Western North American Naturalist

Volume 70 | Number 3 Article 4

10-11-2010

Estimation procedures for understory biomass and fuel loads in sagebrush steppe invaded by woodlands

Alicia L. Reiner
USDA Forest Service, Adaptive Management Services Enterprise Team, Sparks, Nevada, alreiner@fs.fed.us

Robin J. Tausch
USDA Forest Service, Rocky Mountain Research Station, Reno, Nevada, rtausch@fs.fed.us

Roger F. Walker
University of Nevada, Reno, walker@cabnr.unr.edu

Recommended Citation

Reiner, Alicia L.; Tausch, Robin J.; and Walker, Roger F. (2010) "Estimation procedures for understory biomass and fuel loads in sagebrush steppe invaded by woodlands," *Western North American Naturalist*: Vol. 70 : No. 3 , Article 4.
Available at: https://scholarsarchive.byu.edu/wnan/vol70/iss3/4

Western North American Naturalist 70(3), © 2010, pp. 312–322

ESTIMATION PROCEDURES FOR UNDERSTORY BIOMASS AND FUEL LOADS IN SAGEBRUSH STEPPE INVADED BY WOODLANDS

Alicia L. Reiner[1], Robin J. Tausch[2], and Roger F. Walker[3]

ABSTRACT.—Regression equations were developed to predict biomass for 9 shrubs, 9 grasses, and 10 forbs that generally dominate sagebrush ecosystems in central Nevada. Independent variables included percent cover, average height, and plant volume. We explored 2 ellipsoid volumes: one with maximum plant height and 2 crown diameters and another with live crown height and 2 crown diameters. Dependent variables were total, live, leaf, and dead biomass. Simple, multiple, linear, and power equations were investigated. Models were chosen based on scatter plots, residual plots, and R^2 and SEE values. In general, simple power equations provided the best-fit regressions. For shrubs, the ellipsoid volume computed with maximum plant height best predicted total plant weight, and the ellipsoid volume computed with the live crown height best predicted shrub foliage weight. In addition to regression equations for biomass, ratios for division of that biomass into 1-, 10-, 100-, and 1000-hour fuels were derived for common large shrubs. Regression equations were also derived to relate litter mat sizes of major shrub species to litter weights. The equations in this paper could be used to predict biomass in other areas of the Great Basin if training data were taken to validate or adjust these models.

Key words: biomass prediction, allometric relationships, fuel loads, shrubs, perennial grasses, perennial forbs, pinyon-juniper woodlands.

Biomass estimates are needed to assess fuels, primary productivity, carbon content and budgets, nutrient cycling, food abundance, treatment effects, and competition within plant communities; they are also needed to assess the effects of different fire regimes on plant communities (Rittenhouse and Sneva 1977, Murray and Jacobson 1982, Tausch and Tueller 1988, Hierro et al. 2000). However, few studies have developed biomass regression equations for common species in sagebrush-steppe ecosystems. Regression analysis is the method most often used to predict the weight of both the entire plant and selected subparts from crown or basal measurements or aerial cover estimates (Telfer 1969, Ludwig et al. 1975, Brown 1976, Roussopoulos and Loomis 1979, Thomson et al. 1998). 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, Vora 1988), and many 3-dimensional shapes describing the crown volume of plants can be calculated from these measurements (Mawson et al. 1976, Murray and Jacobson 1982). Empirical studies correlating shrub crown measurements with fuel loading by size class are rare, especially for sagebrush communities (Brown 1982, Frandsen 1983). Time-lag categories are conventionally defined as the time required for dead fuels with diameter size classes of <0.62 cm (<0.25 inch), 0.62–2.54 cm (0.25–1 inch), 2.54–7.62 cm (1–3 inch), and >7.62 cm (>3 inch)—called 1-, 10-, 100-, and 1000-hour fuels, respectively—to equilibrate by 63% with ambient moisture (Pyne et al. 1996). In this study, we break live fuels into the same size categories and also refer to them as 1-, 10-, 100- and 1000-hour fuels. Although live fuels do not change in moisture content like dead fuels, subdividing live fuels into size categories can give managers a more concise picture of biomass as well as potential fuel loadings if fuels were treated by methods such as lop and scatter.

For understory fuel components of Great Basin ecosystems other than large shrubs and perennial forbs, several methods can be used to estimate biomass and fuels. In situations where plant density and small size make measuring individual plant crowns too time consuming, estimates of percent cover and average height in sample plots can be used to predict plant biomass (Alaback 1986). After regressions are

---

[1] USDA Forest Service, Adaptive Management Services Enterprise Team, 1200 Franklin Way, Sparks, NV 89430.
[2] USDA Forest Service, Rocky Mountain Research Station, 920 Valley Road, Reno, NV 89512.
[3] Department of Natural Resources and Environmental Science, University of Nevada, Reno, NV 89557.

TABLE 1. Stand characteristics differentiating the phases of woodland succession for Underdown Canyon, Nevada (adapted from Miller et al. 2008).

