant dimensions have historically been used with multiple regression analysis (Murray and Jacobson 1982, Hierro et al. 2000). The ellipsoid (see formula next page), which has been used in one form or another in several previous studies because it best describes the shape of many shrubs (Thomson et al. 1998, Hierro et al. 2000), was tested as the independent variable in the simple regressions.

Power models were tested in addition to linear models because they are often used in biomass regression analysis (Rittenhouse and Sneva 1977, Murray and Jacobson 1982, Hierro et al. 2000). Robust methods of computing regression models as well as OLS models with outliers removed were tested in the cross validation analysis to examine the predictive capabilities of these two methods. Robust analyses were performed using the Least Absolute Deviations (LAD), Tukey's biweight and Andrew's Sine options in NCSS. Outliers were chosen and removed from the "no outlier" models based on the characteristics of the data set as shown in scatter plots for each test.

Ellipsoid linear regression model:  $w = a + bv$

where:  $v = \text{ellipsoid}$   
 $w = \text{total plant weight}$   
 $a, b = \text{constants}$   
 $\text{ellipsoid} = (3.14159/6) * H * C_1 * C_2$   
 $H = \text{total plant height}$   
 $C_1 = \text{longest crown diameter}$   
 $C_2 = \text{crown diameter perpendicular to the longest}$

Power regression model:  $w = a(v^b)$  or  $\ln(w) = \ln(a) + b\ln(v)$

where: (w, v, a, and b are as defined above.)

Multiple linear regression model:  $w = a + b(H) + c(C_1) + d(C_2)$

where:  $c, d = \text{constants}$   
(w,  $C_1$ ,  $C_2$ , H, a and b are as defined above.)

Multiple power regression model:  $w = a(H^b) * (C_1^c) * (C_2^d)$

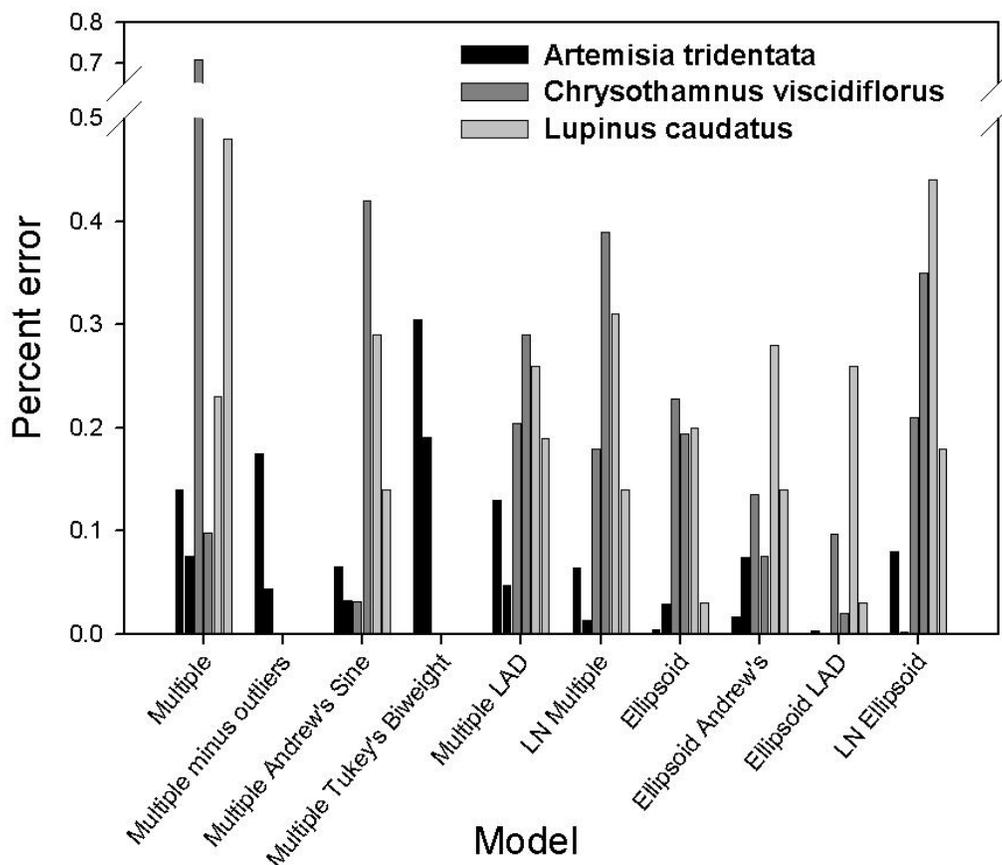
or  $\ln(w) = \ln(a) + b\ln(H) + c\ln(C_1) + d\ln(C_2)$   
where: (w,  $C_1$ ,  $C_2$ , H, a, b, c and d are as defined above.)

Cross validations were done by splitting the data set into two equal parts.

Regression models were created using one set (the "model" set) and validating the models with the second set (the "validation" set). Before the split, the data were first grouped by elevation category and data at the mid elevation were further grouped by tree dominance

category. Data were assigned evenly distributed random numbers between 0 and 1 using the Excel 2000 (version 9.0.2720) “RAND” function within each of these groupings. The data in each group were then sorted by the random numbers. The first half of the data within each group was assigned to the model set and the second half to the validation set. Data were split by these treatment groupings to insure that equal numbers of sample points from each elevation and tree dominance treatment were included in the model and validation sets, as recommended by Fox (1997). The regression model created from the model set was used to calculate estimated weights of each plant in the validation set. The percent error between the sums of actual versus regression-estimated weights was used to graphically compare the various models in each cross validation test. Two separate cross validation tests were performed. For each test the data were divided using a unique set of random numbers.

Variation in percent error between the first and second rounds of cross validation was present for all species tested. This variation between rounds of cross validation leads us to believe that, when divided in half for split-sample cross validation, our sample sizes are too small for the inherent variation of the species tested to use the results of only two rounds of cross validation with confidence. Average percent error was below 5% for sagebrush for the ellipsoid model when used with the OLS method. In several cases, (i.e., rabbitbrush < 6%) the robust models had lower percent errors than the OLS models. For the species tested, robust methods sometimes improved the predictive capabilities of the regression equation (Figure 5).

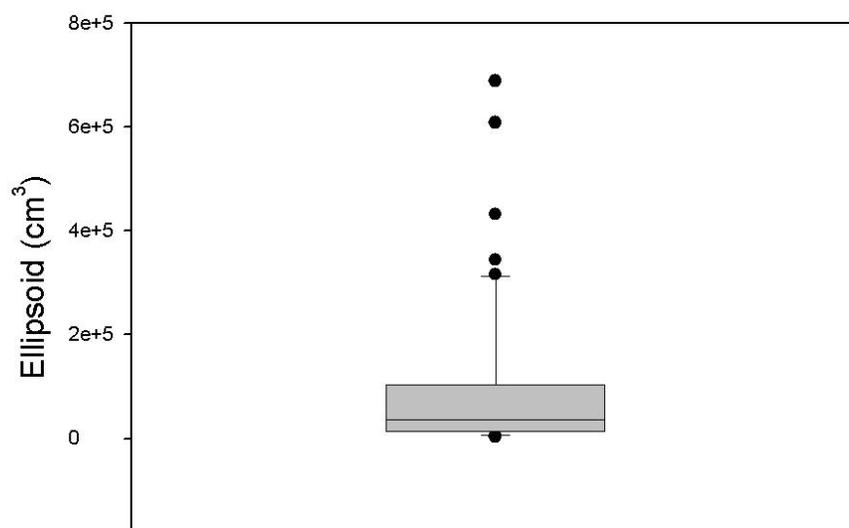


**Figure 5.** Error between sum of actual and predicted weights for two rounds of split-sample cross validations for *Artemisia tridentata vaseyana*, *Chrysothamnus viscidiflorus* and *Lupinus caudatus*. The Tukey's biweight model and the multiple, no-outlier model were not examined for rabbitbrush or tailcup lupine.

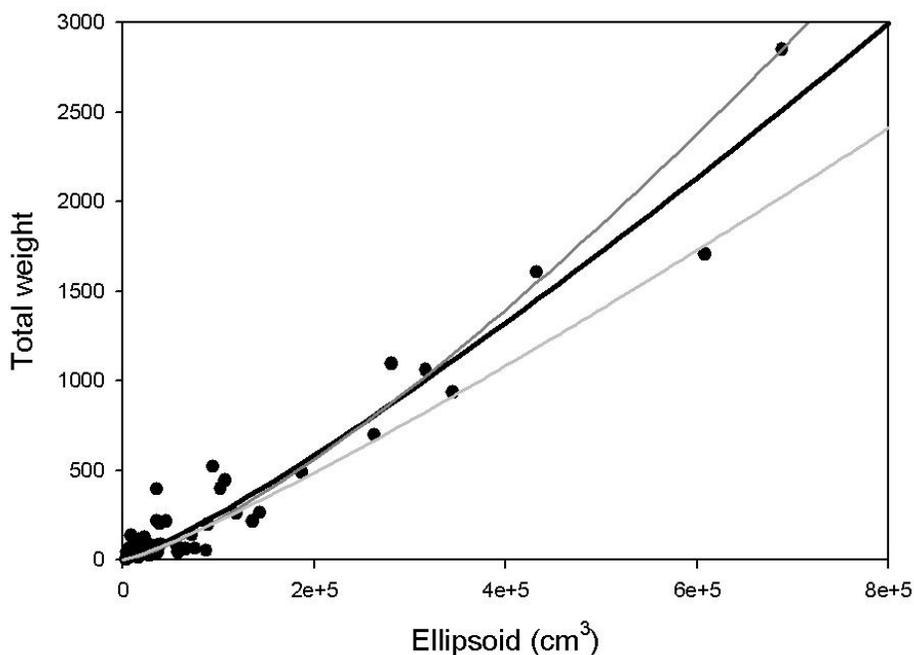
### Biomass computation and analysis

Size-weight regression models were created using a custom non-linear regression program (Tausch and Tueller 1988). Although robust models sometimes performed better than OLS models in some of the cross validation cases, the OLS method was selected for the final models for predicting biomass to maintain uniformity in analysis. Also, the size distribution of many species sampled had a right skew and the robust

methods of regression analysis were under-emphasizing the largest plants, leading to regression models that provided poor predictions. For example, the Wyoming big sagebrush data were skewed to the right (Figure 6). Both the regression equations created with the LAD and Andrew's Sine robust methods for Wyoming big sagebrush were dominated by the smaller sized plants, leading to poor estimates in the higher end of the data range for these equations (Figure 7). The ellipsoid model was chosen to calculate biomass because it performed well in the cross validations, had uniform results across all species and was the simplest model. All regression equations predict weight in grams from variables in cm, cm<sup>2</sup> or cm<sup>3</sup>.



