Prediction of available forage production of big sagebrush
by William Henry Creamer IV

A thesis submitted in partial fulfillment of the requirements for the degree of Master of Science in Range Science
Montana State University

Abstract:
The objective of this study was to develop a simple, reliable method to estimate the contribution of sagebrush taxa to range production. Regression equations were developed for mountain big sagebrush (Artemisia tridentata vaseyana), Wyoming big sagebrush (A. t. wyomingensis), and basin big sagebrush (A. t. tridentata) in high and low use form classes. Linear measurements including major and minor axis, height, and crown depth, along with average cover, and combinations of these measurements were used to predict total annual winter forage production. Colinearities among some variables required the development of 3 groups of variables (based on major or minor axis or elliptical area) to be used in the model building. A natural logarithm transformation of the dependent variable, forage, was necessary to stabilize nonconstant variance. Reliability of the relationships was based on the adjusted R2 statistic. Adjusted R2 values were similar for each subspecies and form class combination among variable groups. The variable group based on the measure of the maximum diameter (major axis) was selected as the most efficient variable group based on ease of measurement of the variables and high adjusted R2 values. Adjusted R2 values ranged from 0.78 to 0.90 for 3 to 4 variable models in this variable group. When the variable average seedhead weight was added to this variable group, adjusted R2 values improved. Values ranged from 0.87 to 0.93 for 4 to 5 variable models. Two variable models accounted for nearly as much variation in each case. The variables major axis and average cover were often the most meaningful. Major axis alone accounted for > 69% of the variation in low use taxa but < 59% in high use taxa. Average cover alone accounted for > 61% of the variation in all taxa form class combinations investigated and in the case of high use basin big sagebrush it accounted for 81% of the variation in production.

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APPROVAL

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William Henry Creamer IV

This thesis has been read by each member of the thesis committee and has been found to be satisfactory regarding content, English usage, format, citations, bibliographic style, and consistency, and is ready for submission to the College of Graduate Studies.

1 March 1991
Date

Carl L. Wambolt
Chairperson, Graduate Committee

Approved for the Major Department

3/1/91
Date

L. C.
Head, Major Department

Approved for the College of Graduate Studies

March 8, 1991
Date

Henry L Parsons
Graduate Dean

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To my wife, Patty, for her steadfast support.

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ABSTRACT

The objective of this study was to develop a simple, reliable method to estimate the contribution of sagebrush taxa to range production. Regression equations were developed for mountain big sagebrush (*Artemisia tridentata vaseyana*), Wyoming big sagebrush (*A. t. wyomingensis*), and basin big sagebrush (*A. t. tridentata*) in high and low use form classes. Linear measurements including major and minor axis, height, and crown depth, along with average cover, and combinations of these measurements were used to predict total annual winter forage production.Colinearities among some variables required the development of 3 groups of variables (based on major or minor axis or elliptical area) to be used in the model building. A natural logarithm transformation of the dependent variable, forage, was necessary to stabilize nonconstant variance. Reliability of the relationships was based on the adjusted R^2 statistic. Adjusted R^2 values were similar for each subspecies and form class combination among variable groups. The variable group based on the measure of the maximum diameter (major axis) was selected as the most efficient variable group based on ease of measurement of the variables and high adjusted R^2 values. Adjusted R^2 values ranged from 0.78 to 0.90 for 3 to 4 variable models in this variable group. When the variable average seedhead weight was added to this variable group, adjusted R^2 values improved. Values ranged from 0.87 to 0.93 for 4 to 5 variable models. Two variable models accounted for nearly as much variation in each case. The variables major axis and average cover were often the most meaningful. Major axis alone accounted for > 69% of the variation in low use taxa but < 59% in high use taxa. Average cover alone accounted for > 61% of the variation in all taxa form class combinations investigated and in the case of high use basin big sagebrush it accounted for 81% of the variation in production.

INTRODUCTION

Big sagebrush (*Artemisia tridentata* Nutt.) is the most widespread and abundant shrub on rangelands of the western United States (McArthur et al. 1979). Sagebrush dominated vegetation comprises over 58 million hectares in the 11 western states (Beetle 1960). It occurs from southern British Columbia, Alberta and Saskatchewan to central New Mexico, northern Arizona and northern Baja, Mexico. Its western limit is the mountain chain formed by the Cascade, Sierra, and southern California coastal ranges, and the northern Baja mountains. Its eastern limit is the Rocky Mountains in the southern half of its range and the western Dakotas in the northern portion (Harvey 1981).

Big sagebrush provides cover and forage for a variety of rangeland wildlife species. Elk (*Cervus elaphus nelsoni*) and mule deer (*Odocoileus hemionus*) browse sagebrush heavily during the fall and winter (McNeal 1984). The distribution of pronghorn antelope (*Antilocarpa americana*) and sage grouse (*Centrocercus urophasianus*) are closely associated with the distribution of big sagebrush (Sundstrom et al. 1973, Roberson 1984). It provides excellent cover for elk calving, waterfowl and songbird nesting, and small mammals (Ewaschuk 1972). Sagebrush is also important to other ecosystem functions such as snow accumulation, nutrient cycling, wind chill reduction and shading.

A procedure to predict the forage produced by the sagebrush complex is important to determine carrying capacity of the range, to detect trends in forage production and to measure plant response to management. The high forage values of sagebrush make it important for range managers to accurately estimate forage production. Methods that involve clipping or harvesting are costly, time consuming, and destructive (Uresk et al. 1977). Non-destructive procedures based on easily measured plant dimensions to estimate production and biomass have been developed for a variety of other plants (Tufts 1919, Pechanec and Pickford 1937, Weaver 1977, Andrew et al 1979).

The big sagebrush complex consists of 4 subspecies (Beetle 1960, Beetle and Young 1965). Three subspecies, Mountain big sagebrush (*A. t.* ssp. *vaseyana* (Rydb.) Beetle), Wyoming big sagebrush (*A. t.* ssp. *wyomingensis* Beetle and Young), and Basin big sagebrush (*A. t.* ssp. *tridentata*) were of interest for this study. Differences in growth form, distribution, ecology, phenology, animal preference, and forage qualities are well defined among these subspecies (Beetle 1960, Winward 1970, Depuit et al. 1973, Kelsey et al. 1976, Morris et al. 1976, Welch et al. 1981, Harvey 1981, Personius et al 1987, Striby et al 1987, Wambolt et al 1987). While taxonomic differences may be subtle, regression equations used to predict forage production for each subspecies may be unique. Previous historical use, as it affects shrub morphology, may also affect prediction equations (Hughes et al. 1987).

The objectives of this study were 1) to develop regression equations using easily measured plant dimensions to accurately predict forage production for mountain, Wyoming, and basin big sagebrush, and 2) to determine the effects, if any, of historical use, based on present form classes, on regression analyses.