Characteristics	Phase I (low)	Phase II (mid)	Phase III (high)
Tree canopy	1–25% ($\bar{x}$ = 12%)	26–60% ($\bar{x}$ = 38%)	61–90% ($\bar{x}$ = 74%)
Tree biomass ($kg \cdot ha^{-1}$)	2152	6722	14,213
Shrub layer	intact	nearly intact to significant thinning	>75% dead

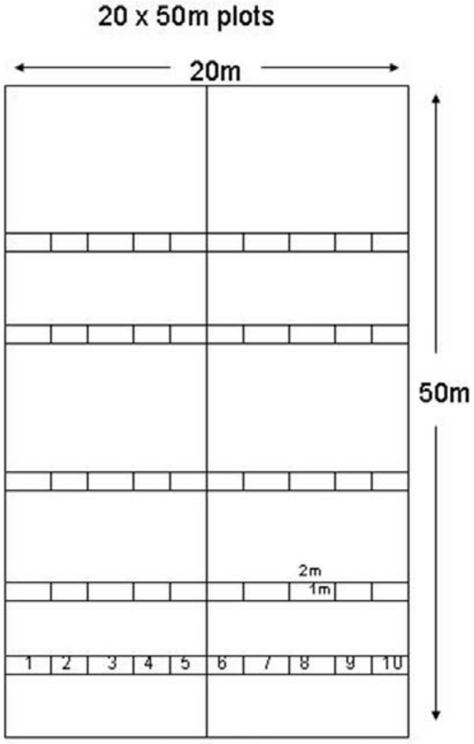

Fig. 1. Plot layout showing a macroplot containing belt transects divided into quadrats.

derived, destructive sampling can be reduced or eliminated, allowing for faster, less obtrusive field sampling. Few studies have quantified litter amounts associated with common shrubs within Great Basin ecosystems. Existing studies on sagebrush relate annual litter production, rather than actual litter mat, to shrub size and biomass (West and Gunn 1974, Mack 1977). In this study, we derived estimates of biomass contained in shrub litter mats based on litter mat area.

The purpose of this study was to develop regression equations to predict understory biomass and fuel loads by species for common shrubs, grasses, and forbs in sagebrush ecosystems. The data will inform a larger ecological research project conducted in Underdown Canyon, Shoshone Mountains, Nevada (Reiner 2004, Dhaemers 2006). We hope these regression equations can serve, with minimal adjustments, as a basis for predicting biomass of the studied species in other sagebrush-steppe/ pinyon-juniper woodlands of Nevada. These regression equations focus on predictions of live biomass for forbs and grasses and on predictions of foliage and live and dead fuels by timelag categories for larger shrubs.

METHODS

Data Collection

We gathered data for shrubs, grasses, and forbs in research plots in Underdown Canyon, Shoshone Mountain Range, central Nevada (38°10′N, 117°25′E). The plots were located in sagebrush ecosystems on side-valley alluvial fans between 2070 and 2350 m (6800 and 7700 feet) and were stratified on each fan into the low, mid, and high tree-dominance areas (Table 1) that were present. The plots in Underdown Canyon are located on land managed by both the Humboldt-Toiyabe National Forest, Austin Ranger District, and the Battle Mountain District of the Bureau of Land Management. The plots typify much of the sagebrush ecosystems of the central Great Basin that are being increasingly dominated by woodlands (Miller et al. 2008). Underdown Canyon is oriented east to west, and its geology is dominated by volcanic tuff. An intermittent stream runs down the canyon. 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. Data were gathered in the summer of 2001 and 2002.

Within the canyon, the woodlands are characterized primarily by singleleaf pinyon (*Pinus monophylla* Torr. & Frém.), Utah juniper (*Juniperus osteosperma* [Torr.] Little), and scattered hybrids of Utah and western juniper (*Juniperus occidentalis* Hook.) (Terry et al. 2000). At the lower elevations, Wyoming big sagebrush (*Artemisia tridentata* Nutt. ssp. *wyomingensis* Beetle and Young), Sandberg bluegrass (*Poa secunda* J. Presl), and bottlebrush squirreltail (*Elymus elymoides* [Raf.] Swezey) dominate the understory. At higher elevations, mountain big sagebrush (*Artemisia tridentata* Nutt. ssp. *vaseyana* [Rydb.] Beetle), Idaho fescue (*Festuca idahoensis* Elmer), and occasional little sagebrush (*Artemisia arbuscula* Nutt.) occupy the site. Vegetation occurs in patches of variable tree dominance classified as low, mid, and high tree dominance (Table 1) or Phase I, Phase II, and Phase III (Miller and Tausch 2001, Miller et al. 2008).

Biomass equations presented in this paper were developed in support of a larger study which involved understory sampling in forty 50 × 20-m macroplots stratified across low, mid, and high tree-dominance areas as well as 3 elevations: 2070–2100 m (6800–6900 ft); 2200–2230 m (7200–7300 ft); and 2350 m (7700 ft) (Dhaemers 2006). Understory vegetation in each macroplot was sampled in fifty 1 × 2-m quadrats located contiguously along 5 belt transects positioned perpendicular to the long axis of the plot (Fig. 1). Belt transects were located in a stratified, random manner along the length of the plot and spanned the width of the plot. Data gathered within these plots will be used to calculate plant weight per unit area using the regressions presented here.

We used 2 methods to measure understory plant species in the quadrats. All shrubs rooted in the quadrats were measured by species using the following metrics: longest crown diameter, crown diameter perpendicular to the longest, maximum plant height, crown height of live foliage, and basal diameter (stem diameter 4 cm above the top of the litter layer). Percent of dead material comprising the crown of each shrub was also estimated. Perennial forbs were measured by species for 2 crown diameters and the maximum height, and perennial grasses were measured by species for 2 basal diameters and the maximum height. To facilitate the measuring process, when herbaceous plants were small and abundant, grasses and forbs were sampled by species in each quadrat by estimating the percent cover of their basal areas plus a measurement of average height throughout the quadrat.