**Figure 6.** Boxplot of the 16-50% dead category of Wyoming big sagebrush with volume (cm<sup>3</sup>) expressed as the ellipsoid.



**Figure 7.** Scatter plot of data points in the 16-50% dead category of Wyoming big sagebrush which were used to create the three simple power regression models shown. The ellipsoid, shown on the X axis was the independent variable and the total weight, shown on the Y axis, was the dependent variable. The Ordinary Least Squares regression is shown in black, the LAD robust regression is in dark gray and the Andrew's Sine robust regression is in the lightest gray.

The final equation form used was chosen based on the scatter and residual plots for each species. When scatter plots showed no differences in the size/weight relationships between years, samples gathered during the summer of 2002 were added to 2001 for combined data sets. When scatter plots of independent variables versus dependent variables suggested a curvilinear relationship, the power equation was used, otherwise, the linear equation was used. Residual plots of Y vs. DY and X vs. DY were examined to further support model choice. Scatter plots and  $R^2$  values were examined to choose between simple and multiple regression equations for situations in which more than one independent variable was available. Scatter and residual plots were also used to

check for outliers. When the investigation of outliers indicated that they likely represented data recording errors, they were removed from the data set for computation of the final regression model.

### **Grass and forb biomass predictions**

Regression models were created for each grass and forb species when sample size was sufficient. Crown dimension measurements were used to calculate the ellipsoid crown volume used in regression equations for the forbs and large grass species with measured crowns. In cases where the percent cover measurement method was used, it was multiplied by microplot area to compute an area in  $\text{cm}^2$ . The area and the average height were individually used in multiple regression models to predict plant weights. Both the average height and the percent cover were individually plotted in scatter plots against the plant weights. Generally, the data sets based on percent cover and average height had more variation than data sets of crown measured plants. In some cases the relationship observed in the scatter plot between average height and total microplot weight was very poor. When adding average height to percent cover in a multiple regression equation did not increase the  $R^2$ , the average height variable was not included in the final regression equation. Several species of grasses and forbs were measured via the percent cover method as well as the crown dimension method depending on the abundance in which they were found in each plot. Regression models for each measurement method were used to predict weights for these species based on the method

used for their measurement. Also, for each species measured, crown area was summed by plot and converted to a percent cover.

Many of the less abundant species of grasses and forbs sampled in the macroplots had too few samples available for regression analysis by individual species. Generic grass and forb regressions were created to predict the weights of species for which sample sizes were not sufficient for single species regressions. Samples from several less abundant species were combined to create these regressions. For the grasses, a generic regression equation was created to predict weights of less abundant species of grasses measured using the crown measurement method. For the forbs, equations were needed for both the crown measurement method and the percent cover method. For the crown measured forbs, large plant size and small plant size regression models were created by grouping forb species by size in order to obtain the best fit models from the data available.

### **Shrub biomass predictions**

For shrubs, the ellipsoid volume used in regression analysis was calculated from the two diameters and total shrub height (VOL2) and from the two crown diameters and the foliage height (VOL1). VOL2 was generally used to predict total shrub weight and VOL1 to predict foliage weight. Biomass for the various components of the shrubs was calculated by first predicting total weight, total live weight and foliage weight by species. Total dead weight for shrubs was calculated by subtracting total live weight from total weight. A multiple regression model was created to estimate the weight of the fuel

components for 100 percent dead standing shrubs based on total height and basal diameter.

Regression equations were not used to predict every fuel size category (1, 10, 100 hour live and dead) for shrubs because sample sizes were too small for predicting the larger diameter fuels. Smaller shrubs that lacked the larger diameter fuels were the most common in the plots. Amounts of shrub fuel by size classes in the individual plants were calculated from average percentages developed from actual fuel weights of the sampled shrubs. It was observed in the field that the amount of dead material varied considerably in each live shrub. This was generally observed to be related to the level of tree competition. In areas of higher tree dominance, a greater presence of shrubs with large amounts of dead material was observed. To better deal with this variation, samples of abundant shrub species were divided into several categories based on the field estimates of percent dead. Average percentages of fuel by size classes were calculated individually for each of the percent dead categories in order to more accurately predict the ratio of live to dead fuels as well as the distribution of fuels among the timelag categories. Several variations of the percent dead categories were tested and compared based on correlation with the sampled plants. The distributions in the weights by fuel size category which resulted from grouping plants by the field estimated percent dead categories for fuel weight calculation were compared with the actual breakdown of fuel weights for the same plants grouped by actual percent dead categories.

To search for best divisions for the percent dead categories, the following methods were used. The actual percent dead of each shrub was calculated based on the ratio of

live to dead material weighed for the plant. Then, categorical limits hypothesized to divide major live to dead ratio groups within the shrub data sets were selected based on familiarity with the data set. Next, using these limits, shrub data were separated into two sets of categories, one based on field estimates of their percent dead and the other based on the actual percent dead. The distribution of the live and dead fuel sizes were compared between the estimated and actual percent dead categories. The first approximations for limits of the categories did not perform well, and so several variations on the limits were compared to find suitable category limits. Divisions were adjusted until the live to dead ratio, and also the distribution of fuel sizes within the live and dead fuels of the field estimated percent dead categories, best matched the corresponding actual percent dead category. The field estimated percent dead categories used in the final analysis provided the best predictors of fuel size distributions.

Amounts of dead fuels by timelag category for each plant were calculated for each percent dead category by multiplying the total dead weight by the average percentages of each fuel size determined from the measured plants. This procedure was repeated for live fuels. Less abundant shrubs species for which few samples were gathered were not separated into percent dead categories for fuel estimation. Percentages of fuel size categories for less abundant shrubs were generally predicted by grouping the entire shrub data set to calculate average percents of each fuel class.

### **Shrub litter**

Shrub litter weight was estimated for sagebrush and rabbitbrush species using regression equations based on relationships developed between shrub crown area and litter mat weight. Because shrub litter samples were taken to be representative of the entire littermat, the weight per  $\text{cm}^2$  computed for each 10 x 10 cm litter sample was multiplied by the entire shrub littermat areas in order to derive an estimated total littermat weight. Because it was desirable to extrapolate litter weights to shrubs for which we had no littermat area data, an average ratio of littermat area to crown area was calculated for both sagebrush and rabbitbrush data. Crown area was multiplied by this multiplier and reduced to littermat area in order to predict littermat weights from shrub crown areas with a regression equation.

### **Treatment analysis**

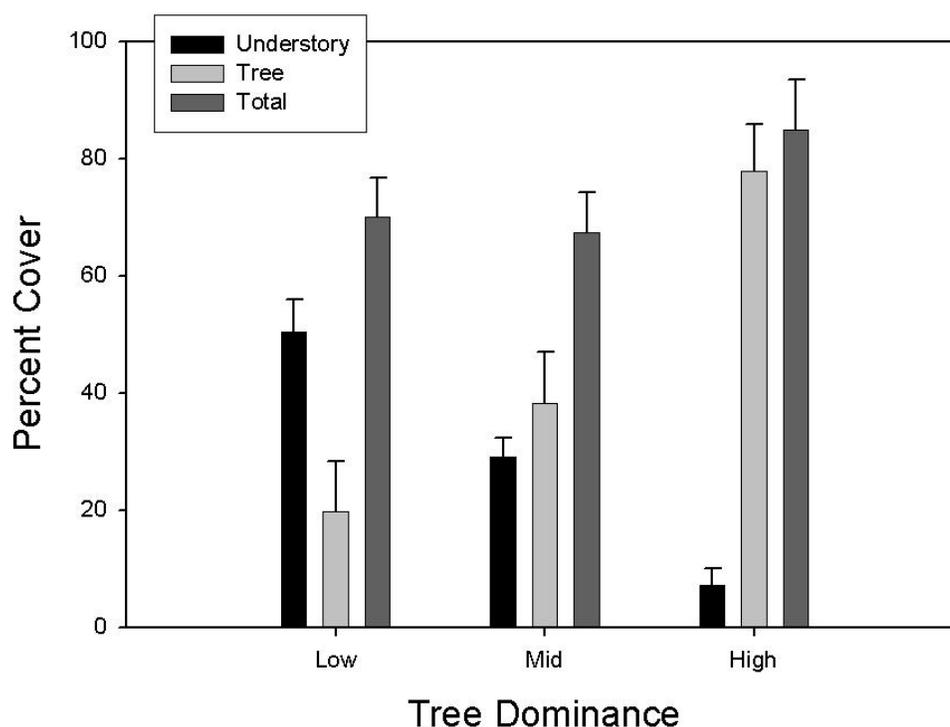
For analyses comparing elevation and tree dominance treatments, fuel loadings were predicted by individual for each species using the appropriate understory species biomass equations and summed for each plot. Shrub litter was estimated for every shrub and summed by plot whereas downed woody material was computed on a plot basis. For fuels analyses, all grass and forb biomass was considered dead to approximate the cured condition of the fuels during high fire season when fire behavior prediction is most needed (Anderson 1982). Also, one third of the shrub leaves were considered ephemeral, and therefore dead (Brown 1982). For analyses comparing lifeforms, only biomass representing the current year's growth was analyzed. Current year's growth was

computed as total leaf weight of shrubs, total weight of forbs and 86% of bunchgrasses. An average of 14% of the weight of sampled bunch grasses was dead material, so 14% of bunchgrass biomass was considered previous year's growth and not included in the analysis. Tree foliage biomass (Tausch 2004) was the variable used to analyze tree dominance because it most aptly describes the ecological influence of the tree component of the community (Tausch and Tueller 1990). Analysis of covariance and ANOVA were performed using the statistical program, Statistix 7.0, to test null hypotheses regarding the effects of tree dominance and elevation on fuel loads and community composition by lifeform. Alpha levels of 0.05 or lower were considered significant results.

## Results and Discussion

### Community composition overview

Total vegetation cover was relatively consistent across the three categories of tree dominance (Figure 8). Trees represented only about one-third of the total vegetation cover in the plots with low tree dominance. Understory and tree cover were approximately equal in the mid tree dominance plots. Total cover declined slightly in the mid tree dominance plots as understory declined more than tree cover increased from low to mid tree dominance. Total cover increased in the high tree dominance plots, with understory cover making up less than 10 percent of the total cover.