LITERATURE REVIEW

Preface

Rapid and reliable techniques for estimating plant production and biomass are needed in range, wildlife, and ecosystem studies (Harniss and Murray 1976, Ganskopp and Miller 1986). Methods that accurately estimate production or biomass from easily obtained plant dimensions are important to resource managers to determine carrying capacity, response to defoliation, and seeding success (Murray and Jacobson 1982, Rittenhouse and Sneva 1977). Detailed succession studies, nutrient cycling, and competition in plant communities also require estimates of plant biomass and production (Ganskopp and Miller 1986). Procedures that involve harvesting plants or parts of plants are time consuming, destructive and costly (Uresk et al.1977). Using the weight estimate technique (Pechanec and Pickford 1937) requires a considerable amount of training and clipping to verify estimates. The technique also results in mental fatigue after several hours of use (Cabral and West 1986).

A rapid, accurate technique that requires little training is clearly desirable. One approach is to establish a mathematical relationship between 1 or more easily obtained plant measurements and harvest data. This procedure is called double sampling or dimension analysis. Uresk et al. (1977) estimated that clipping big sagebrush phytomass was 120 times more expensive than dimension analysis.

Dimension Analysis for Trees

Foresters use plant measurements for estimates of biomass including board feet, cubic feet, and cords. Tufts (1919) found a high correlation between trunk circumference and weight of the top of fruit trees. Since then many others (Kittredge 1944, Attiwill 1962, Baskerville 1965, Grier and Waring 1974, Brown 1978, Weaver and Lund 1982) have used various combinations of trunk diameter, total height, live crown length, ratios of live crown length to total height, and crown widths to estimate tree biomass. These researchers showed strong relationships from these simple measurements in most cases.

Dimension Analysis for Shrubs

In 1958, Evans and Jones addressed the importance of a method for determining forage production in which clipping or mowing was not necessary. Since that time, much attention has been directed towards predicting production and biomass for a variety of shrubs with a variety of variables. In most cases, very strong relationships, with high r and R^2 values have been reported.

Measures of crown and shrub areas and volumes have been used successfully to predict different plant fractions (Uresk et al. 1977, Rittenhouse and Sneva 1977, Dean et al. 1981, Weaver 1977). Murray and Jacobson (1982) found that different plant shapes used to calculate relationships to weight varied between plant species. They suggest that the observer should decide the most appropriate shape in the field, and obtain the necessary measurements to calculate the area or volume that best approximates that shape.

Lyon (1968), estimated twig production for serviceberry (*Amelanchier alnifolia*) from volumetric relationships based on crown heights and diameters. Weaver (1977), found that shrub masses were easily predicted from simple measurements of their sizes and that size-mass relationships were similar for twelve ecologically diverse Montana shrubs. Also in 1977, Rittenhouse and Sneva used elliptical crown area to predict production of aerial biomass for Wyoming big sagebrush. In 1981, Harvey used similar measurements and included basal area, age, circumference, and shrub volumes to estimate aboveground production for Wyoming and mountain big sagebrushes, and also plains silversage (*A. cana*), fringed sagewort (*A. frigida*), and cudweed sagewort (*A. ludoviciana*). Thus, a large variety of variables have been used in dimension analysis of shrubs. The most useful appear to be variables that express crown size (Murray and Jacobsen 1982).

Log-log and quadratic models have been useful for a number of species (Bently et al. 1970, Rittenhouse and Sneva 1976, Bryant and Kothmann 1979). Under or overestimation of biomass appears to be a problem with the log-log models (Tausch 1989). Bryant and Kothmann (1979) noted that the equation which should be used to predict weight from crown volume depends not only on plant species, but also sampling date. Bonham (1989) concludes that because the magnitude of differences among years, seasons, and locations is so great that individual site-year equations should be used until sufficient data are available for evaluation of site-regional equations.

Canopy Cover

Hanley (1978) stated that canopy cover is a frequently measured and useful parameter in range analysis. Cover has been presented as the "best single measure of a plant species' importance in a community" (Lindsay 1956, Daubenmire 1959). It is an index of the ecological size of the plant. It serves as a criterion of relative dominance and the influence of plants on precipitation interception and soil temperature. Compared with other parameters such as biomass or productivity, canopy cover is relatively easily measured. Evaluations precise enough for research purposes do not require excessive field time.

A variety of methods have been devised for measuring plant canopy cover, but advantages and disadvantages vary with types of vegetation sampled and degrees of confidence and precision required. The line intercept method (Canfield 1941) is a frequently used technique for measuring canopy cover of shrubs in the Great Basin. Kinsinger et al.(1960) compared results of line interception, variable plot, and loop methods for shrub cover in Nevada and found the line interception method to be the most accurate. Hanley (1978) reported that the line-interception method and the 0.1 m^2 quadrat method are equivalent in accuracy of measuring canopy coverage of big sagebrush, but that the line-interception method is more advantageous when a high degree of precision and confidence is required. One disadvantage of cover data as mentioned by Taylor (1986) is that in some species, canopy cover may vary considerably among seasons and years.

The value of canopy coverage measurements for predicting browse mass was recognized by Weaver (1986). He postulates that if browse can be accurately predicted from canopy coverages, it will allow a wildlife manager to estimate quantities of available browse by analysis of an aerial photograph of the site.

Taxonomy of Big Sagebrush

The name *Artemisia tridentata* was first given to this species by Nuttall (1841) from a collection made by the Lewis and Clark expedition in 1804. In 1916, Rydberg recognized variations among *A. tridentata* and classified it as a complex of 5 separate species. In 1965, Beetle and Young's classification, though similar to Rydberg's, assigned collections to subspecies rather than species. Their separation of 3 subspecies: *A. t. vaseyana* (mountain big sagebrush), *A. t. wyomingensis,* (Wyoming big sagebrush), and *A. t. tridentata,* (basin big sagebrush), has been widely accepted.

Since 1965 research has verified differences in ecology, phenology, growth form, palatability, and chemical composition among these three subspecies (Beetle 1960, Winward and Tisdale 1969, Winward 1970, Ward 1971, Morris et al. 1976, Wallmo et al 1977, McArthur 1979, Beetle and Johnson 1982, Blaisdell et al 1982,). The need to more accurately categorize sagebrush taxa for the purpose of improving resource management was summarized by A. A. Beetle who said in 1977,

> "It is no longer fashionable to refer in a general way to sagebrush... This wide variety in ecological adaptation, distribution, and significance reflects important differences in site potential and consequently in management technique. Knowledge of the ecological

characteristics of the species, and in many instances the subspecies of sagebrush will be an important tool to the range manager."

Value to Wildlife

Sagebrush taxa provide cover and forage for big game animals. Julander and Low (1976) found mule deer to be closely associated with sagebrush grasslands. They found mule deer were scarce in pre-pioneer and pioneer times, but deer numbers increased dramatically between 1925-1950. The reasons for this increase include: predator control, limited harvests, and a change in range composition from grass to shrubs.

Antelope distribution is closely associated with the distribution of Wyoming big sagebrush (Sundstrom et al. 1973). These animals are obligates to sagebrush and have been known to travel large distances to find sagebrush browse when local sources are unavailable due to snow cover. Bighorn sheep studies in Montana and Idaho have found that sagebrush taxa can comprise 30-40% of winter diets (Schallenberger 1966).

The most closely associated game bird is the sagegrouse. All of the requirements for breeding, nesting, rearing, and feeding are found in the sagebrush dominated ecosystem (Wallestad and Pyrah 1974, Remington 1985).