For each transect, we collected one biomass sample of each species that was found in the transect. For each shrub measured as well as for each grass or forb where crown dimensions were measured, an individual of that species was randomly located off the end of the transect outside the macroplot, measured, and then clipped to ground level. Biomass for the species was obtained by randomly selecting then clipping one subsampling quadrat on each transect. The shrubs were separated into live and dead categories of foliage, 1-, 10-, 100-, and 1000-hour fuels, and total biomass. 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.

We sampled shrub litter mats in the summer of 2003 under 18 yellow 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 shrubs growing outside of tree footprints to avoid sampling tree litter mats. A square 10 × 10-cm 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 O_i and O_e 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. We floated litter samples to remove rocks then dried and weighed the samples.

Regression Analysis

We used several types of exploratory data analysis to choose the most appropriate regression models. We examined scatter plots, residual plots, and R^2 statistics and performed some cross-validation exercises. We explored simple and multiple regressions with various independent variables in linear and curvilinear forms, because both are often used in biomass estimation (Rittenhouse and Sneva 1977, Murray and Jacobson 1982, Draper and Smith 1998, Hierro et al. 2000). When scatter plots of independent variables versus dependent variables suggested a curvilinear relationship, we examined the power equation; otherwise, we generally used the linear equation. We examined residual plots of Y versus DY and X versus DY as additional support for 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 used to check for outliers. We also created scatter plots of data by species, wherein data were grouped by elevation. These scatter plots showed minor elevation trends for a few species but were not defined enough to make elevation an independent variable or factor by which to separate regressions.

We formed models from one or several potential independent variables. Many different volume shapes have been investigated to describe the shape of shrubs (Mawson et al. 1976, Murray and Jacobson 1982). We found that the ellipsoid volume calculated from crown measurements approximated shrub shape well. We calculated 2 types of ellipsoid volumes for shrubs. The first volume, VOL1, was calculated from the 2 crown diameters and the live foliage height and generally predicted foliage weight best. The second volume, VOL2, was calculated from the 2 crown diameters and the maximum shrub height and tended to predict total shrub weight best. Dependent variables were total weight, live weight, and foliage weight. A multiple regression model was created to estimate the weight of the fuel components for 100% dead-standing shrubs based on maximum height and basal diameter for which total dead weight was the dependent variable. The ellipsoid volume was also created for large and perennial forbs and grasses from height and diameter measurements. For small and abundant grasses and forbs measured with the percent cover and average height method, we calculated simple and multiple regressions using percent cover and height as independent variables.

Ellipsoid linear regression model:

$$w = \mathrm{a} + \mathrm{b}v,$$

where v = ellipsoid, w = total plant weight, and a, b = constants.

Ellipsoid power regression model:

$$w = \mathrm{a}(v^{\mathrm{b}}) \text{ or } \ln(w) = \ln(\mathrm{a}) + \mathrm{b}\ln(v),$$

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

Ellipsoid volume 1:

$$\mathrm{VOL1} = (3.14159/6) * H * C_1 * C_2$$

and **ellipsoid volume 2:**

$$\mathrm{VOL2} = (3.14159/6) * F * C_1 * C_2,$$

where H = maximum plant height, F = foliage height, C_1 = longest crown diameter, C_2 = crown diameter perpendicular to the longest.

Area/height multiple linear regression model:

$$w = \mathrm{a} + \mathrm{b}(A) + \mathrm{c}(H),$$

where a, b, c = constants, A = area, and H = height.

Area/height multiple power regression model:

$$w = \mathrm{a}(A^{\mathrm{b}})*(H^{\mathrm{c}}) \text{ or } \ln(w) = \ln(\mathrm{a}) + \mathrm{b}\ln(A) + \mathrm{c}\ln(H),$$

where A, H, a, b, and c are defined as above.

Size–weight regression models were created with linear and nonlinear regression analyses using a custom program which employs an iterative procedure (Tausch and Tueller 1988). To eliminate the potential for bias, data were not log transformed (Baskerville 1971). Scatter plots and residual plots were graphed in NCSS and Excel (NCSS 2001, Microsoft Corporation 2002). Regression equations were developed for each species where sample size was sufficient. All regression equations predict weight in grams from variables in cm, cm^2, or cm^3.

Determinations of Shrub Fuel-Size Distribution

In order to predict the amounts of shrub fuel by size classes in the individual plants, we found it necessary to develop percentage multipliers derived from actual fuel-size distributions of the sampled shrub species. First, regression equations were used to predict foliage biomass, live biomass, and total biomass for the 3 largest shrub species: Wyoming big sagebrush, mountain big sagebrush, and yellow rabbitbrush. Then, data sets for the 3 shrub species mentioned above were combined, and fuel-size categories (1-, 10-, 100-, and 1000-hour live and dead) were estimated as percentages of total live or dead weight. Smaller shrubs that lacked the larger-diameter fuels made up a large portion of the population and, therefore, of the plants sampled. As a result, shrub sample sizes were sometimes too small for estimating the larger-diameter fuels, such as 100- and 1000-hour classes.

In the field, the amount of dead material varied considerably in each live shrub, and this variation appeared to be related to the level of tree competition. In areas of higher tree dominance, shrubs with large amounts of dead material were more frequent. To account for this variation, we divided samples of abundant shrub species into categories based on the field estimates of percent dead. We calculated percentages of field-sampled live and dead fuel by the fuel-size classes. Sampled plants grouped by the field-estimated percent dead were then compared with the actual percent-dead categories measured for the same plants and for the distributions of fuels by size category. Percent-dead category divisions were adjusted until the live-to-dead ratio and the distribution of fuel sizes for the field-estimated percent-dead category values best matched the actual measured percentages.