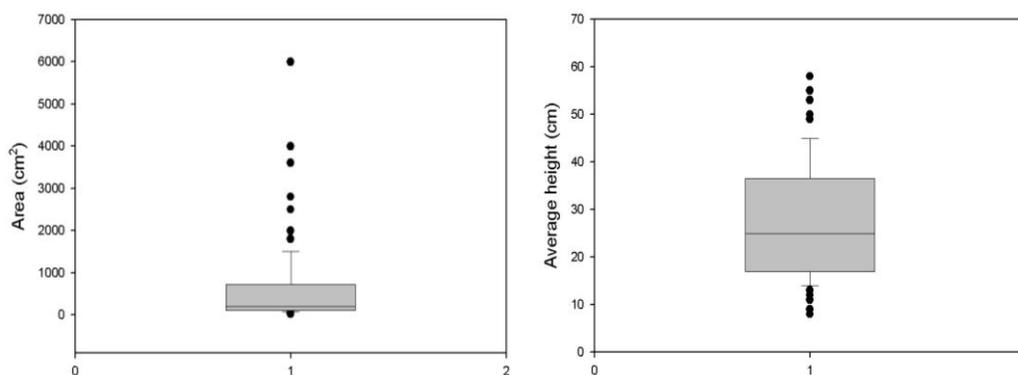


**Figure 8.** Percent cover of understory, trees and total vegetation for the mid elevation plots. Error bars represent standard deviations.

## Biomass computations

Example species: Idaho fescue

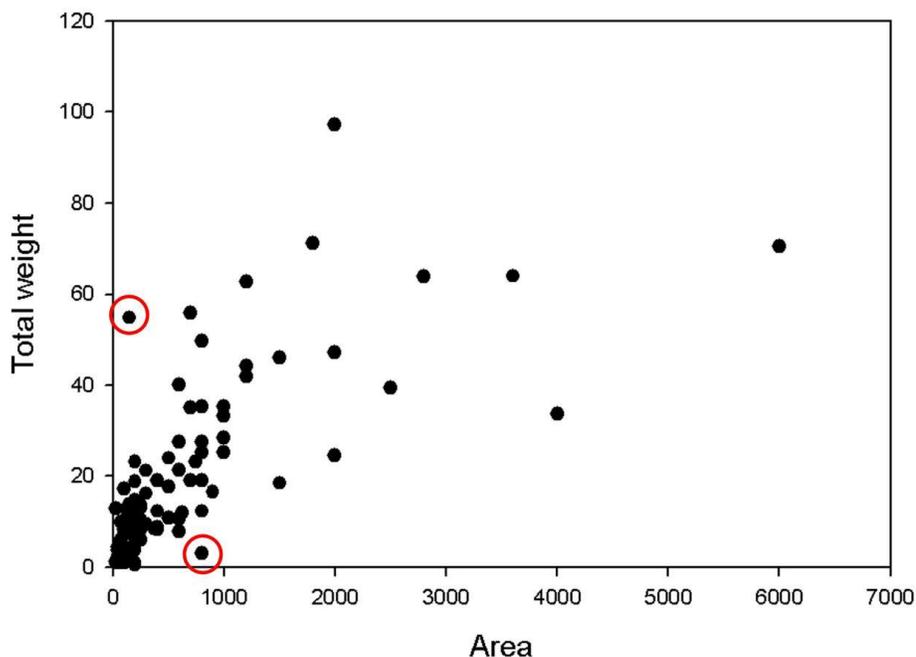
Because describing all the scatter and residual plots created for the following regression analysis results would prove redundant, the data set of the percent cover estimated Idaho fescue will serve as an example of diagnostic plot use throughout the study. First, box and scatter plots were created to examine data set characteristics such as distribution, shape, possible model shape, variance and influence of outliers. For the Idaho fescue data set, the boxplot of area (derived from percent cover) showed a right-tailed distribution. The boxplot for the average height variable showed a more normal distribution (Figure 9).



**Figure 9.** Boxplots of area and average height for Idaho fescue.

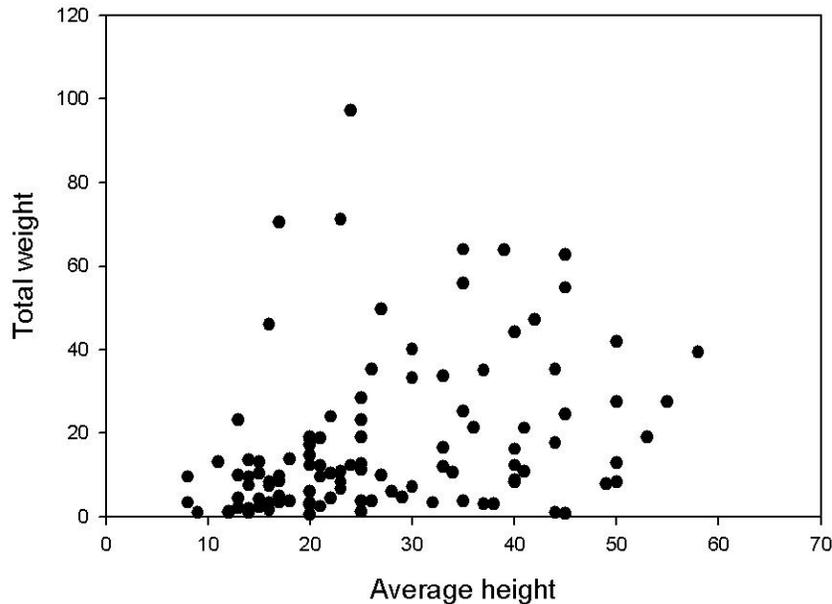
The relationship between area and total weight in the scatter plot was slightly curvilinear. This scatter plot also showed that error increases with plant size for this data set (Figure 10). Two potentially influential outliers were circled in the plot. These points were chosen for inspection as outliers because, at their particular locations along the X

axis, their Y values do not coincide with the range of Y values of the rest of the data set. Before further analysis, original field sheets were checked for these points to identify the possibility of data entry errors causing these outliers.



**Figure 10.** Scatter plot of area versus total weight for Idaho fescue. Outliers are circled.

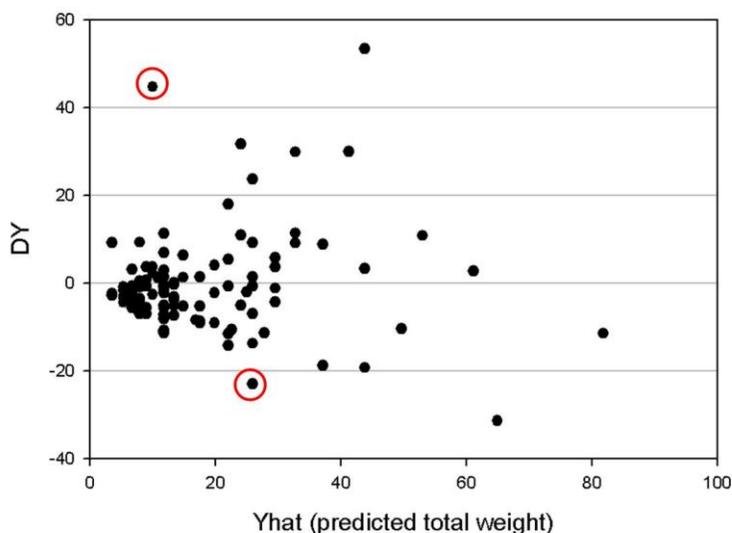
The scatter plot of average height versus total weight showed a large amount of variation and very little discernable trend (Figure 11). When average height was added to the regression equation of area predicting total weight,  $R^2$  was not improved. Because average height had a large amount of variation and did not improve the regression equation, it was not included in the regression equation or further residual analyses.



**Figure 11.** Scatter plot of average height versus total weight for Idaho fescue.

After it was determined to use only the area data to predict total weight of Idaho fescue, a simple regression was run. The power form of the regression equation was used to better fit the curvilinear trend found in the scatter plot. After the regression model was fit, the  $\hat{Y}$  (predicted values for Y) and X values were plotted against the residuals, or the DY ( $DY = \hat{Y} - Y$ ) values, to examine model fit and the influence of outliers (Draper and Smith 1998). If the equation form, linear or power, would have been unclear from the scatter plot(s), the linear equation would have been fit also, and residual plots of power and linear equations compared. The DY versus  $\hat{Y}$  residual plot shows a funnel shape, indicating heteroskedasticity in the form of increasing error (Figure 12). Although in most cases this increasing error would suggest a data transformation, the data set was analyzed without transformation because log transformations result in an increase in the bias of summed biomass estimates (Baskerville 1972, Lee 1982, Tausch and Tueller

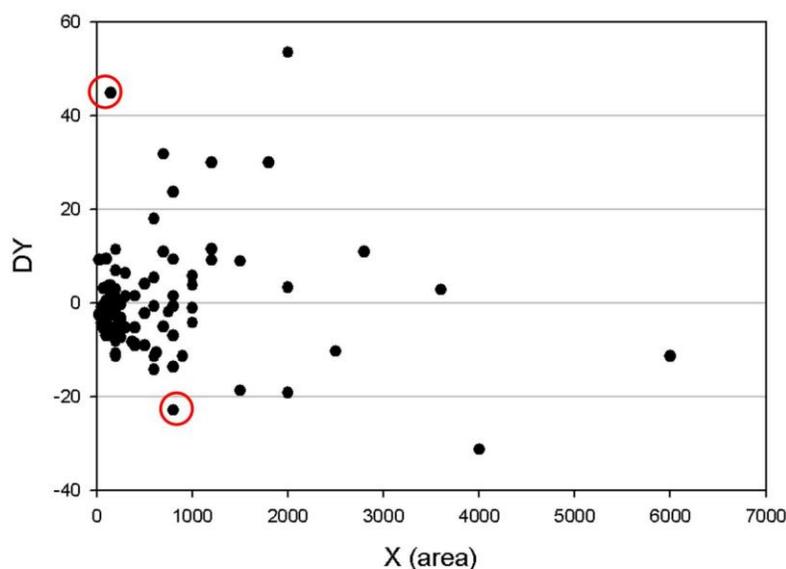
1988). An iterative procedure from Tausch and Tueller (1988) was used to fit regression equations. However, because the assumption of normally distributed error is not met well, caution should be used in interpreting statistical treatments of this regression equation, including F-tests (Lee 1982, Draper and Smith 1998). The DY versus Yhat residual plot also shows that the potentially influential outliers (circled) have generally larger residuals than other points in their range of the X axis.