Big sagebrush maintains a crude protein level near 11% throughout the winter (Welch and McArthur 1979). This compares to crude protein levels of about 4% for grasses. Thus, big sagebrush represents a valuable winter forage for browsing ungulates.

McNeal (1984) noted a "...surprising amount of sagebrush utilization at elk feeding sites" on the Gardiner winter range. Greer et al. (1970) (in McNeal 1984) found that big sagebrush comprised as much as 5% of the diet of Yellowstone Park elk. McNeal (1984) postulates that big sagebrush use by elk on the winter range may reflect special need for nutrients not provided by grass after the long migration. Elk also use big sagebrush grasslands heavily in the fall and winter for thermal and hiding cover (Mackie 1980). These areas provide safe calving grounds for the elk during the spring.

Form Classes

Cook and Stoddard (1960) showed that repeated herbage removal could induce a hedged appearance in big sagebrush. McNeal (1984) found that subjectively assigned form classes in big sagebrush reflected actual browsing use. Kelsey (1985) observed no visible morphological change in mountain big sagebrush following 2 years of clipping 50% of annual growth. Several years of continuous use are probably required to visibly alter plant morphology (Personius 1985).

Weaver (1977) concluded that if browse biomass estimates, based on lightly browsed shrubs were applied to plants with reduced (through browsing) diameters, actual browse would be overestimated. However, potential browse and above ground biomass would be underestimated. Hughes, Varner, and Blankenship (1987) found that treatments which greatly modified plant form will probably require regression equations separate from those for undisturbed vegetation. Equations to predict browse for both heavily and lightly used shrubs are therefore needed.

STUDY AREA DESCRIPTION

Location

The study area is located near Gardiner (Figure 1) in the Gallatin National Forest of southwestern Montana. Gardiner lies in the Yellowstone River valley at 1694 m (5505 ft) surrounded by peaks reaching 3353 m (11,000 ft).

Stands (Table 1) of each subspecies of big sagebrush in either high or low use form classes were located in an area bounded by Bear Creek to the east, U.S. Highway 89 to the south, and Little Trail Creek to the west. Stand #5 was located in Yankee Jim Canyon, about 22 km northwest of Gardiner. The Absaroka-Beartooth Wilderness forms a less distinct northern boundary.

Table 1. Description and location of individual stands.

Stand	ssp	Form class	Elev. (m)	Habitat type	soil group	Legal desc.
1	*A.t.va*	low	2195	A.t.va/Feid	silt loam	SE corner, SW1/4 sec. 7, T9S, R9E
2	*A.t.va*	high	2049	A.t.va/Agsp	sandy	NE corner, NE1/4 sec.13, T9S, R9E
3	*A.t.wy*	low	1646	A.t.wy/Agsp	sandy loam	SW corner, NE1/4 sec.16, T9S, R9E
4	*A.t.wy*	high	1854	A.t.wy/Agsp	sandy loam	SW corner, SW1/4 sec.10, T9S, R8E
5	*A.t.tr*	low	1707	A.t.tr/Agsp	silt loam	NW corner, NW1/4 sec. 3, T8S, R7E
6	*A.t.tr*	high	1951	A.t.tr/Agsp	silt	NE corner, SE1/4 sec.18, T9S, R9E

Common names of scientific name abbreviations are: A.t.va - mountain big sagebrush; A.t.wy - Wyoming big sagebrush; A.t.tr - basin big sagebrush; Feid - Idaho fescue; Agsp - Bluebunch wheatgrass.

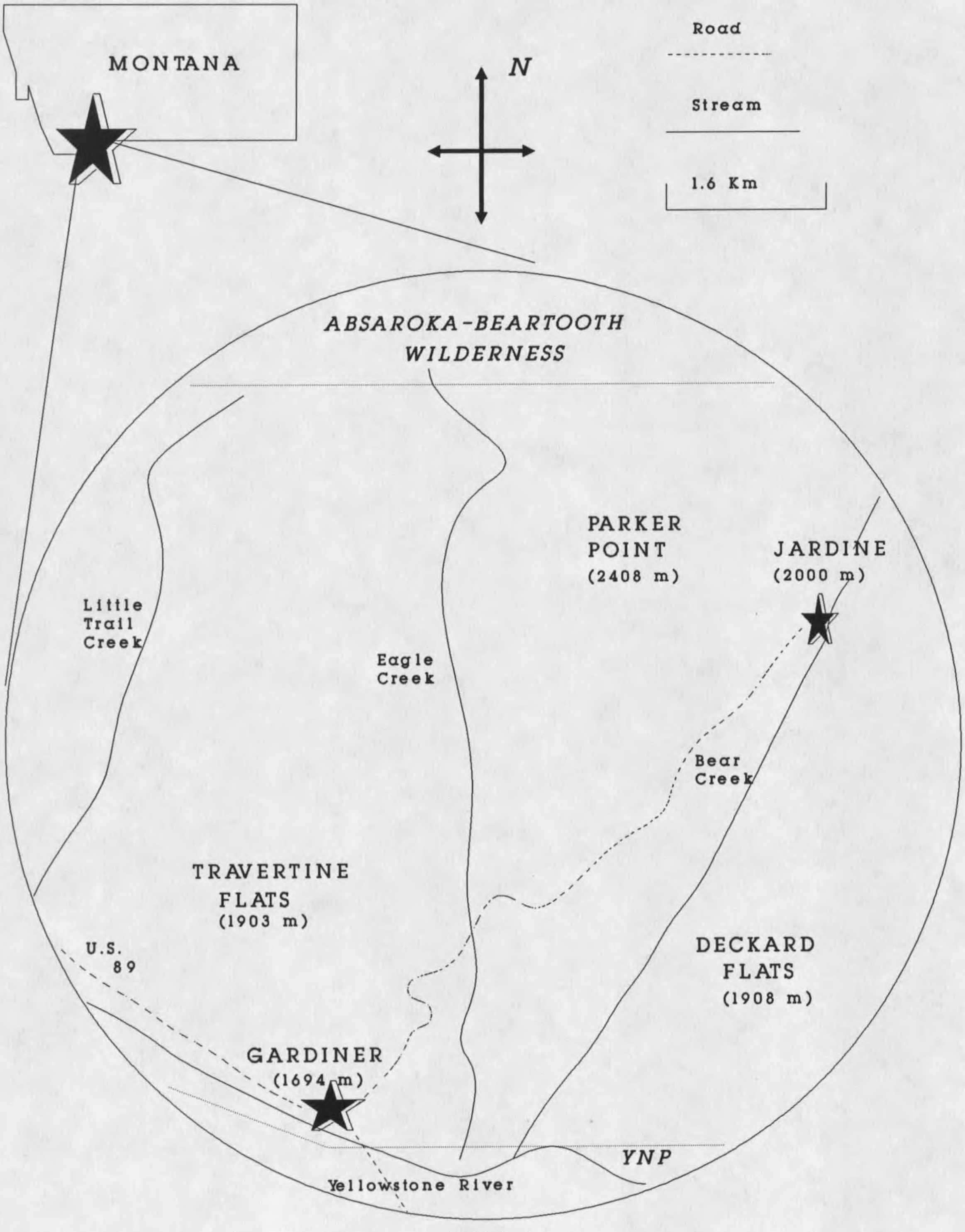

Figure 1. Map of the Gardiner study area.