TABLE 2. Average proportions of live and dead fuels by time-lag class for *Artemisia tridentata wyomingensis, Artemisia tridentata vaseyana,* and *Chrysothamnus viscidiflorus,* combined, by field-estimated percent-dead category.

	Time-lag class			
Field-estimated percent dead	1 hour	10 hour	100 hour	1000 hour
Live fuels				
0	0.270	0.122	0.430	0
1–15	0.155	0.147	0.595	0.021
16–50	0.158	0.280	0.467	0
51–100	0.156	0.234	0.536	0
Dead fuels				
0	0	0	0	—
1–15	0.54	0.461	0	—
16–50	0.559	0.328	0.113	—
51–100	0.405	0.387	0.209	—

RESULTS

Grass and Forb Equations

We utilized regression equations based on the ellipsoid volume for 10 species of bunch grasses and large forbs with life forms where the required crown dimension measurements were possible (Appendix 1). The most effective equations for biomass predictions varied by species. For a few of the forb species, the linear form was most effective in predicting plant weight ($R^2 = 0.61$ to $R^2 = 0.99$). For the remaining forbs and the 2 grass species, the power regression predicted biomass most effectively ($R^2 = 0.41$ to $R^2 = 0.81$).

We formulated simple and multiple regression equations for the smaller grasses and forbs measured in the field using their percent cover and average height (Appendix 2). Percent cover converted to an area (cm^2) generally predicted biomass better than average height. We did not add average height to the regression equation if R^2 and scatter and diagnostic plots did not support its inclusion. For 4 live forbs and 3 grasses, a multiple power regression using both area and average height worked best ($R^2 = 0.33$ to $R^2 = 0.99$). Tall woolly buckwheat (*Eriogonum elatum*) 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 Great Basin wildrye (*Leymus cinereus*) and Sandberg bluegrass were linear regressions with area only ($R^2 = 0.34$ to $R^2 = 0.49$). The Sandberg 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. Small size, irregular shape, and scattered distributions were challenges to cover estimation, and thus to fitting a cover/weight regression equation to this species.

Determinations of Shrub Fuel-Size Distribution

For the 3 most abundant shrub species (Wyoming big sagebrush, mountain big sagebrush, and yellow rabbitbrush), 3–4 categories based on percent dead were found to provide the best results. The percent-dead categories found to best predict Wyoming big sagebrush biomass and fuel-size class distributions were 0, 1–15, 16–50, and 51–100 (Table 2). Categories for mountain big sagebrush were 0–15, 16–50, and 51–100. The distributions of the big sagebrush species were similar, as both had a majority of the plants in the 16–50-percent-dead category. For rabbitbrush the categories were 0, 1–50, and 51–100, reflecting how rabbitbrush generally has a higher ratio of live-to-dead material. The rabbitbrush differed from sagebrush in that over one-half of the plants were in the lowest percent-dead category, having no discernible dead material.

Amounts of dead fuels by time-lag category for each plant are 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 is repeated for live fuels using the live fuel-multipliers. Less abundant shrubs species for which few samples were gathered were not separated into percent-dead categories for fuel estimation.

Table 3. Regression equations used to predict various subsets of *Chrysothamnus vicsidiflorus* weight (y) in grams for various percent-dead categories. Variables are as defined in Appendix 3.

Percent dead	y	A	b	x_1	Equation	n	SEE (% of mean)	R^2
0	L	1.81×10^{-2}	7.19×10^{-1}	VOL2	$y = a(x^b)$	104	95.8	0.56
0	F	1.35×10^{-2}	6.38×10^{-1}	VOL2	$y = a(x^b)$	103	109.3	0.46
1–50	T	3.18×10^{-2}	6.74×10^{-1}	VOL2	$y = a(x^b)$	64	54.5	0.72
1–50	L	4.54×10^{-2}	5.94×10^{-1}	VOL2	$y = a(x^b)$	64	60.1	0.63
1–50	F	2.66×10^{-2}	5.18×10^{-1}	VOL2	$y = a(x^b)$	64	87.1	0.38
51–99	T	4.05×10^{-6}	1.54×10^{0}	VOL2	$y = a(x^b)$	37	52.3	0.93
51–99	L	1.55×10^{-5}	1.33×10^{0}	VOL2	$y = a(x^b)$	37	52.8	0.92
51–99	F	1.18×10^{-3}	8.18×10^{-1}	VOL2	$y = a(x^b)$	37	86.8	0.65
100	D	5.32×10^{-2}	1.69×10^{0}	HT	$y = a(x^b)$	37	89.9	0.26

Shrub Regression Analyses

We developed separate regression models to predict total weight, live weight, and foliage weight for each percent-dead category for each of 3 more abundant shrub species: Wyoming big sagebrush, mountain big sagebrush (Appendixes 3, 4), and yellow rabbitbrush (Table 3). The simple power equation best fit the data in all but 2 cases. These exceptions, both standing-dead sagebrush cases, were best predicted with multiple power equations using height and basal diameter as independent variables. The ellipsoid volume based on maximum shrub height (VOL2) 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% dead plants were quite low (0.26–0.60), dead-standing shrubs make up a very small portion of fuel loads, and use of these equations to predict biomass should not drastically affect total landscape fuel loads. Results are divided into fuel-load categories using the total biomass estimate and the information in Table 2.