**Figure 12.** Residual plot of Yhat versus DY for Idaho fescue. Outliers are circled.

The residual plot of DY versus X also shows somewhat of a funnel shape, implying increasing error variance to a slightly lesser degree than the DY versus Y residual plot (Figure 13). The outliers again have very large DY values for their location on the X axis. The first outlier ( $X=150$ ,  $Yhat=10$ ,  $DY=44.7$ ), located above the majority of the data in the scatter plot, highly influences the regression line because it is located very near the left end of the line. This outlier was removed because it has a large degree of leverage and is not representative of the rest of the data set. The second outlier

( $X=800$ ,  $\hat{Y}=26$ ,  $DY=-22.9$ ), located below a majority of the data points in the scatter plot (Figure 10), was located more centrally along the X-axis. The second outlier has less leverage on the regression equation than the first outlier due to its central position on the X-axis. However, the second outlier was also removed, even though it was slightly less influential than the first outlier, in order to balance removal of outliers above and below (in the Y direction) the majority of the data points. Throughout the study, field data were also consulted during outlier removal in order to extract points which were obvious data recording errors.



**Figure 13.** Residual plot of X versus DY for Idaho fescue. Outliers are circled.

### Grass and forb biomass

The crown measurements for ten species of bunch grasses and large forbs that were measured in the field were used to compute the ellipsoid volume by species for inclusion in the regression equations. Data from 2002 were added to 2001 data sets to

increase sample sizes for all species except for *Cryptantha flavoculata* Payson. Because the relationship between the ellipsoid volume and weight varied by year, the 2002 data were not added to the *C. flavoculata* data set. The most effective equations for biomass predictions varied by species (Table 2). For a few of the forb species, the linear regression equation form was the most effective ( $R^2=0.61$  to  $R^2=0.99$ ). For the remaining forb and two grass species the power regression form was the most effective ( $R^2=0.41$  to  $R^2=0.81$ ).

**Table 2.** Regression equations used to predict total plant weight (Y) for grasses and forbs from the ellipsoid volume (X) calculated from crown dimensions.

Species	a	b	Equation	n	R <sup>2</sup>
<i>Antennaria rosea</i>	7.45E-02	4.76E-02	$y=a(x^b)$	24	0.64**
<i>Arabis holboellii</i>	1.94E-02	4.95E-03	$y=a+bx$	25	0.61**
<i>Astragalus purshii</i>	-1.08E-01	3.68E-02	$y=a+bx$	11	0.80**
<i>Cryptantha flavoculata</i>	2.54E-02	8.00E-01	$y=a(x^b)$	18	0.69**
<i>Eriogonum elatum</i>	1.40E-01	3.61E-01	$y=a(x^b)$	11	0.41**
<i>Eriogonum umbellatum</i>	1.63E+00	1.13E-03	$y=a+bx$	35	0.70**
<i>Lupinus caudatus</i>	1.41E-03	9.80E-01	$y=a(x^b)$	85	0.81**
<i>Lygodesmia spinosa</i>	2.03E-01	5.06E-04	$y=a+bx$	19	0.99**
<i>Achnatherum thurberianum &amp; Stipa comata</i>	2.13E-01	2.66E-01	$y=a(x^b)$	16	0.62**
<i>Festuca idahoensis</i>	3.08E-02	7.20E-01	$y=a(x^b)$	20	0.75**

Note: All regression analyses were created using a custom non-linear program.

\*\* indicates a P value less than 0.01.

Simple and multiple regression equations were created for fifteen species of grasses and forbs measured in the field using the average height and percent cover method (Table 3). Data from 2002 were added to 2001 data sets for all species. For these, different equation forms were found to give the best results. For four live forbs and three grasses, a multiple power regression using both area and average height worked best ( $R^2=0.33$  to  $R^2=0.99$ ). One forb was best predicted with multiple linear regression

( $R^2=0.62$ ). Four grass-like species were best predicted with a power regression using only area ( $R^2=0.50$  to  $R^2=0.95$ ). The best fit regression equations for two grass species were linear regressions with area only ( $R^2=0.34$  to  $R^2=0.49$ ). The Sandberg's bluegrass data set had the lowest  $R^2$ , despite the fact that it had the largest number of observations of all the grasses and forbs. Because of its small size, irregular shape and scattered distributions, Sandberg's bluegrass is particularly difficult for biomass estimation.

**Table 3.** Regression equations used to predict total plant weight for grasses and forbs using percent cover and average height.

Species	a	b <sub>1</sub>	x <sub>1</sub>	b <sub>2</sub>	x <sub>2</sub>	Equation	n	R <sup>2</sup>
<i>Arenaria aculeata</i>	1.85E-1	7.14E-1	AREA	4.27E-1	AHT	$y=a((x_1^{b_1})(x_2^{b_2}))$	44	0.47**
<i>Eriogonum elatum</i>	-9.23E-2	1.51E-2	AREA	2.66E-1	AHT	$y=a+(b_1x_1)+(b_2x_2)$	38	0.62**
<i>Lupinus caudatus</i>	1.52E-1	6.60E-1	AREA	3.24E-1	AHT	$y=a((x_1^{b_1})(x_2^{b_2}))$	163	0.61**
<i>Phlox hoodii</i>	6.44E-2	7.75E-1	AREA	6.26E-1	AHT	$y=a((x_1^{b_1})(x_2^{b_2}))$	75	0.75**
<i>Crepis accuminata</i>	9.68E-2	5.95E-1	AREA	1.37E-1	AHT	$y=a((x_1^{b_1})(x_2^{b_2}))$	17	0.71**
<i>Carex vallicola</i>	4.76E-3	1.39E+0	AREA			$y=a(x^b)$	7	0.95**
<i>Achnatherum thurberianum</i> & <i>Stipa comata</i>	2.24E-2	9.44E-1	AREA	3.19E-1	AHT	$y=a((x_1^{b_1})(x_2^{b_2}))$	35	0.81**
<i>Elymus elemoides</i>	3.42E-2	9.65E-1	AREA			$y=a(x^b)$	128	0.50**
<i>Festuca idahoensis</i>	5.47E-1	5.78E-1	AREA			$y=a(x^b)$	107	0.66**
<i>Koleria machrantha</i>	2.78E-1	5.86E-1	AREA			$y=a(x^b)$	37	0.51**
<i>Leymus cineris</i>	2.87E+0	3.45E-3	AREA			$y=a+bx$	16	0.34*
<i>Poa fendleriana</i>	5.51E-1	1.20E-2	AREA			$y=a+bx$	21	0.49**
<i>Poa secunda</i>	1.34E-1	2.64E-1	AREA	4.26E-1	AHT	$y=a((x_1^{b_1})(x_2^{b_2}))$	185	0.33**
<i>Bromus tectorum</i>	8.88E-3	4.54E-1	AREA	1.32E+0	AHT	$y=a((x_1^{b_1})(x_2^{b_2}))$	14	0.99**

Note: All regression analyses were created using a custom non-linear program.

AREA = estimated aerial coverage.

AHT = average height of aerial percent cover estimated samples.

\*\* indicates a P value less than 0.01.

\* indicates a P value less than 0.05.

Although the crown dimension measurement method was too time consuming a technique to use in areas with a high density of small plants, it produced data sets with less variation than the percent cover method. For example, Idaho fescue was measured using both methods. Only twenty plants were measured with the crown measurement

method, producing a regression  $R^2$  of 0.75, whereas the regression formed from the 107 plants measured with the percent cover method had an  $R^2$  of 0.66. Some of the variation lowering  $R^2$  values for data sets from the percent cover method could be due to the difficulty field data collectors had with consistently identifying the percent cover of sparsely distributed plants.

Four generic regression models were developed to predict the less abundant grasses and forbs, one model for the grasses and three models for the forbs (Table 4). These regressions were created from species not represented in other single-species regression equations (Table 5). Data from 2002 were added to 2001 data for all cases. The linear models were found to fit best in all generic regression cases. For the generic percent cover forb regression and the generic grass regression, the preliminary linear model fit had a negative intercept. In these cases, to avoid negative weight estimates, regressions were forced through the origin.  $R^2$  for the finalized generic regressions ranged from 0.33 to 0.98.

**Table 4.** Regression equations used to predict total plant weight for groups of species by generic lifeform in Underdown Canyon.

Species	a	b	$x_1$	Equation	n	$R^2$
generic forb (percent cover)		7.00E-02	AREA	$y=bx$	27	(S) 0.72**
small generic forb (crown measured)	3.01E-01	2.85E-03	VOL2	$y=a+bx$	16	0.41**
large generic forb (crown measured)	2.41E-01	1.13E-03	VOL2	$y=a+bx$	9	0.98**
generic grass (crown measured)		2.75E-03	VOL2	$y=bx$	32	(S) 0.31**

Note: Regression analyses were created using a custom non-linear program unless marked by “(S)” in which case regressions were performed using Statistix 7.0.

VOL2 = ellipsoid volume calculated from total height.

AREA = estimated aerial coverage.

\*\* indicates a P value less than 0.01.

\* indicates a P value less than 0.05.

**Table 5.** Species grouped to create generic regression equations.

## Generic forb (percent cover) regression

*Antennaria rosea* Greene  
*Erigeron aphanactis* Greene  
*Eriogonum umbellatum* Torr.  
*Penstemon deustus* Dougl.  
*Penstemon watsonii* Gray  
*Lygodesmia spinosa* Nutt.  
*Cordylanthus ramosus* Nutt.

## Small generic forb (crown measured) regression

*Chaenactis douglasii* Hook. & Arn.  
*Eriogonum ovalifolium* Benth.  
*Erigeron aphanactis*

## Large generic forb (crown measured) regression

*Castilleja linarifolia* Benth.

## Generic grass (crown measured) regression

*Poa secunda*  
*Poa fendleriana* Vasey  
*Elymus elymoides*  
*Achnatherum hymenoides* (Roem. & Schult.)Barkworth

**Shrub biomass**

Separate regression models were developed to predict total weight, live weight and foliage weight for each percent dead category for each of three more abundant shrub species, Wyoming big sagebrush, Mountain big sagebrush and rabbitbrush, to predict fuels more accurately (Tables 6-8). Data from 2002 were added to the 2001 data set in all three cases. The simple power equation was found to be the best model in all but two cases. These exceptions, both dead standing sagebrush, were best exhibited with multiple power regression equations. VOL2, the ellipsoid volume based on total shrub height, predicted total and live weight better than VOL1, which was based on foliage height.