Topography

The topography of the study area is characterized by relatively flat or rolling benchlands rising to high steep-sided mountains. The rain shadow produced by these mountains makes the benches and slopes of the Gardiner valley an important wintering area for mule deer, and elk. Bison, bighorn sheep, and antelope also use some portions of the area as well. These benches are dissected by deeply entrenched streams (McNeal 1984). Slopes of 50-60 % rise from the Yellowstone River and Bear Creek to the 1-2 km wide basalt bench which extends from the Park line northwest to Little Trail Creek. Slopes then rise abruptly into the Absaroka Mountains from Deckard and Travertine Flats. Overall, elevation increases 1100 m within 5 km of the Yellowstone River. Morainal topography provides a more gradual ascent into the mountains in the Eagle Creek drainage (McNeal 1984).

Much of the study area has a south and west facing aspect which greatly enhances its value as a winter range. North and east facing slopes are found along stream channels and in the mountains. Concave and convex shaped slopes of 2 - 70 % rise are present (McNeal 1984).

Climate

Thornthwaite's (1948) classification shows the Gardiner area as humid with a summer water deficiency. However, convectional showers are common and provide some growing season moisture. Winter storms are more widespread and can be severe. Snow may be 1-2 m deep in nearby mountains yet absent in Gardiner (McNeal 1984).

Farnes' (1975) precipitation map of the area illustrates the dry climate created by the rain shadow in the Gardiner valley with isohyets closely following land contours and greatly increasing with elevation. Annual average precipitation ranges from 30.5 cm (12 in) along the Yellowstone River, to about 40 cm (16 in) on the basalt benches and up to 76.1 cm (30 in) in the surrounding mountains. Roughly half of this moisture occurs as snow.

The U.S. Weather Bureau station at Mammoth is located about 300 m higher and 8 km upstream (south) from Gardiner. This station provides a good representation of climatic conditions for the study area. Weather data collected over 100 years show annual average precipitation of 41.2 cm (16.25 in). February is the driest month, averaging 2.7cm (1.05 in) and June is the wettest month, averaging 4.9 cm (1.92 in). The mean annual temperature is 4.1° C (39.9° F). January is the coldest month averaging -7.4° C (18.7° F) and July is the warmest month averaging 17.3° C (63.1° F).

Typically, the growing season is mid-April to mid-September although a killing frost can occur during any month. Fall regrowth can be substantial if conditions are favorable (McNeal 1984).

Soils

Soils in the area are the result of glacial scouring, morainal deposition and outwash sediments. The parent materials are a mixture of granites and limestones derived from glacial action in areas to the south and east. The soil climate is characterized by cold winters and dry summers.

Glaciation has resulted in variable soil depths. Shallow soils of only a few cm occur in glacially scoured areas and deep soils of several m occur in depositional areas. The glacial till in the study area has a sandy loam texture and a high course fragment content. Course fragment size ranges from gravels to boulders. The surface is covered with granite erratics which probably came from the Black Canyon of the Yellowstone (Pierce 1979 in McNeal 1984).

Mollisols are the most common soils. Soil families range from loamy-skeletal Aridic Haploborolls to fine-loamy Pachic Argiborolls (Gallatin N. F., U. S. Forest Service soils survey in McNeal 1984). Inceptisols can occur near bedrock outcrops and Alfisols occur in forested areas.

Vegetation

Study area vegetation is predominantly sagebrush-grassland. Over 54% of the area is open sagebrush-grass range with another 14% having sagebrush dominated understory and a scattered tree overstory. About 27% of the area is continuous forest which begins at 2300 m. The remaining 5% is clearcut (McNeal 1984).

Three subspecies of big sagebrush and black sagebrush (*Artemisia nova* A. Nels.) occur sympatrically throughout the study area. Black sagebrush is closely associated with calcareous soils and dominates the overstory in sandy till covering travertine (a decorative, Pleistocene-aged limestone rock formed from hot calcareous spring water). Mountain big sagebrush is the most frequent and dominant shrub in the area and is the only sagebrush taxon found above 2100 m (McNeal 1984). Wyoming big sagebrush is found on deep sandy loam soils resulting from glacial outwash and more recently placed alluvial silts. Basin big sagebrush grows downslope of basalt outcrops, on lower portions of steep slopes, along irrigation ditches or in other areas where soil moisture is artificially increased.

Bluebunch wheatgrass (*Agropyron spicatum* (Pursh) Scribn.) and Idaho fescue (*Festuca idahoensis* Elmer) are the 2 most important understory species on the study area. Dominance by either species is related to their respective tolerances for aridity (McNeal 1984). Bluebunch wheatgrass dominates lower elevation sites with steep south facing exposures, sandy soil, and other sites with moisture limiting factors. Idaho fescue is a prominent grass at higher elevations, on north facing slopes, and on deep silty soil sites where moisture is not limiting. Other locally important grasses are prairie junegrass

(*Koeleria pyramidata* (Lam.) Beauv.), needleandthread (*Stipa comata* Trin. & Rupr.), and Indian ricegrass (*Oryzopsis hymenoides* (R. & S.) Ricker).

Wildlife

The study area is part of the northern Yellowstone winter range. Large herds of elk often move into the study area during the winter months. Most of the elk summer on the Yellowstone Plateau while a smaller number summer in the mountainous Absaroka-Beartooth Wilderness (McNeal 1984). Small summer herds begin to congregate on benches and exposed hillsides along the Yellowstone River and its tributaries as fall snows deepen in the mountains. This assemblage of elk is a portion of the northern Yellowstone elk herd. Although estimates vary, there may have been as many as 25,000 animals during the winter of 1987-1988 in the entire northern elk herd.

Elk begin arriving in the Gardiner area as early as mid-November (McNeal 1984). Many continue their migration to the area as conditions in the mountains and on the Yellowstone Plateau worsen. Elk migration in large numbers beyond the Park boundary may occur 1 year in 2 or 2 years in 3 (Houston 1978). The number of elk using the study area may vary from a few hundred to several thousand depending on the year (McNeal 1984). Some may travel as far as 113 km to reach the Gardiner area (Craighead et al. 1972). The winter range north of the Park is indispensable in severe winters to offset the lack of suitable wintering areas within the Park. Most of the elk have usually left the study area by May and returned to popular summering areas.

McNeal (1984) estimates that 400 or more mule deer are seasonal occupants of the Gardiner winter range while Montana Fish, Wildlife and Parks Dept. surveys estimate over 600 in the winter of 1989-90. Most of the deer appear to spend summers in the nearby mountains of the Absaroka-Beartooth Wilderness,in Yellowstone Park or on the study area itself. They usually begin to arrive on the study area around October 1 and may remain through June.

Other big game animals infrequently appear on the Gardiner winter range. Small bands of bighorn sheep (*Ovis canadensis*) winter along the bluffs of the Yellowstone River and Bear Creek near Deckard Flats. Moose (*Alces alces*) are occasional visitors to the area. During deep snow winters, a few bison (*Bison bison*) migrating down the Yellowstone River valley may cross the Park boundary onto the Deckard Flats area and remain for short periods of time (McNeal 1984). Since 1984, the bison have migrated further down the Yellowstone River. In the winter of 1988 bison traveled as far as Yankee Jim Canyon, some 14 miles north of Gardiner.