Sample sizes were small for the 5 less abundant species of shrubs and semishrubs: low sagebrush, mormon tea (*Ephedra viridis* Cov), slenderbush buckwheat (*Eriogonum microthecum* Nutt.), prickly phlox (*Leptodactylon pungens* [Torr.] Nutt.), and mountain snowberry (*Symphoricarpos oreophilus* A. Gray). Consequently, we did not divide the data sets into percent-dead categories to create regression equations to predict percentages of fuels (Appendix 5). When available, data from 2002 were added to data from 2001 for all of these species. Due to lack of distinct leaves or small sample sizes, we did not create separate regression equations for foliage weight for mormon tea or the semishrubs. The power equation and VOL2 yielded the best models for these shrubs. When it was found in abundance, we measured slenderbush eriogonum using the percent-cover method and used a multiple regression equation of percent cover and average height. Percentages of fuels by time-lag class for the less abundant shrubs and semishrubs were derived the same as for the more abundant shrubs, using the ratios in Appendix 6.

Shrub Litter Analysis

The amounts of litter under sagebrush did not differ among species, so the data sets for mountain big sagebrush and Wyoming big sagebrush were combined for analysis. However, the amounts of litter were higher at the upper elevations, so we created separate sagebrush regression equations for litter collected above and below 2290 m (7500 ft) elevation. The larger sagebrush litter loads at upper elevations appear to reflect the greater productivity found at these sites as a result of higher water availability. For both sagebrush and rabbitbrush, the litter mat area averaged 79% of the crown area. Litter equations were based on the area of the litter mat under the sagebrush. Regression equation fit for sagebrush had R^2 values of 0.74 and 0.75 for above and below 2290 m elevation, respectively (Appendix 7). There was too much variation in the 16-sample rabbitbrush data set to create a useful regression. The median density of 0.016 g · cm^{-2} was used to estimate rabbitbrush litter biomass based on the area of each litter mat.

DISCUSSION

Results of this research are comparable to previous related efforts. Rittenhouse and Sneva (1977) found the height and crown diameters of Wyoming big sagebrush to be well correlated to both the weight of leaf and of woody shrub material. R^2 values for Wyoming big sagebrush from this study are comparable to those found by Rittenhouse and Sneva (1977), considering that regression equations in this study were formulated specifically for each of several percent-dead categories. Although our methods differed widely from Frandsen (1983), a comparison of results is interesting. We found most live woody shrub weight to fall within the 100-hour time-lag category and most dead woody shrub weight to fall in the 1-hour category. However, Frandsen found most woody shrub mass (live and dead combined) to fall in the 10-hour time-lag category for shrubs comparable in size to shrubs in our study (height 0.4–0.6 m).

Although the crown-dimension measurement method was too time consuming a technique to use in areas with a high density of small perennial plants or annual species, it produced data sets with less variation than the percent cover method. For example, Idaho fescue was measured using both methods. The 20 plants measured with the crown measurement method produced a regression R^2 of 0.75; whereas the 107 plots 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 small and sparsely distributed plants.

The effect of increasing tree dominance on the shrub species had a significant impact on shrub biomass prediction. When a measure of the amount of dieback, or relative proportion of dead material, in the shrub was determined, the precision of the predictions improved.

Many of the less abundant species of grasses and forbs 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. These equations are specific to predicting the biomass for the rarer species in the larger Underdown Canyon study and are therefore not discussed in this paper. They are available in Reiner (2004).

In choosing models to describe plant size–weight regressions, we found several tools useful. Graphical analyses such as scatter plots and residual plots are useful in determining potential models and model fit. R^2 is a useful measure when used in conjunction with other plots and statistics. Cross-validation and bootstrapping procedures using iterative programming could also be used to evaluate model predictive capabilities. When an exceedingly large data set is not available, the PRESS statistic (Green 1983) might be a useful tool to diagnose the predictive capabilities of various models. Tree regressions might be interesting to apply to various measurements and environmental variables—such as elevation, tree dominance, aspect, and climate—to determine the most influential factors for multiple regressions (Brieman et. al. 1984).

Care should be taken in applying these regression equations to other geographic areas. We created these regressions from plants in one canyon; thus the data set may not be representative of these species in other areas. Also, these models were constructed from data obtained in 2001 and 2002, which were years with nearly average precipitation. Plants respond physiologically to climatic variables (Rittenhouse and Sneva 1977), and so the applicability of these regressions to plants in climatic regimes that vary across space could be questionable.

LITERATURE CITED

ALABACK, P.B. 1986. Biomass regression equations for understory plants in coastal Alaska: effects of species and sampling design on estimates. Northwest Science 60:90–103.

BASKERVILLE, G.L. 1971. Use of logarithmic regression in the estimation of plant biomass. Canadian Journal of Forestry 2:49–53.

BRIEMAN, L., J.H. FRIEDMAN, R.A. OLSHEN, AND C.J. STONE. 1984. Classification and regression trees. Chapman and Hall/CRC, Washington, DC.

BROWN, J.K. 1976. Estimating shrub biomass from basal stem diameters. Canadian Journal of Forest Research 6:153–158.

______. 1982. Fuel and fire behavior prediction in big sagebrush. Research Paper INT-290, USDA Forest Service, Ogden, UT.