VOL1 was a better predictor of foliage weight than VOL2. Individual regressions formed to predict total and live weight for the selected biomass components within each percent dead category had  $R^2$  values between 0.56 and 0.94.  $R^2$  values for equations predicting foliage biomass were the lowest for predicting the foliage biomass of shrubs more than one-half dead ( $R^2=0.31$  to  $R^2=0.65$ ). For shrubs less than one-half dead the prediction of foliage had  $R^2$  values of 0.46 to 0.87. Although  $R^2$  values for equations predicting the total dead weight of 100 percent dead plants were quite low, lying between 0.26 and 0.60, these  $R^2$  values were acceptable because these equations were only used to predict a small subset of the entire shrub population.

**Table 6.** Regression equations used to predict various subsets of *Artemisia tridentata vaseyana* weight (y) for various percent dead categories.

Percent dead	y	a	b <sub>1</sub>	x <sub>1</sub>	b <sub>2</sub>	x <sub>2</sub>	Equation	n	R <sup>2</sup>
0-15	T	1.26E-02	8.50E-01	VOL2			$y=a(x^b)$	53	0.83**
0-15	L	1.36E-02	8.35E-01	VOL2			$y=a(x^b)$	53	0.81**
0-15	F	4.46E-02	5.89E-01	VOL1			$y=a(x^b)$	52	0.59**
16-50	T	1.48E-01	6.58E-01	VOL2			$y=a(x^b)$	111	0.72**
16-50	L	2.36E-01	5.90E-01	VOL2			$y=a(x^b)$	111	0.70**
16-50	F	4.29E-02	5.73E-01	VOL1			$y=a(x^b)$	110	0.62**
51-99	T	1.73E+00	4.56E-01	VOL2			$y=a(x^b)$	18	0.64**
51-99	L	1.64E+00	3.62E-01	VOL2			$y=a(x^b)$	17	0.64**
51-99	F	1.99E+00	4.00E-01	VOL1			$y=a(x^b)$	17	0.31*
100	D	7.11E-01	7.01E-01	THT	1.20E+00	BD	$y=a((x_1^{b_1})(x_2^{b_2}))$	117	0.60**

Note: All regression analyses were created using a custom non-linear program.

T = total weight.

L = live weight.

D = dead weight.

THT = total height.

BD = Basal diameter.

VOL1 = ellipsoid volume calculated from foliage height.

VOL2 = ellipsoid volume calculated from total height.

\*\* indicates a P value less than 0.01.

\* indicates a P value less than 0.05.

**Table 7.** Regression equations used to predict various subsets of *Artemisia tridentata wyomingensis* weight (y) for various percent dead categories.

Percent dead	y	a	b <sub>1</sub>	x <sub>1</sub>	b <sub>2</sub>	x <sub>2</sub>	Equation	n	R <sup>2</sup>
0-15	T	3.57E-02	8.10E-01	VOL2			$y=a(x^b)$	29	0.84**
0-15	L	2.15E-02	8.51E-01	VOL2			$y=a(x^b)$	29	0.87**
0-15	F	3.95E-02	5.84E-01	VOL1			$y=a(x^b)$	29	0.87**
16-50	T	3.39E-04	1.18E+00	VOL2			$y=a(x^b)$	50	0.94**
16-50	L	4.56E-05	1.31E+00	VOL2			$y=a(x^b)$	50	0.94**
16-50	F	5.87E-04	9.54E-01	VOL1			$y=a(x^b)$	50	0.78**
51-99	T	4.33E-01	5.82E-01	VOL2			$y=a(x^b)$	13	0.72**
51-99	L	1.38E-01	5.95E-01	VOL2			$y=a(x^b)$	13	0.73**
51-99	F	1.33E-01	4.61E-01	VOL1			$y=a(x^b)$	13	0.35*
100	D	6.20E-01	1.66E+00	THT	-3.66E-01	BD	$y=a((x_1^{b_1})(x_2^{b_2}))$	18	0.44**

Note: Methods and variables are as defined in Table 6.

**Table 8.** Regression equations used to predict various subsets of *Chrysothamnus vicidiflorus* weight (y) for various percent dead.

Percent dead	y	a	b	x <sub>1</sub>	Equation	n	R <sup>2</sup>
0	L	1.81E-02	7.19E-01	VOL2	$y=a(x^b)$	104	0.56**
0	F	1.35E-02	6.38E-01	VOL2	$y=a(x^b)$	103	0.46**
1-50	T	3.18E-02	6.74E-01	VOL2	$y=a(x^b)$	64	0.72**
1-50	L	4.54E-02	5.94E-01	VOL2	$y=a(x^b)$	64	0.63**
1-50	F	2.66E-02	5.18E-01	VOL2	$y=a(x^b)$	64	0.38**
51-99	T	4.05E-06	1.54E+00	VOL2	$y=a(x^b)$	37	0.93**
51-99	L	1.55E-05	1.33E+00	VOL2	$y=a(x^b)$	37	0.92**
51-99	F	1.18E-03	8.18E-01	VOL2	$y=a(x^b)$	37	0.65**
100	D	5.32E-02	1.69E+00	THT	$y=a(x^b)$	37	0.26**

Note: Methods and variables are as defined in Table 6.

For estimation of fuel subparts (1, 10, 100 and 1,000 hour live and dead, with fuels greater than 3” constituting the 1,000 hour fuels) for the three most abundant shrub species, Wyoming big sagebrush, Mountain big sagebrush and rabbitbrush, three to four categories based on percent dead were found to provide the best fuels estimation. The categories found to best predict Wyoming big sagebrush fuel size class distributions from

average percentages were 0, 1 to 15, 16 to 50 and 51 to 100 percent dead (Table 9).

Categories for Mountain big sagebrush were 0 to 15, 16 to 50 and 51 to 100 (Table 10).

Categories for rabbitbrush were 0, 1 to 50 and 51 to 100, reflecting that rabbitbrush had a higher ratio of live to dead material (Table 11). The distributions of the big sagebrush species were similar, as both had a majority of the plants in the 16 to 50 percent dead category. The rabbitbrush differed in that over one-half of the plants were in the lowest percent dead category, having no discernable dead material (Figure 14).

**Table 9.** Average percentages of live and dead fuel subparts for *Artemisia tridentata wyomingensis* by field estimated percent dead category.

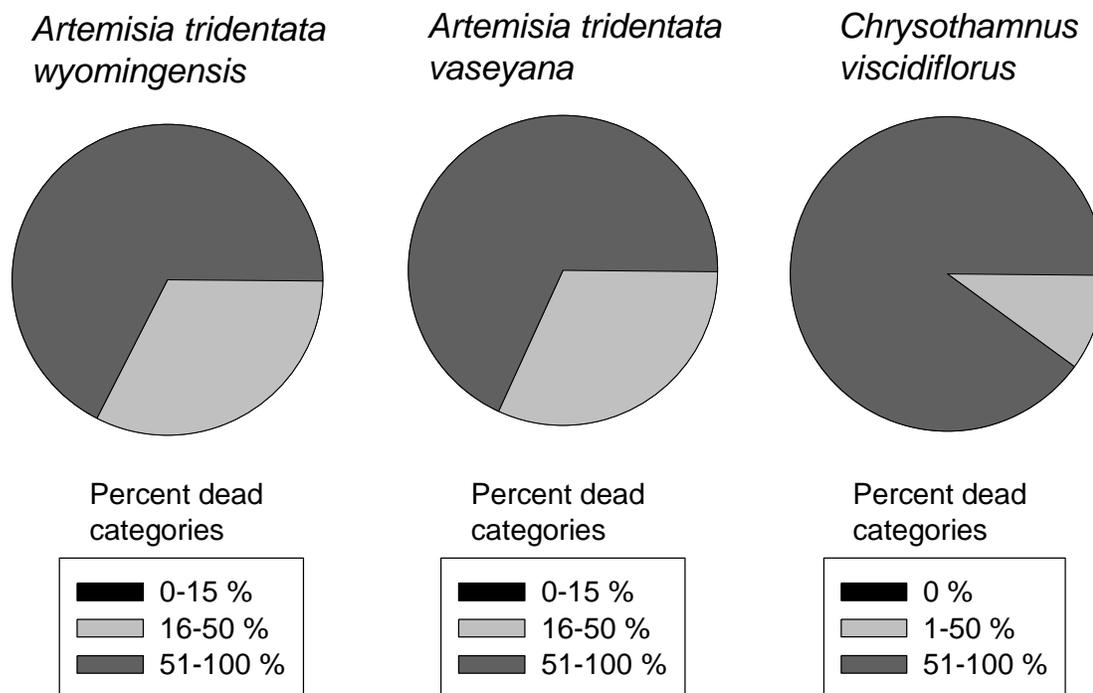
Percent dead	Live				Dead		
	1 hour	10 hour	100 hour	1,000 hour	1 hour	10 hour	100 hour
0	0.270	0.122	0.430	0	0	0	0
1 to 15	0.155	0.147	0.595	0.021	0.54	0.461	0
16 to 50	0.158	0.280	0.467	0	0.559	0.328	0.113
51 to 100	0.156	0.234	0.536	0	0.405	0.387	0.209

**Table 10.** Average percentages of live and dead fuel subparts for *Artemisia tridentata vaseyana* by field estimated percent dead category.

Percent dead	Live				Dead		
	1 hour	10 hour	100 hour	1000 hour	1 hour	10 hour	100 hour
0 to 15	0.258	0.264	0.259	0.000	0.562	0.115	0.322
16 to 50	0.167	0.230	0.480	0	0.549	0.292	0.159
51 to 100	0.098	0.188	0.635	0	0.404	0.325	0.272

**Table 11.** Average percentages of live and dead fuel subparts for *Chrysothamnus viscidiflorus* by field estimated percent dead category.