Additional large animal species sometimes present in the area are Grizzly bears (*Ursus arctos*) and black bears (*U. americanus*) which are present in the fall and spring in association with the large herbivores. Coyote (*Canus latrans*), bobcat (*Lynx rufus*) and mountain lion (*Felis concolor*) also may be present in the area.

METHODS AND MATERIALS

Data Collection

Stands of mountain, Wyoming, and basin big sagebrushes were located in both high and low use form classes during June of 1989. Subspecies were initially identified taxonomically following the classification of Beetle (1960). Identifications were later verified in the lab using the ultraviolet light technique developed by Stevens and McArthur (1974). Form class was determined by the overall appearance of each shrub. Browsing by elk and mule deer over a number of years result in a very distinctive growth form (Figure 2). Continuous browsing over time produces shorter, more intricately branched crowns. This gives the plant a dense, hedged, club-like appearance. Lightly browsed plants exhibit longer leaders and a more bushy appearance. The crowns are more open, growthy, and relatively unbranched. High use stands were located on south or west facing slopes, in more remote areas (Fig. 2: B, D, F). Stands of low use plants were usually situated near areas where human occupation or interference (i.e. roads) inhibited elk and mule deer use, and in 1 case, where deep snows prevented winter access (Fig. 2: A, C, E). The following 6 stands were located: high use Wyoming big sagebrush (ATWH), low use Wyoming big sagebrush (ATWL), high use mountain big sagebrush (ATVH), low use mountain big sagebrush (ATVL), high use basin big sagebrush (ATTH), and low use basin big sagebrush (ATTL) (Figure 2).

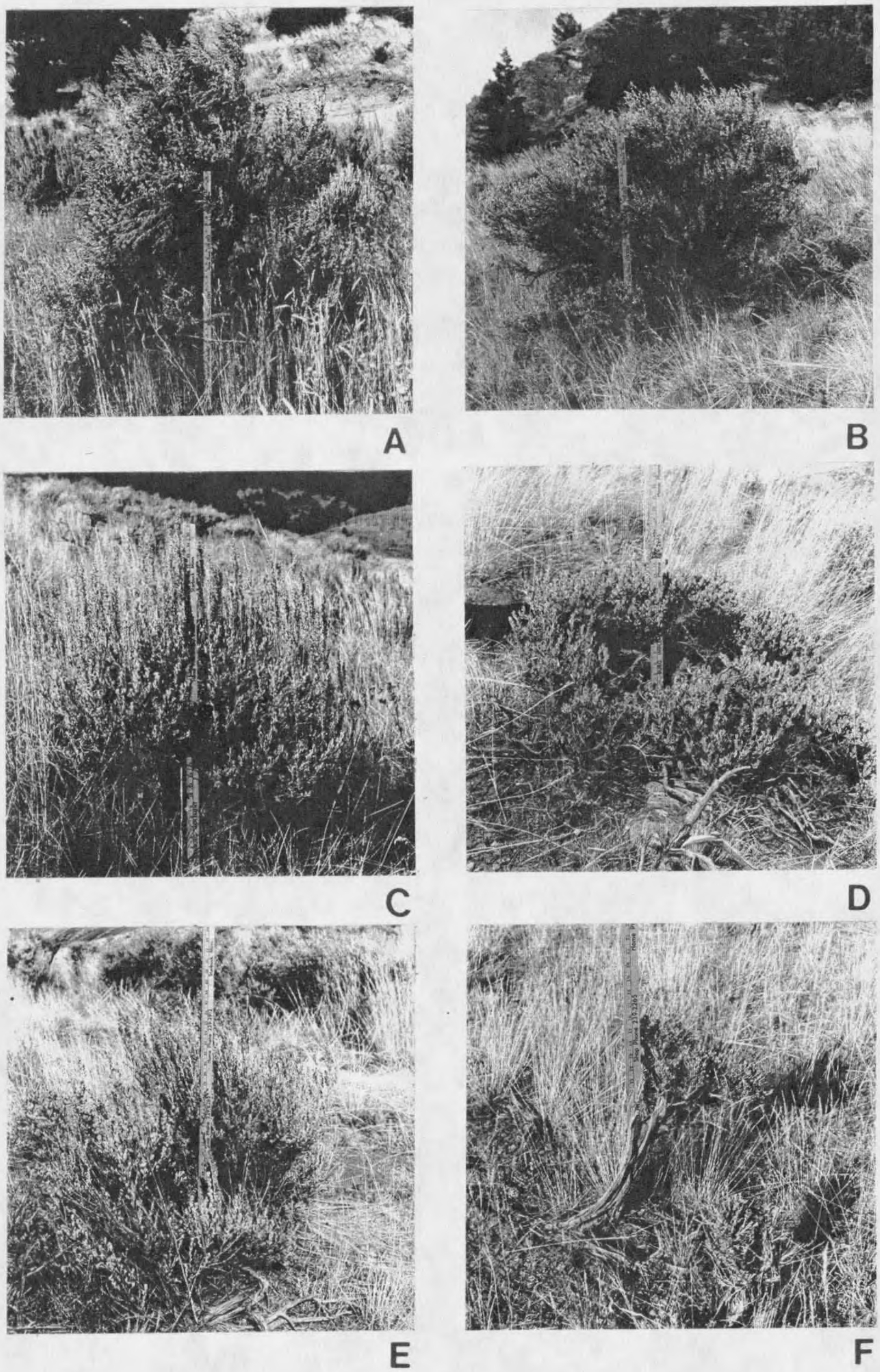

Figure 2. Combinations of subspecies and form classes used in the study. (A) low use basin big sagebrush (ATTL), (B) high use basin big sagebrush (ATTH), (C) low use mountain big sagebrush (ATVL), (D) high use mountain big sagebrush (ATVH), (E) low use Wyoming big sagebrush (ATWL), (F) high use Wyoming big sagebrush (ATWH).

Sampling started in late July, 1989, and continued through September, 1989. This allowed for the nearly complete abscission of the ephemeral leaves which are not considered available winter browse. Only the current crop of perennial leaves persists over winter (Miller and Shultz 1987).

A stratified random sampling design was used in order to obtain a representative sample of the different sized shrubs at each site. Randomly selected plants were determined (relatively) to be either small, medium or large for the site. The final proportion of small, medium and large shrubs sampled, equaled an occular estimate of the proportion of different sized shrubs for each site. This sampling design prevented the sampling of all one size class. Thirty shrubs were sampled on each site.

Shrub Measurements

The overall height (HT) of each sagebrush plant was measured to the nearest cm from its base to the highest non-reproductive foliage. This study was interested in forage available to deer and elk and therefore the maximum plant height was set at 140 cm. (55 in). Plant heights for mountain and Wyoming big sagebrush were well below this height (Appendix A). However, some basin big sagebrush individuals can reach heights of over 2 m., so only plants under 135 cm. in height were sampled.