Dhaemers, J.M. 2006. Vegetation recovery following spring prescribed fire in pinyon-juniper woodlands of central Nevada: effects of elevation and tree cover. Master's thesis, University of Nevada, Reno, NV.

Draper, N.R., and H. Smith. 1998. Applied regression analysis. 3rd edition. John Wiley & Sons, Inc., New York, NY.

Frandsen, W.H. 1983. Modeling big sagebrush as a fuel. Journal of Range Management 36:596–600.

Green, E.J. 1983. Evaluating the predictive capabilities of regressions with PRESS. Forest Science 29:712–714.

Harniss, R.O., and R.B. Murray. 1976. Reducing bias in dry leaf weight estimates of big sagebrush. Journal of Range Management 29:430–432.

Hierro, J.L., L.C. Branch, D. Villarreal, and K.L. Clark. 2000. Predictive equations for biomass and fuel characteristics of Argentine shrubs. Journal of Range Management 53:617–621.

Ludwig, J.A., J.F. Reynolds, and P.D. Whitson. 1975. Size-biomass relationships of several Chihuahuan desert shrubs. American Midland Naturalist 94:451–461.

Mack, R.N. 1977. Mineral return via the litter of *Artemisia tridentata.* American Midland Naturalist 97:189–197.

Mawson, J.C., J.W. Ward, and R.M. DeGraaf. 1976. Program HTVOL: the determination of tree crown volume by layers. Research Paper NE 354, USDA Forest Service, Upper Darby, PA.

Microsoft Corporation. 2002. Microsoft Excel [software]. Redmond, WA. Available from: http://www.microsoft.com

Miller, R.F., and R.J. Tausch. 2001. The role of fire in pinyon and juniper woodlands: a descriptive analysis. Pages 15–30 *in* K.E.M. Gassir and T.P. Wilson, editors, Invasive species: the role of fire in the control and spread of invasive species symposium. Miscellaneous Publication No. 11, Tall Timbers Research Station, Tallahassee, FL.

Miller, R.F., R.J. Tausch, D.E. McArthur, D.D. Johnson, and S.C. Sanderson. 2008. Age structure and expansion of pinyon-juniper woodlands: a regional perspective in the Intermountain West. Research Paper RMRS-RP-69, USDA Forest Service, Rocky Mountain Research Station, Fort Collins, CO. 15 pp.

Murray, R.B., and M.Q. Jacobson. 1982. An evaluation of dimension analysis for predicting shrub biomass. Journal of Range Management 35:451–454.

NCSS. 2001. NCSS statistical software. 329 North 1000 East, Kaysville, UT 84037.

Pyne, S.J., P.L. Andrews, and R.D. Laven. 1996. Introduction to wildland fire. 2nd edition. John Wiley & Sons, Inc., New York, NY.

Reiner, A.L. 2004. Fuel load and understory community changes associated with varying elevation and pinyon-juniper dominance. Master's thesis, University of Nevada, Reno, NV.

Rittenhouse, L.R., and F.A. Sneva. 1977. A technique for estimating big sagebrush production. Journal of Range Management 30:68–70.

Roussopoulos, P.J., and R.M. Loomis. 1979. Weights and dimensional properties of shrubs and small trees of the Great Lakes conifer forest. Research Paper 178, North Central Experiment Station, USDA Forest Service.

Tausch, R.J., and P.T. Tueller. 1988. Comparison of regression methods for predicting single-leaf pinyon phytomass. Great Basin Naturalist 48:39–45.

Telfer, E.S. 1969. Weight–diameter relationships for 22 woody species. Canadian Journal of Botany 47:1851–1855.

Terry, R.G., R.S. Nowak, and R.J. Tausch. 2000. Genetic variation in chloroplast and nuclear ribosomal DNA in Utah juniper (*Juniperus osteosperma,* Cupressaceae): evidence for interspecific gene flow. American Journal of Botany 87:250–258.

Thomson, E.F., S.N. Mirza, and J. Afzal. 1998. Predicting the components of aerial biomass of fourwing saltbush from shrub height and volume. Journal of Range Management 51:323–325.

Uresk, D.W., R.O. Gilbert, and W.H. Rickard. 1977. Sampling big sagebrush for phytomass. Journal of Range Management 30:311–314.

Vora, R.S. 1988. Predicting biomass of five shrub species in northeastern California. Journal of Rangeland Management 41:63–65.

West, N.E., and C. Gunn. 1974. Phenology, productivity and nutrient dynamics of some cool desert shrubs. US/IBP Desert Biome Research Memo 47-7.

Received 28 May 2009
Accepted 18 February 2010

Appendix 1. Regression equations used to predict total plant weight (y) in grams for grasses and forbs from the ellipsoid volume (x) in cm^3 calculated from crown dimensions.