Percent dead	Live			Dead	
	1 hour	10 hour	100 hour	1 hour	10 hour
0	0.629	0.006	0	0	0
1 to 50	0.583	0.129	0	0.985	0.015
51 to 100	0.478	0.236	0	0.848	0.152



**Figure 14.** Percent of plant numbers within each percent dead category by species.

Because sample sizes for the five less abundant species of shrubs and semi shrubs were small (low sagebrush; Mormon tea, *Ephedra viridis* Cov.; slenderbush eriogonum, *Eriogonum microthecum* Nutt.; prickly phlox, *Leptodactylon pungens* (Torr.)Nutt.; and mountain snowberry, *Symphoricarpos oreophilus* A. Gray), the data sets were not divided into percent dead categories to create regression equations to predict percentages of fuels (Table 12). Data from 2002 were added to 2001 data for all of these species when they were available. Separate regression equations for foliage weight were not created for Mormon tea or the semi shrubs due to lack of distinct leaves or small sample sizes. Weights of the very few 100 percent dead standing low sagebrush and mountain snowberry were estimated using Wyoming big sagebrush regression equations. From scatter and residual plots created, the power equation and VOL2 were found to yield the

best models for these shrubs. In some cases when it was abundant, slenderbush eriogonum was measured using the percent cover method. A multiple regression equation using percent cover and average height to predict weight was used in these situations (Table 12). Fuel size category calculations were based on average percent as was done for the most abundant three shrub species. However, due to small sample sizes, only mountain snowberry was broken down into individual percent dead categories to calculate fuel size distributions (Table 13).

**Table 12.** Regression equations used to predict various subsets of plant weight (y) for various percent dead categories for less abundant species of shrubs and semi-shrubs in Underdown Canyon.

Species	y	a	b <sub>1</sub>	x <sub>1</sub>	b <sub>2</sub>	x <sub>2</sub>	Equation	n	R <sup>2</sup>
<i>Artemisia arbuscula</i>	T	7.16E-8	2.02	VOL2			$y=a(x^b)$	19	0.96**
<i>Artemisia arbuscula</i>	L	4.25E-7	1.80	VOL2			$y=a(x^b)$	19	0.94**
<i>Artemisia arbuscula</i>	F	6.62E-3	6.78E-1	VOL1			$y=a(x^b)$	19	0.56**
<i>Ephedra viridis</i>	T		1.26E-3	VOL2			$y=a*x_1$	14	(S) 0.90**
<i>Ephedra viridis</i>	L		1.13E-3	VOL2			$y=a*x_1$	14	(S) 0.90**
<i>Eriogonum microthecum</i>	T	8.53E-2	4.69E-1	VOL2			$y=a(x^b)$	19	0.78**
<i>Eriogonum microthecum</i>	T	7.50E-2	8.79E-1	AREA	2.15E-1	AHT	$y=a((x_1^{b_1})(x_2^{b_2}))$	26	0.71**
<i>Leptodactylon pungens</i>	T	1.15E-1	4.90E-1	VOL2			$y=a(x^b)$	22	0.59**
<i>Leptodactylon pungens</i>	L	2.33E-1	3.75E-1	VOL2			$y=a(x^b)$	22	0.34**
<i>Symphoricarpos oreophilus</i>	T	5.52E-3	7.99E-1	VOL2			$y=a(x^b)$	52	0.84**
<i>Symphoricarpos oreophilus</i>	L	6.21E-3	7.66E-1	VOL2			$y=a(x^b)$	52	0.84**
<i>Symphoricarpos oreophilus</i>	F	3.92E-3	6.67E-1	VOL2			$y=a(x^b)$	52	0.73**

Note: Regression analyses were created using a custom non-linear program unless otherwise noted by "(S)," in which case regressions were performed using Statistix.

AREA = estimated aerial coverage.

AHT = average height of aerial percent cover estimated samples.

Other variables and methods are as defined in Table 6.

**Table 13.** Average percentages of live and dead fuel subparts for less abundant shrub species by field estimated percent dead category or measurement method.

Species	Foliage	Live			Dead	
		1 hour	10 hour	100 hour	1 hour	10 hour
<i>Artemisia arbuscula</i>	r	0.185	0.325	0.396	0.499	0.551
<i>Ephedra viridis</i>	0.215	0.394	0.283	0.109	0.634	0.366
<i>Eriogonum microthecum</i> , crown measured	0.212	0.719	0	0	0.069	0
<i>Eriogonum microthecum</i> , percent cover		0.752	0	0	0	0
<i>Leptodactylon pungens</i>	0.376	0.549	0.074	0	1	0
<i>Symphoricarpos oreophilus</i> , 1-15% dead	r	0.693	0.21	0	1	0
<i>Symphoricarpos oreophilus</i> , 16-99% dead	r	0.678	0.16	0.019	0.94	0.06

Note: r denotes that foliage biomass was predicted from a regression equation.

### Shrub litter

Because the amounts of litter under sagebrush increased with elevation, separate regression equations were created from plants collected above and below 7500 feet in elevation for sagebrush. However, rabbitbrush litter samples could not be separated by elevation to estimate litter loads due to their more limited distribution in the canyon. The higher sagebrush litter loads in the upper elevations appear to reflect the higher productivity found at these sites as a result of higher precipitation and more water availability. For both sagebrush and rabbitbrush, the littermat area was found to average 79% of the crown area. Regression equations fit for the sagebrush were almost linear and had  $R^2$  values of 0.74 and 0.75 (Table 14). There was too much variation in the 18-sample rabbitbrush data set to create a useful regression. The median density of 0.016 g/cm<sup>2</sup> was used to extrapolate rabbitbrush litter to the area of each littermat.

**Table 14.** Regression equations used to predict sagebrush litter by elevation in Underdown Canyon.

Elevation	y	a	b	x	equation	n	R <sup>2</sup>
>7500'	litter weight	3.60E-02	1.06E+00	litter area	$y=a(x^b)$	27	0.74**
<7500'	litter weight	1.87E-01	9.51E-01	litter area	$y=a(x^b)$	9	0.75**

Note: All regression analyses were created using a custom non-linear program.  
\*\* indicates a P value less than 0.01.

## Treatment analyses

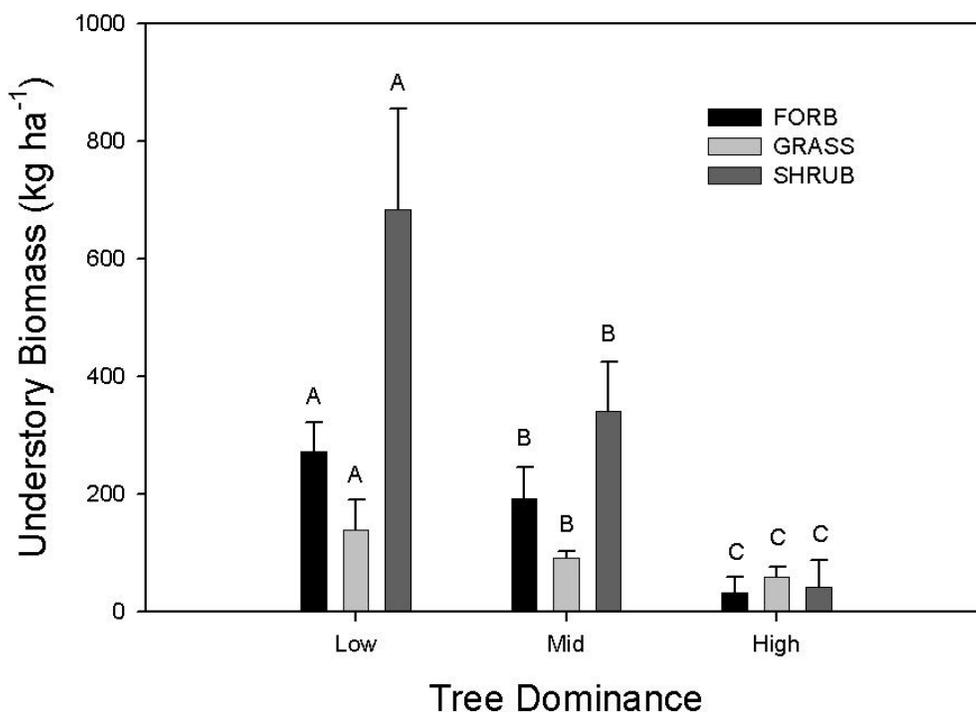
### Understory community trends

The understory biomass declined as tree dominance increased (Figure 15).

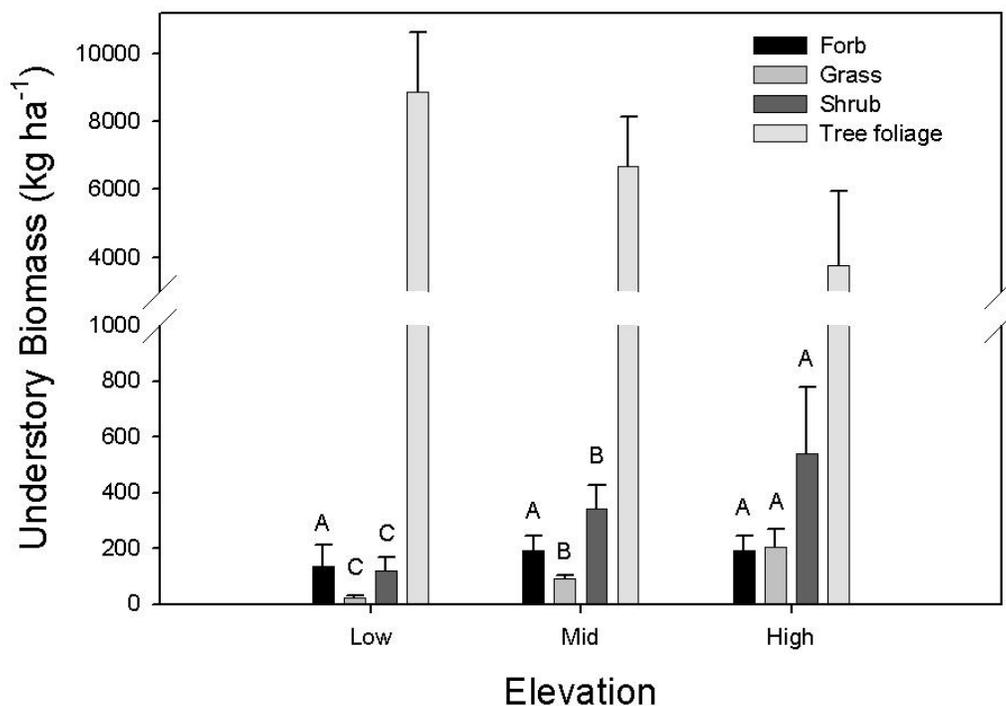
Understory dominance appeared to shift from shrubs being the most dominant, followed by forbs and then grasses to grasses being the most dominant as tree dominance increased. In the ANOVA, all three lifeforms, grass, forb and shrub, were significantly different ( $P = 0.0016$ ,  $<0.0001$ , and  $<0.0001$ , respectively) between all three categories of tree dominance. The shrubs had the steepest decline in biomass with increasing tree dominance, forbs decreased moderately and grass lifeforms decreased the least.