Two measurements of crown width were taken (Rittenhouse and Sneva 1977). The major axis (MJ) was considered to be the maximum horizontal distance across the plant crown from living plant tissue to living plant tissue. The minor axis (MN) was the maximum crown width perpendicular to the major axis, and was also measured from living tissue to living tissue. Only photosynthetic plant tissue was used for the beginning and the end points of these distances. Non - photosynthetic openings in the canopy were considered continuous and are included in these measurements. All measurements were to the nearest 1 cm.

Line intercept canopy cover measurements (Canfield 1941) were collected along 4 crown axes for each shrub sampled. Intercepts were defined as actively growing plant material. This includes perennial leaves, current growth twigs, and reproductive stalks. Cover measurements were made along the major and minor axes and along 2 additional axes. These axes were perpendicular to each other and 45 degrees to the intersection of the major and minor axes. Total cover to the nearest cm for each axis was measured. These 4 cover totals were summed and divided by 4 to yield the variable average cover (AC) for each plant. The crown depth (CD) was measured for each shrub sampled. This is the vertical distance in cm of the foliated portion of the crown (Dean et al. 1981). Several measurements were collected and averaged for each plant. Only vegetative leaders were measured.

The reproductive stalks or seedheads were clipped at the base, counted for each plant, and oven dried for 48 hours at 60° C. After drying, seedheads were weighed to the nearest 0.1 g. Average seedhead weight (AS) was calculated as the weight of the seedheads divided by the number of the seedheads.

After these measurements were collected in the field, the green foliage was removed from the plant. This includes perennial leaves, ephemeral leaves (if any), and current twig growth. Young twigs were easily discernible on the basis of color, texture of the bark, and leaf bud scars. Browsing ungulates may remove more than just the current twig growth, but for the purpose of this study, only current twig growth is considered available annual winter forage.

After oven drying for at least 48 hours at 60° C. the foliage was weighed to the nearest 0.1 g. This variable, forage (F), became the dependent variable for the regression analysis.

Basal stem numbers and diameters have been measured for big sagebrush (Dean et. al. 1981), and used successfully for independent variables in regression analysis. Basal stem diameters were therefore measured for each plant, but most of the sagebrush plants encountered had several trunks of irregular shape. This made collection of this variable very awkward and time consuming. This was not an easily measured variable for future use of this studies results, nor was it considered free from human bias. Thus basal stem diameters were not included in the variables used in the regression analysis.

Other Variables

The previously described field measurements were used to derive other variables to be used in the regression analysis. Various combinations of the field measurements yielded variables that represent elliptical crown area, crown volume, shrub volume, and circular crown areas based on 2 different crown radii.

Elliptical canopy area was determined by the formula $E = pi(MJ/2)(MN/2)$, where MJ and MN are the major and minor axes, respectively. Crown volume was defined as $CV = E(CD)$, where E is the elliptical area and CD is the crown depth. Shrub volume was defined as $SV = E(HT)$, where HT is the plant height and E is the elliptical area of the canopy. Peek (1970), and Harvey (1981) refer to this variable as crown volume.

The crowns of heavily browsed plants appeared more rounded, so circular crown areas were considered. This follows Murray and Jacobson's (1982) suggestion that the observer determine the appropriate plant shape in the field. Two variables that represent circular area of the canopy were investigated. The circular area (C1) for the major axis was determined by the formula, $C1 = pi(MJ/2)^2$, where MJ is the major axis. And the circular area (C2) for the minor axis was determined by the formula $C2 = pi(MN/2)^2$, where MN is the minor axis.

Data Analysis

The intention of this study was to 1) develop reliable regression equations to predict annual available forage from each of the 3 big sagebrushes in both high or low use form class, and 2) to compare and contrast easily computed regression models for each taxon and form class. The models for each of the 6 combinations of subspecies and form class were developed separately. Several models were considered and compared for each subspecies and form class combination.

Models were evaluated on the basis of adjusted R^2 values. The adjusted R^2 statistic is calculated by adjusting the coefficient of determination (R^2) for the number of parameters in the model and the sample size. This adjustment prevents the R^2 statistic from becoming artificially inflated as the number of variables in the model increases (Neter et al. 1985). Adjusted R^2 values are generally similar to R^2 values, though somewhat smaller.

Scatter diagrams were constructed for each pair of independent and dependent variables to identify any curvilinear tendencies. The variable "height (HT)" for low use mountain big sagebrush (ATVL) was determined to have a curvilinear relationship with the dependent variable "forage (F)" and was added to the model as HT^2 for ATVL. No other curvilinear relationships were found. The dependent variable "forage (F)" was log transformed (natural logarithm) to stabilize nonconstant variance exhibited in the initial plots of predicted values versus residual error terms. Nonconstant variance is a direct result of the sampling method. The log transformation is a powerful variance stabilizing transformation and widely used (Murray and Jacobson 1977, Rittenhouse and Sneva 1977, Dean et al. 1981).

Colinearity analysis for each taxon and form class combination identified colinearities among some of the variables. The variables, "major axis (MJ)", and "minor axis (MN)", were determined to be nearly colinear with each other and also with the variable "elliptical area (E)". This may be caused by the fact that the crowns of the plants sampled were all similarly shaped. Information derived for the 3 variables is nearly identical so inclusion of more than 1 of these variables in any 1 model is inappropriate (Neter et al. 1985). Variables were separated into 3 groups to split up the variables "major axis (MJ)", minor axis (MN)" and "elliptical area (E)" and thereby avoid colinearities (Table 2). Each of 3 groups of independent variables was analyzed in the model building procedure. Models were evaluated and compared on the basis of the adjusted R^2 statistic.

Table 2. Groups of independent variables. Each variable group includes only "major axis (MJ)" or "minor axis (MN)" or "elliptical area (E)" in addition to the other variables measured.

Group 1	Group 2	Group 3
MJ	**MN**	**E**
HT	HT	HT
HT^2	HT^2	HT^2
CD	CD	CD
AC	AC	AC
C1	C2	CV
		SV

Variable abbreviations: MJ-major axis, MN-minor axis, E-elliptical area, HT-height, HT^2 (for ATVL only), CD-crown depth, AC-average cover, C1-circular area1, C2-cir area2, CV-crown volume, SV-shrub vol.

Models are of the form: $\ln(F) = b_0 + X_1 + X_2 + X_3 + X_4 + X_5 + X_6 + X_7 + e$
where: F = Available winter forage
b_0 = y-intercept
X_1 = major (MJ) or minor axis (MN) or elliptical area (E)
X_2 = height (HT)
X_3 = HT^2 for low use mountain big sagebrush (ATVL) only
X_4 = crown depth (CD)
X_5 = average cover (AC)
X_6 = circular area1 (C1) or cir area2 (C2) or crown volume (CV)
X_7 = shrub volume (SV)
e = residual error
all X_n terms have an associated constant = b_n

RESULTS AND DISCUSSION

This chapter is divided into 2 parts. In the first section, the highest adjusted R^2 models for each subspecies and form class combination are presented for groups of variables that were chosen to avoid colinearity. The second section will discuss the best models for each form class-taxon combination along with models that may lend themselves to easy field applications. My choice of the best models on the basis of high adjusted R^2 values, the number of variables in the model and the ease of measuring those variables may not be the highest adjusted R^2 model since the difference between the highest adjusted R^2 model (Tables 3 and 4) and a simpler (fewer variables) model may be very small, often < 1%.