Percent	a	b	Equation	n	SEE (% of mean)	R^2
Antennaria rosea	7.45×10^{-2}	4.76×10^{-1}	$y = a(x^b)$	24	50.1	0.64
Arabis holboellii	1.94×10^{-2}	4.95×10^{-3}	$y = a + bx$	25	82.8	0.61
Astragalus purshii	-1.08×10^{-1}	3.68×10^{-2}	$y = a + bx$	11	41.4	0.80
Cryptantha flavoculata	1.41×10^{-2}	8.28×10^{-1}	$y = a(x^b)$	55	74.5	0.34
Eriogonum elatum	1.40×10^{-1}	3.61×10^{-1}	$y = a(x^b)$	11	58.3	0.41
Eriogonum umbellatum	1.63×10^{0}	1.13×10^{-3}	$y = a + bx$	35	58.7	0.70
Lupinus caudatus	1.41×10^{-3}	9.80×10^{-1}	$y = a(x^b)$	85	70.1	0.81
Lygodesmia spinosa	2.03×10^{-1}	5.06×10^{-4}	$y = a + bx$	19	22.8	0.99
Achnatherum thurberianum and *Stipa comata*	2.13×10^{-1}	2.66×10^{-1}	$y = a(x^b)$	16	35.9	0.62
Festuca idahoensis	3.08×10^{-2}	7.20×10^{-1}	$y = a(x^b)$	20	44.4	0.75

APPENDIX 2. Regression equations used to predict total plant weight (g) for grasses and forbs using percent cover and average height (cm). A = estimated aerial coverage (cm^2); HT = average height (cm) of aerial percent cover estimated samples.

Species	a	b_1	x_1	b_2	x_2	Equation	SEE (% of mean)	n	R^2
Arenaria aculeata	1.85×10^{-1}	7.14×10^{-1}	A	4.27×10^{-1}	HT	$y = a((x_1^{b1})(x_2^{b2}))$	75.7	44	0.47
Eriogonum elatum	-9.23×10^{-2}	1.51×10^{-2}	A	2.66×10^{-1}	HT	$y = a + (b_1 x_1) + (b_2 x_2)$	97.8	38	0.62
Lupinus caudatus	1.52×10^{-1}	6.60×10^{-1}	A	3.24×10^{-1}	HT	$y = a((x_1^{b1})(x_2^{b2}))$	97.8	163	0.61
Phlox hoodii	6.44×10^{-2}	7.75×10^{-1}	A	6.26×10^{-1}	HT	$y = a((x_1^{b1})(x_2^{b2}))$	62.0	75	0.75
Crepis accuminata	9.68×10^{-2}	5.95×10^{-1}	A	1.37×10^{-1}	HT	$y = a((x_1^{b1})(x_2^{b2}))$	55.9	17	0.71
Carex vallicola	4.76×10^{-3}	1.39×10^{0}	A			$y = a(x^b)$	22.3	7	0.95
Achnatherum thurberianum and *Stipa comata*	2.24×10^{-2}	9.44×10^{-1}	A	3.19×10^{-1}	HT	$y = a((x_1^{b1})(x_2^{b2}))$	47.2	35	0.81
Elymus elymoides	3.42×10^{-2}	9.65×10^{-1}	A			$y = a(x^b)$	106.9	128	0.50
Festuca idahoensis	5.47×10^{-1}	5.78×10^{-1}	A			$y = a(x^b)$	61.3	107	0.66
Koleria machrantha	2.78×10^{-1}	5.86×10^{-1}	A			$y = a(x^b)$	50.4	37	0.51
Leymus cinerus	2.87×10^{0}	3.45×10^{-3}	A			$y = a + bx$	65.3	16	0.34
Poa fendleriana	5.51×10^{-1}	1.20×10^{-2}	A			$y = a + bx$	54.9	21	0.49
Poa secunda	1.34×10^{-1}	2.64×10^{-1}	A	4.26×10^{-1}	HT	$y = a((x_1^{b1})(x_2^{b2}))$	76.5	185	0.33
Bromus tectorum	8.88×10^{-3}	4.54×10^{-1}	A	1.32	HT	$y = a((x_1^{b1})(x_2^{b2}))$	20.6	14	0.99

APPENDIX 3. Regression equations used to predict various subsets of *Artemisia tridentata vaseyana* weight (y) in grams for various percent-dead categories. D = dead weight (g), F = foliage weight (g), L = live weight (g), T = total weight (g), BD = basal diameter (cm), HT = maximum height (cm), VOL1 = ellipsoid volume (cm^3) calculated from foliage height, VOL2 = ellipsoid volume (cm^3) calculated from maximum height.

Percent dead	y	a	b_1	x_1	b_2	x_2	Equation	n	SEE (% of mean)	R^2
0–15	T	1.26×10^{-2}	8.50×10^{-1}	VOL2			$y = a(x^b)$	53	58.5	0.83
0–15	L	1.36×10^{-2}	8.35×10^{-1}	VOL2			$y = a(x^b)$	53	60.1	0.81
0–15	F	4.46×10^{-2}	5.89×10^{-1}	VOL1			$y = a(x^b)$	52	86.7	0.59
16–50	T	1.48×10^{-1}	6.58×10^{-1}	VOL2			$y = a(x^b)$	111	49.3	0.72
16–50	L	2.36×10^{-1}	5.90×10^{-1}	VOL2			$y = a(x^b)$	111	48.6	0.70
16–50	F	4.29×10^{-2}	5.73×10^{-1}	VOL1			$y = a(x^b)$	110	59.6	0.62
51–99	T	1.73×10^{0}	4.56×10^{-1}	VOL2			$y = a(x^b)$	18	70.0	0.64
51–99	L	1.64×10^{0}	3.62×10^{-1}	VOL2			$y = a(x^b)$	17	55.6	0.64
51–99	F	1.99×10^{-1}	4.00×10^{-1}	VOL1			$y = a(x^b)$	17	139.8	0.31
100	D	7.11×10^{-1}	7.01×10^{-1}	HT	1.20	BD	$y = a((x_1^{b1})(x_2^{b2}))$	117	88.1	0.60

APPENDIX 4. Regression equations used to predict various subsets of *Artemisia tridentata wyomingensis* weight (y) in grams for various percent dead categories. Variables are as defined in Appendix 3.