The biomass of grasses and shrubs in the mid density plots increased significantly ( $P < 0.0001$  and  $P = 0.0008$ , respectively) with elevation (Figure 16). The slight increase in forb biomass was not significant. However, a decrease in tree foliage biomass in the same plots with increasing elevation appears partly responsible for the understory increase. In the Analysis of covariance, the significance of F values for the elevation effect on each of the lifeforms decreased when tree foliage biomass was added as a covariant, demonstrating that tree dominance is partially responsible for the apparent

results of elevation in the ANOVA tests (Table 15). The ecological reasons for higher production at the higher elevations is most likely due to higher amounts of available water.



**Figure 15.** Understory biomass versus tree dominance for the mid elevation plots. In order to compare between lifeforms fairly, understory biomass is calculated in this analysis as current year's growth which includes the biomass of forbs and smaller grasses, 86% of large bunch grasses (to avoid including the average 14% of dead material in large bunch grasses), and shrub leaves. Lifeforms with the same letter among different tree dominance treatments did not significantly differ at the  $\alpha = 0.05$  level according to the LSD means separation test. Error bars represent standard deviations.



**Figure 16.** Understory biomass by lifeform versus elevation for the mid tree dominance plots. Methods are as defined in Figure 15.

**Table 15.** F-test and significance for a comparison of ANOVA and Analysis of covariance for the variation in the plot biomass of forbs, grasses and shrubs over the elevation classes. Tree foliage biomass in the plots is used as the covariant. Only mid tree dominance plots were compared in this analysis.

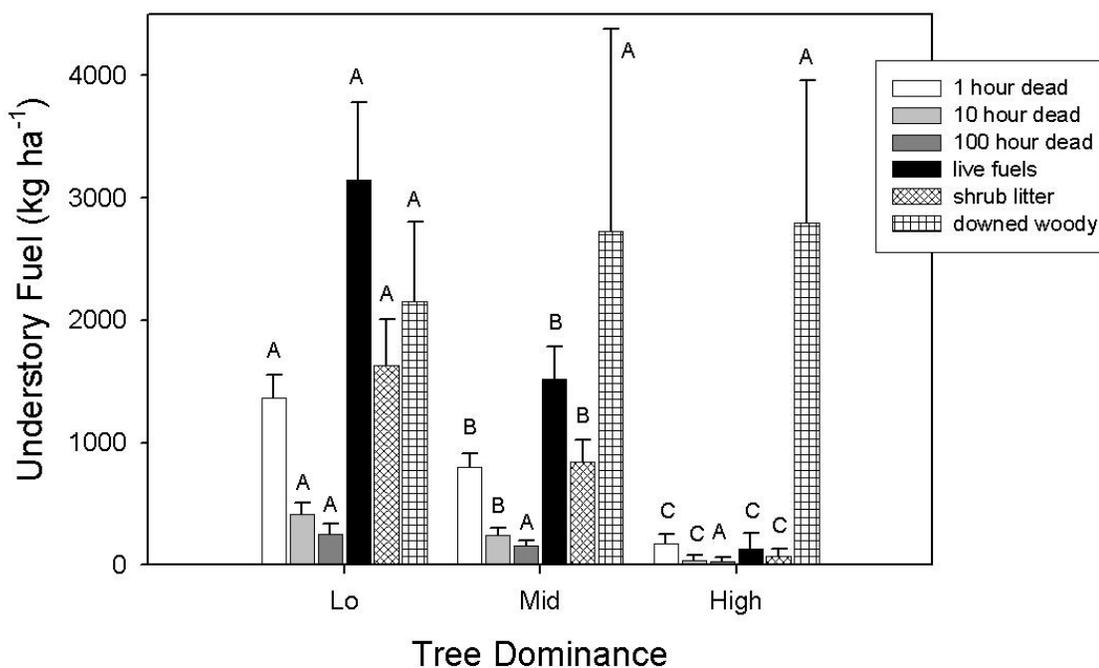
lifeform	Covariance Analysis		ANOVA
	elevation	tree	elevation
Forb	0.66	0.36	1.65
Grass	8.31**	6.42*	34.46**
Shrub	1.55	5.44*	12.06**

Note: P values are denoted as: \*\* =  $P < 0.01$ , \* =  $P < 0.05$ .

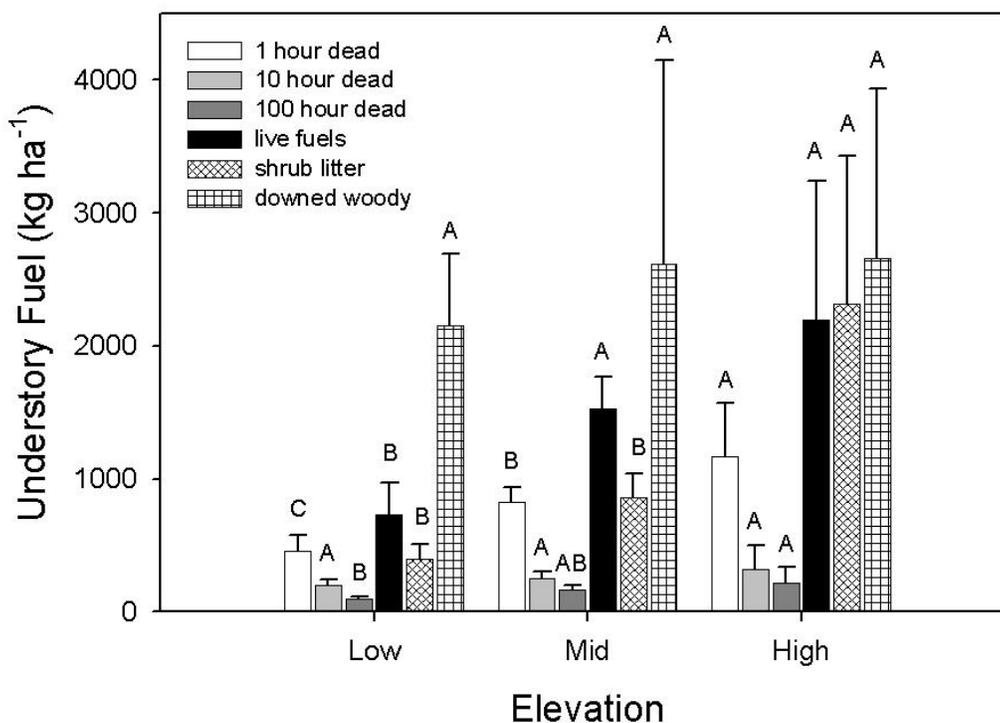
## Fuels trends

At the mid elevation, understory fuels changed markedly with tree dominance. Most understory fuel size components decreased significantly ( $P < 0.0001$  for shrub litter, live fuels, 1, 10 and 100 hour dead fuels, and  $P = 0.0133$  for 1 hour dead fuels) with increasing tree dominance (Figure 17). Total live and dead understory fuels at the mid elevation plots, not including downed woody, averaged  $6815 \text{ kg ha}^{-1}$  ( $3.04 \text{ tons ac}^{-1}$ ) in the low tree dominance plots to  $3556 \text{ kg ha}^{-1}$  ( $1.59 \text{ tons ac}^{-1}$ ) in the mid and finally to  $429 \text{ kg ha}^{-1}$  ( $0.19 \text{ tons ac}^{-1}$ ) in the high tree dominance plots. The only fuel subpart that did not change significantly with tree dominance in the ANOVA was downed woody material. This lack of variation in downed woody material between tree dominance treatments is most likely because downed woody material is comprised of tree fuels as well as shrub fuels. As shrub-generated downed woody fuels declined with increasing tree dominance, tree-generated downed woody fuels increased.

In the mid tree dominance plots the understory fuels generally increased with elevation (Figure 18). The changes in shrub litter, 1, 10 and 100 hour dead fuels and total live fuels with increasing elevation were significant ( $P < 0.0001$ ,  $P = 0.0007$ ,  $P < 0.0001$ ,  $P < 0.0001$  and  $P < 0.0001$ , respectively). However, this variation could have been due in part to tree dominance decreasing in the same plots with increasing elevation. As with the Analysis of covariance results for the individual lifeforms, adding tree foliage biomass as a covariant to the analysis reduced the significance of the elevation effect, suggesting tree dominance is the dominating factor (Table 16).



**Figure 17.** Understory fuels versus tree dominance at mid elevation plots. For fuels analyses, all grass and forb biomass was considered dead and one-third of shrub leaves were considered ephemeral and therefore dead (Brown 1982) and included in the 1 hour dead fuel category. The remaining two-thirds of the shrub leaves are considered live and included in the 1 hour live fuels. Fuels with the same letter among different tree dominance treatments did not significantly differ at the  $\alpha = 0.05$  level according to the LSD means separation test. Error bars represent standard deviations.



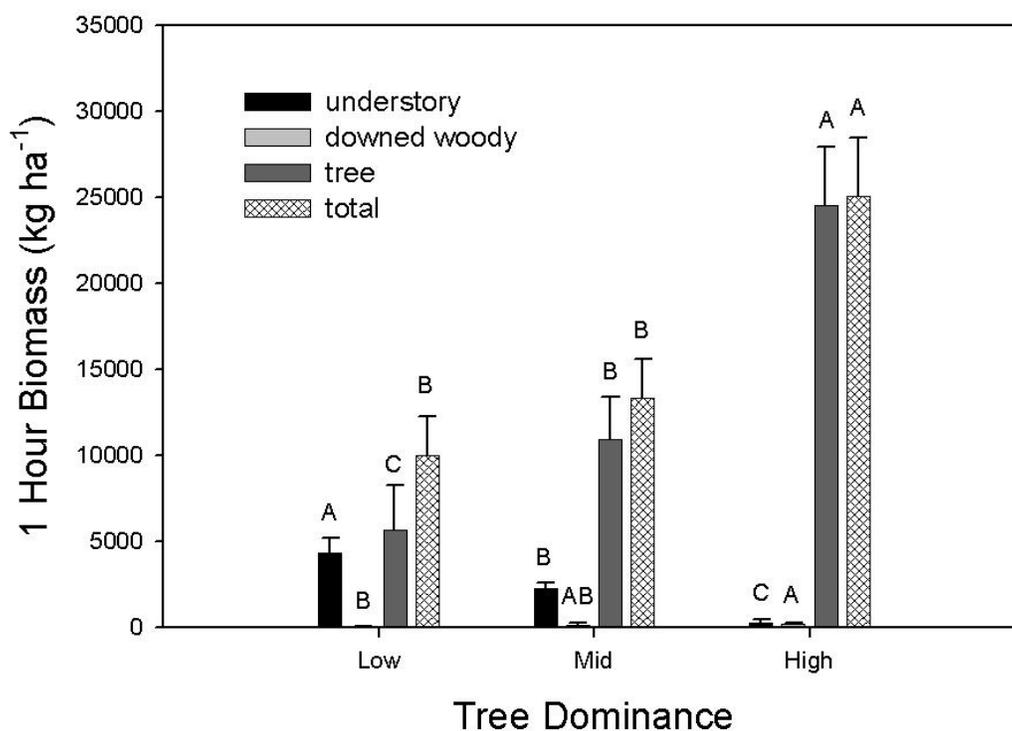
**Figure 18.** Understory fuels versus elevation for mid tree density plots. Methods are as described in Figure 17.