Comparison of 3 Groups of Variables

Colinearities among the variables MJ, MN, and E mandated the investigation of 3 separate variable groups (Table 2) in the model building process. While it is not possible to compare adjusted R^2 values with a test statistic, Table 3 indicates that differences among the 3 variable groups in adjusted R^2 values are small. That is, each variable group predicts annual winter forage production for all 3 subspecies and form classes of big sagebrush with essentially the same precision. This is also the case when the variable "average seedhead weight (AS)" is included in the model (Table 4).

Table 3. Highest adjusted R^2 equations for each subspecies and form class combination in each of the 3 variable groups (Table 2).

Taxon and form class	Group 1 Models	Adj R^2	R^2	Root MSE
ATVL	$\ln(F)=.647+.034(MJ)+.031(AC)-.0002(C1)$	.88	.89	.35
ATVH	$\ln(F)=.311+.037(MJ)+.047(AC)-.0003(C1)+.017(CD)$	.90	.91	.24
ATWL	$\ln(F)=.322+.048(MJ)+.017(AC)-.0003(C1)$	.88	.90	.24
ATWH	$\ln(F)=.535+.008(MJ)+.026(AC)+.029(HT)+.025(CD)$	.84	.86	.26
ATTL	$\ln(F)=2.18+.013(MJ)+.019(AC)-.010(HT)+.035(CD)$	.78	.82	.35
ATTH	$\ln(F)=1.89+.011(MJ)+.037(AC)+.005(HT)-.00005(C1)$	.88	.89	.21
	Group 2 Models			
ATVL	$\ln(F)=1.059+.054(MN)+.025(AC)-.0004(C2)$	.89	.90	.34
ATVH	$\ln(F)=.794+.041(MN)+.047(AC)-.0005(C2)+.009(HT)+.033(CD)$	.89	.91	.25
ATWL	$\ln(F)=.729+.043(MN)+.031(AC)-.0003(C2)$	.81	.83	.30
ATWH	$\ln(F)=-.008+.055(MN)+.030(AC)-.0007(C2)+.024(HT)$	.84	.87	.26
ATTL	$\ln(F)=2.53+.009(MN)+.020(AC)$	.73	.75	.40
ATTH	$\ln(F)=1.93+.021(MN)+.027(AC)-.0002(C2)+.006(HT)-.010(CD)$	.89	.91	.20
	Group 3 Models			
ATVL	$\ln(F)=1.34+.0005(E)+.029(AC)+.0002(HT^2)-.000006(SV)$	.81	.83	.44
ATVH	$\ln(F)=1.67-.0003(E)+.065(AC)-.008(HT)+.00001(CV)$	.90	.92	.23
ATWL	$\ln(F)=.124+.0008(E)+.018(AC)-.02(HT)-.000007(SV)-000002(CV)+.068(CD)$	.83	.87	.28
ATWH	$\ln(F)=-.246+.0007(E)+.031(AC)+.043(HT)-.000009(SV)-.00004(CV)+.082(CD)$	.85	.88	.25
ATTL	$\ln(F)=1.41+.0003(E)+.020(AC)-.005(HT)-.00001(CV)+.082(CD)$	.78	.82	.36
ATTH	$\ln(F)=2.39+.030(AC)+.007(HT)-.016(CD)$	.88	.89	.21

Equation abbreviations; F-Forage(g), MJ-Major axis(cm), MN-Minor axis (cm), HT-Height (cm), AC-Average cover (cm), CD-Crown depth (cm), C1-Circular area1(cm^2), C2-Circular area2 (cm^2), SV-Shrub vol. (cm^3), E - Elliptical area (cm^2), CV - Crown volume (cm^3), Abbreviations for taxon and form class: ATVL-low use mountain big sagebrush, ATVH - high use mountain big sagebrush, ATWL - low use Wyoming big sagebrush, ATWH - high use Wyoming big sagebrush, ATTL - low use basin big sagebrush, ATTH-high use basin big sagebrush. Root $MSE=MSE^{1/2}$.

Table 4. Highest adjusted R^2 equations for each subspecies and form class combination when average seedhead weight (AS) is added to each group as an independent variable.

Taxon and form class	Group 1 Models	Adj R^2	R^2	Root MSE
ATVL	ln(F)=.65+.380(AS)+.029(AC)+.038(MJ)-.0002(C1)	.90	.91	.33
ATVH	ln(F)=.31+.047(AC)+.037(MJ)+.017(CD)-.0003(C1)	.90	.91	.24
ATWL	ln(F)=.51+3.72(AS)+.018(AC)+.044(MJ)-.026(CD) -.0002(C1)	.93	.94	.18
ATWH	ln(F)=.68+.86(AS)+.026(AC)+.009(MJ)+.043(HT)	.87	.89	.24
ATTL	ln(F)=1.95+1.00(AS)+.023(AC)+.008(MJ)	.89	.90	.25
ATTH	ln(F)=1.89+.027(AC)+.011(MJ)-.005(HT) - .00005(C1)	.88	.89	.21
	Group 2 Models			
ATVL	ln(F)=1.45+.633(AS)+.055(MN)+.017(AC)-.0003(C2) -.031(CD)	.93	.94	.27
ATVH	ln(F)=.794+.041(MN)+.047(AC)-.0005(CA2)+.009(HT) +.033(CD)	.89	.91	.25
ATWL	ln(F)=.856+4.69(AS)+.047(MN)+.026(AC)-.0004(C2) -.037(CD)	.88	.90	.24
ATWH	ln(F)=.203+.644(AS)+.043(MN)+.030(AC)-.0005(C2) +.022(HT)	.86	.88	.25
ATTL	ln(F)=1.78+1.06(AS)+006(MN)+.022(AC)+.006(HT)	.86	.88	.28
ATTH	ln(F)=1.93+.022(MN)+.027(AC)-.0002(C2)+.006(HT) -.010(CD)	.89	.91	.20
	Group 3 Models			
ATVL	ln(F)=1.30+.623(AS)+.0006(E)+.021(AC)+.0002(HT^2) -.000007(SV)	.86	.88	.38
ATVH	ln(F)=1.73-.307(AS)-.0003(E)+.065(AC)-.008(HT) +.00001(CV)	.90	.92	.23
ATWL	ln(F)=.097+3.84(AS)+.0006(E)+.018(AC)-.018(HT) -.000005(SV)-.000009(CV)	.87	.90	.24
ATWH	ln(F)=.474+.772(AS)+.0004(E)+.772(AC)+.038(HT) -.000007(SV)	.87	.89	.24
ATTL	ln(F)=1.60+1.02(AS)+.0002(E)+.020(AC)+.010(HT) -.000001(SV)	.89	.91	.25
ATTH	ln(F)=2.39+.030(AC)+.007(HT)-.016(CD)	.88	.89	.21

Equation abbreviations; F-Forage(g), MJ-Major axis(cm), MN-Minor axis (cm), AS-Average seedhead weight (g), HT-Height (cm), AC-Average cover (cm), CD-Crown depth(cm), C1-Circular area1(cm^2, C2-Circular area2 (cm^2), SV-Shrub volume (cm^3), E-Elliptical area (cm^2), CV-Crown volume (cm^3). Abbreviations for taxon and form class: ATVL-low use mountain big sagebrush, ATVH-high use mountain big sagebrush, ATWL - low use Wyoming big sagebrush, ATWH - high use Wyoming big sagebrush, ATTL - low use basin big sagebrush, ATTH - high use basin big sagebrush. Root MSE=MSE$^{1/2}$.