Percent dead	y	a	b_1	x_1	b_2	x_2	Equation	n	SEE (% of mean)	R^2
0–15	T	3.57×10^{-2}	8.10×10^{-1}	VOL2			$y = a(x^b)$	29	66.9	0.84
0–15	L	2.15×10^{-2}	8.51×10^{-1}	VOL2			$y = a(x^b)$	29	63.7	0.87
0–15	F	3.95×10^{-2}	5.84×10^{-1}	VOL1			$y = a(x^b)$	29	44.0	0.87
16–50	T	3.39×10^{-4}	1.18×10^{0}	VOL2			$y = a(x^b)$	50	43.2	0.94
16–50	L	4.56×10^{-5}	1.31×10^{0}	VOL2			$y = a(x^b)$	50	47.0	0.94
16–50	F	5.87×10^{-4}	9.54×10^{-1}	VOL1			$y = a(x^b)$	50	68.1	0.78
51–99	T	4.33×10^{-1}	5.82×10^{-1}	VOL2			$y = a(x^b)$	13	42.4	0.72
51–99	L	1.38×10^{-1}	5.95×10^{-1}	VOL2			$y = a(x^b)$	13	42.6	0.73
51–99	F	1.33×10^{-1}	4.61×10^{-1}	VOL1			$y = a(x^b)$	13	90.5	0.35
100	D	6.20×10^{-1}	1.66×10^{0}	HT	-3.66×10^{-1}	BD	$y = a((x_1{}^{b1})(x_2{}^{b2}))$	18	80.4	0.44

APPENDIX 5. Regression equations used to predict various subsets of plant weight (y) in grams for various percent-dead categories for less abundant species of shrubs and semi-shrubs in Underdown Canyon, Nevada. A = estimated aerial coverage (cm^2); HT = average height (cm) of aerial percent cover estimated samples; (S) = These regressions were performed in Statistix and no SEE (% of the mean) is available. Other variables and methods are as defined in Appendix 3.

Species	y	A	b_1	x_1	b_2	x_2	Equation	n	SEE (% of mean)	R^2
Artemisia arbuscula	T	7.16×10^{-8}	2.02×10^{0}	VOL2			$y = a(x^b)$	19	33.5	0.96
Artemisia arbuscula	L	4.25×10^{-7}	1.80×10^{0}	VOL2			$y = a(x^b)$	19	14.93	0.94
Artemisia arbuscula	F	6.62×10^{-3}	6.78×10^{-1}	VOL1			$y = a(x^b))$	19	62.5	0.56
Ephedra viridis	T		1.26×10^{-3}	VOL2			$y = a^*x$	14	(S)	0.90
Ephedra viridis	L		1.13×10^{-3}	VOL2			$y = a^*x$	14	(S)	0.90
Eriogonum microthecum	T	8.53×10^{-2}	4.69×10^{-1}	VOL2			$y = a(x^b)$	19	37.5	0.77
Eriogonum microthecum	L	7.50×10^{-2}	8.79×10^{-1}	A	2.15×10^{-1}	HT	$y = a((x_1{}^{b1})(x_2{}^{b2}))$	26	47.7	0.71
Leptodactylon pungens	T	1.15×10^{-1}	4.90×10^{-1}	VOL2			$y = a(x^b)$	22	52.5	0.59
Leptodactylon pungens	L	2.33×10^{-1}	3.75×10^{-1}	VOL2			$y = a(x^b)$	22	69.7	0.34
Symphoricarpos oreophilus	T	5.52×10^{-3}	7.99×10^{-1}	VOL2			$y = a(x^b)$	52	57.3	0.84
Symphoricarpos oreophilus	L	6.21×10^{-3}	7.66×10^{-1}	VOL2			$y = a(x^b)$	52	54.9	0.84
Symphoricarpos oreophilus	F	3.92×10^{-3}	6.67×10^{-1}	VOL2			$y = a(x^b)$	52	76.1	0.73

APPENDIX 6. Average percentages of live and dead fuels by time-lag class for less abundant shrub species by field-estimated percent-dead category. The letter *r* denotes that foliage biomass was predicted from a regression equation. See Appendix 5 for foliage regressions.

		Live			Dead	
Species	Foliage	1 hour	10 hour	100 hour	1 hour	10 hour
Artemisia arbuscula	r	0.185	0.325	0.396	0.499	0.551
Ephedra viridis	0.215	0.394	0.283	0.109	0.634	0.366
Eriogonum microthecum, crown measured	0.212	0.719	0	0	0.069	0
Eriogonum microthecum, percent cover	0.248	0.752	0	0	0	0
Leptodactylon pungens	0.376	0.549	0.074	0	1	0
Symphoricarpos oreophilus, 1–15% dead	r	0.693	0.21	0	1	0
Symphoricarpos oreophilus, 16–99% dead	r	0.678	0.16	0.019	0.94	0.06

APPENDIX 7. Equations used to predict sagebrush litter weight (g) by elevation in Underdown Canyon, Nevada.

Elevation	y	a	b	x	Equation	n	SEE (% of mean)	R^2
>2290 m	litter weight	3.60×10^{-2}	1.06×10^{0}	litter area	$y = a(x^b)$	27	67.0	0.74
<2290 m	litter weight	1.87×10^{-1}	9.51×10^{-1}	litter area	$y = a(x^b)$	9	49.0	0.75