**Table 16.** F-test and significance for a comparison of ANOVA and Analysis of covariance for the variation in the plot biomass of various fuel portions over the elevation classes. Tree foliage biomass in the plots is used as the covariant. Only mid tree dominance plots were compared in this analysis.

fuel	Covariance Analysis		ANOVA
	elevation	tree	elevation
Downed woody	0.50	0.29	0.39
Shrub litter	2.76#	3.95#	14.22**
1 hour dead	1.07	10.17**	12.15**
10 hour dead	0.20	6.83*	1.99
100 hour dead	0.05	6.27*	3.98*
Total live	0.62	5.58*	7.88**

Notes: P values are denoted as: \*\* =  $P < 0.01$ , \* =  $P < 0.05$ , # =  $P < 0.1$ .

Although the understory diminishes with increasing tree dominance, total fuel loads increase. Total 1 hour fuels in the plots are strongly influenced by the level of tree dominance (Figure 19). The 1 hour fuels for the trees (Tausch 2004) approximately double between each category of increasing tree dominance. Between the low and mid tree dominance categories, this increase is mostly offset by the decrease in understory fuels. The result is that total 1 hour fuels do not differ appreciably between the low and mid tree dominance categories. A major increase in total 1 hour fuels then occurs between the mid and high tree dominance categories.



**Figure 19.** 1 hour tree and understory fuels versus tree dominance for mid elevation plots. Tree fuels depicted here are 1 hour live aerial fuels. 1 hour fuels in the understory category here consist of live and dead understory plant data as well as shrub littermat data. Fuels with the same letter between different tree dominance treatments did not significantly differ at the  $\alpha = 0.05$  level according to the LSD means separation test. Error bars represent standard deviations.

## Summary

Overall, simple regression models predicting understory species biomass with the crown volume ellipsoid approach performed better than the multiple regressions in the cross validations. However, the variation between the individual results of the two cross validation tests implies that sample sizes in this study, once divided in half for split-sample cross validation, may not be adequate to effectively use only two rounds of cross validation tests. Similar methods of cross validation may be more useful with larger sample sizes or data containing less variation or possibly by performing large numbers of cross validation test repetitions. If large numbers of split-sample cross validations were performed, a distribution of percent errors could be graphed for each type of regression model/method tested. These distributions could then be compared and the predictive capabilities of models/methods tested could be compared. For this study, the two cross validation tests performed effectively represented only two points in an unknown distribution, and therefore should not be considered representative enough of the unknown distribution to draw definitive conclusions. In addition to the use of a distribution of cross validation results, the PRESS statistic (Green 1983), would be a useful tool to diagnose the predictive capabilities of various models when an exceedingly large data set is not available.

Changes in the understory community composition and fuel loads followed changes in tree dominance and elevation as expected from field observations and previous research. Understory plant biomass declined as tree dominance, as indicated by foliage biomass, increased. Results are similar to previous findings of understory percent

cover decline with increasing tree cover (Blackburn and Tueller 1970, Barney and Frischknecht 1974, Tausch and Tueller 1990, Tausch and West 1995, Bunting et al. 1999, Poulsen et al. 1999, Miller et al. 2000). Understory community biomass generally increased with elevation. This probably reflects greater water availability at the higher elevations. However, the effects of tree dominance generally overpowered the effects of elevation. The understory fuel load results paralleled the community analysis results. Understory fuels decreased with increasing tree density while downed woody fuel, which is a composite of both shrub and tree ground fuels, remained constant. For the mid tree dominance plots, understory fuels other than downed woody increased slightly with elevation due in part to factors discussed earlier for the understory plant community changes. Although the understory contribution to the fuel loads decreases with increasing tree dominance, total fuels increase substantially.

**Results Summary:**

- Forb, grass and shrub biomass as well as total understory fuels decrease with increasing tree dominance.
- Fuel loads of trees plus understory increase with increasing tree dominance.
- Tree dominance appears to override effects of elevation on understory.

## Conclusions

### Synthesis

The effects of fire on landscape containing sagebrush-steppe/pinyon-juniper woodlands are variable and dependent upon existing pre-fire conditions. The loss of the understory component in pinyon-juniper woodlands can lead to poor post-fire recovery of native species and site conversion to a cheatgrass dominated system. The effects of fire upon soil nutrients, organic matter and soil fauna as well as plant community post-fire recovery, depend in part upon the heat imparted from and the organic matter consumed by the fire, which is in turn affected by tree dominance and its associated fuel loads (Neary et al. 1999). In addition to nutrient volatilization, formation of water repellent soils could occur after burns in high dominance stands, however this phenomenon would only effect erosion following major precipitation events which are rare in the Great Basin (personal communication, Ben Rau, Department of Hydrologic Sciences, University of Nevada, Reno, Nevada 775/784-7514). As fuel loads increase in a stand, the potential for higher fire intensities also increases. The lack of understory in high dominance stands coupled with the negative post-fire effects of high fire intensities means that large areas covered by high tree dominance may have lower revegetation rates after fire. Also, the lack of a strong understory component after fire can leave these sites more open to cheatgrass invasion.

Due to the land area currently covered by pinyon and juniper, and the expected increases in pinyon-juniper density and aerial coverage, the negative post-fire effects associated with high density stands may take place over large areas of the Great Basin in a

matter of decades. Only one-fifth of the plots sampled in Underdown Canyon were in the high tree dominance category, whereas over one-half were in the mid tree dominance category. Previous work (Tausch and West 1995) indicates that it takes about 50 years to move a mid tree dominance plot to one with high dominance. Based on this assumption, and the results in Figure 19, over the next 50 years the dominance of the woodlands in Underdown Canyon will increase from about one-fifth in the high category to nearly three-fourths in the high category in 50 years. This increase in tree dominance represents a near doubling of total woodland fuel loads on a watershed scale. When the mid tree dominance stands reach maturity, the post-fire effects and possible threshold transitions of high dominance stands can be expected after wildfires. To further exacerbate the expected maturation of woodlands, future climate scenarios modeled with general circulation models predict an increase in precipitation as well as temperature, which could further enhance woodland expansion (Bachelet et al. 2001). It is hypothesized that the role of fire in reducing pinyon-juniper woodlands was substantial during the Post-Neoglacial drought (Miller and Tausch 2001). Due to the influences of humans on ecological and climate change and the introduction of invasive species, the role wildfire may play in Great Basin ecosystems in the coming decades may be even greater than the role it played in the Post-Neoglacial period. However, post-wildfire effects may be undesirable given the current and likely future states of woodlands in the Great Basin today.

## **Management implications**

Informed land management decisions are needed in the Great Basin to maintain cultural, ecological and economic values of the land in the face of climate change, introduction of invasive species and the ecological impacts of historic and current resource use. The state of woodland expansion and potential negative impacts of high intensity wildfires in high dominance woodlands creates a strong impetus to manage a large portion of these stands for sagebrush-steppe or low dominance woodlands in areas other than sheltered old growth stands. Because most of the negative post-fire effects are associated with high dominance stands, it may be beneficial to manage low and mid dominance woodlands before they become high dominance stands. Due to the large spatial scale of low and mid tree dominance woodlands, low-cost land management tools will be needed to conserve the values associated with sagebrush-steppe and pinyon-juniper woodlands.

Our perception of fire as a land management tool is increasing. Fire occurrence and management is one the most important drivers of ecological change on public lands in the western United States (personal communication, Neil Sugihara, Forest Service, Pacific Southwest Region, 916/640-1054). Due to the cost and logistical requirements of prescribed burns in mountainous terrain where pinyon-juniper woodlands are generally found, very small prescribed burns will not likely be cost effective. Wildland Fire Use fires are another opportunity in which fire can be used as a land management tool. Wildland Fire Use, or the management of naturally ignited fires to achieve resource benefits, may provide land management agencies the opportunity to use fire as a

management tool at relatively low costs. Land management agencies should prioritize creating fire prescriptions and completing associated planning necessary for the use of prescribed and Wildland Fire Use fires to manage sagebrush-steppe/pinyon-juniper woodlands. Mechanical treatments of mid dominance stands may also be an option for treatment of mid dominance pinyon-juniper woodlands. Land managers should also be prepared to treat high dominance woodlands after fire if conversion to a cheatgrass dominated community is expected. Finally, care should be taken during fire or mechanical treatments to avoid massive soil disturbance and cheatgrass seed introduction.

### **Research needs**

Refinements in fuels estimates in sagebrush-steppe/pinyon-juniper ecosystems and their changes with increasing tree dominance will aid in the management of wildland fire as well as the prediction of landscape level fire effects patterns. More detailed studies of the tree litter and aerial fuels contributed by the trees would complement the understory fuels data presented in this study. Also, the fuels data gathered in this study were mainly on alluvial fans which represent the high end of the fuel load spectrum existing in the Great Basin. Information on how fuel loads change with aspect, slope, elevation and soil type would allow for more accurate mapping of sagebrush-steppe/pinyon-juniper fuels at larger and more useful spatial scales.

Also, given current rates of pinyon-juniper woodland treatment, it is likely that many mid dominance stands will mature into high dominance stands before treatment. Further research on treatment of high dominance stands to prevent negative post-fire

effects would help in the management of these stands. From the results of the prescribed burn applied to the area of this study in May of 2002, it appears that fire may not be the best tool to manage large, high dominance stands in close proximity to cheatgrass dominated areas. Mechanical thinning and removal of some fuels for firewood is one treatment option that may hold promise.

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