Best Variable Group

Colinearity analysis indicated that the 3 variables MJ, MN, and E all have strong linear relationships with each other. Further investigation demonstrated the strengths of these linear relationships. Scatter plots (Appendix B) of MJ vs MN for each subspecies and form class revealed a linear relationship for these variables in each case. This evidence indicates that MJ is essentially equal to MN for each taxon and form class combination. Mathematically, E approaches the value of MJ times MN as the constants are absorbed in the b_n term in the regression equation. If MJ = MN, then E is equal to $MJ^2 = MN^2$. Scatter plots of E vs MJ^2 and MN^2 show a strong linear relationship as expected. In the model building process, for this data set, the variables major axis, minor axis, and elliptical area all describe the same information and the 3 variable groups each describe the same relationships. The logical criterion that should determine the "best" variable group then is the ease of measuring the variables used in the model. Group 1 has the advantage of employing the most easily measured variables. The models in this group are based on a measurement of the major axis only. Groups 2 and 3 both require an additional measurement of the minor axis as the major axis must be determined in order to locate the minor axis. This additional measurement increases the amount of field time required and does not seem to increase the accuracy of the models appreciably. Thus, I conclude that Group 1 is the best variable group as the variables are easier to collect and the resulting models are reliable.

Addition of the Variable "Average Seedhead Weight (AS)"

The addition of the variable, "average seedhead weight (AS)" (Table 4) to each variable group does increase the adjusted R^2 values for most taxon-form class combinations. This variable is somewhat time consuming to collect, but, in the cases of ATVL, ATWL, ATTL there is improvement in the adjusted R^2 values, and a decrease in the root MSE in each variable group. For the high use form classes, ATVH and ATTH, there is no increase in the adjusted R^2 values and the increases for ATWH are very small for each variable group. This can be explained in terms of low inflorescence production in heavily used plants. Consequently, the addition of this variable to the model is most meaningful for predicting forage production in low use subspecies.

Low Use Mountain Big Sagebrush (ATVL)

Annual winter forage production can be reliably predicted by the best model (Table 5) for this subspecies and form class combination. All variables are significant at $P<.01$ for the best model. This 3 variable model has easily measured parameters, and a high adjusted R^2 value.

Dean et al. (1981) developed a model for predicting biomass of mountain big sagebrush. Their model included 4 variables with $R^2 = 0.85$. The best model for ATVL is in close agreement and may be more precise as Dean (1981) included the variable crown denseness (%), which is an ocular estimate and required calibration to insure consistency. Instead, the variable average cover (AC) is utilized. AC is preferable as it is a practical, rapid and statistically sound technique, and is less subjective (Canfield 1941).

Table 5. Group 1 models for low use mountain big sagebrush (ATVL).

	ADJ R^2	R^2	ROOT MSE
Best model			
$\ln(F)=.647+.034(MJ)+.031(AC)-.0002(C1)$	.88	.89	.35
3 Variable model			
$\ln(F)=0.621+.037(MJ)+.046(CD)-.00023(C1)$	.83	.84	.42
2 Variable models			
$\ln(F)=1.23+.038(MJ)-.0001(C1)$	.81	.83	.44
$\ln(F)=1.39+.019(MJ)+.041(CD)$	.79	.80	.46
$\ln(F)=1.96+.017(MJ)+.009(AC)$	.78	.80	.47
1 Variable models			
$\ln(F)=1.96+.021(MJ)$	.78	.79	.47
$\ln(F)=2.26+.037(AC)$	.70	.71	.56
Model with AS included			
$\ln(F)=.65+.38(AS)+.038(MJ)+.029(AC)-.0002(C1)$	.90	.91	.33

Equation abbreviations; F-Forage (g), MJ-Major axis (cm), HT-Height (cm), AC-Average cover (cm), CD-Crown depth(cm), C1-Circular areal (cm^2), AS-Average seedhead weight (g). Root $MSE=MSE^{1/2}$.

The next highest adjusted R^2 model also has 3 variables and is similar to the best model except that the variable AC is replaced by CD. There is a decrease in the adjusted R^2 value of 0.05.

Three different 2 variable models predict forage fairly well for ATVL. MJ is included in each with either C1, CD, or AC. The differences in adjusted R^2 values and root MSE terms are negligible. The easiest 2 variable model to use of the 3 models presented includes MJ and C1. This model requires only 1 field measurement as C1 is calculated from the measurement of the major axis and has an adjusted $R^2 = 0.81$.

Two single variables that predict forage for ATVL are MJ and AC. These 2 models represent very easily applied models with reasonably high reliability with adjusted $R^2 = 0.78$ and $R^2 = 0.70$, respectively. It is interesting to note that AC alone accounts for 70% of the variability in predicting forage production for ATVL.

The addition of the variable average seedhead weight (AS),which is significant at $P<.05$, does improve the adjusted R^2 value from .88 to .90 for this subspecies and form class combination. This variable does require more field time to collect, but the collection is straightforward and can be entrusted to less skilled workers. The addition of this variable is useful when a model to describe as much variation as possible is required.

High Use Mountain Big Sagebrush (ATVH)

The highest adjusted R^2 model for ATVH in Table 3 includes 4 variables. But the variable CD is not significant and was excluded. This results in a model with the variables MJ, AC, and C1, (Table 6) which are the same variables used in the best model for ATVL. Two variable models for ATVH include the variables MJ, AC, and C1. Adjusted R^2 values are high and root MSE terms are acceptable. In order to calculate C1, the major axis must be measured. In the case of ATVH, the model which combines AC with C1 has an adjusted R^2 = 0.85 while the 2 variable model that combines MJ and C1 has an adjusted R^2 = 0.69. So in this case, it is necessary to collect 2 variables MJ, and AC in the field and calculate C1 to use the best model. A 2 variable model for ATVH does not improve efficiency.

Table 6. Group 1 models for high use mountain big sagebrush (ATVH)

Best model	ADJ R^2	R^2	ROOT MSE
ln(F)=0.489+.037(MJ)+.050(AC)-.0003(C1)	.90	.91	.24
2 Variable models			
ln(F)=1.36+.066(AC)-.0001(C1)	.85	.86	.29
ln(F)=1.73-.010(MJ)+.063(AC)	.80	.82	.33
ln(F)=0.30+.081(MJ)-.00005(C1)	.69	.71	.42
1 Variable models			
ln(F)=1.75+.046(AC)	.78	.79	.36
ln(F)=2.36+.018(MJ)	.46	.48	.56

Equation abbreviations; F-Forage (g), MJ-Major axis (cm), AC-Average cover(cm), CD-Crown depth(cm), C1-Circular areal(cm^2), Root MSE= $MSE^{1/2}$.

Average cover (AC) alone is again a strong predictor of annual winter forage production, accounting for 78% of the variation for ATVH. But MJ only accounts for 46% of the variation for high use mountain big sagebrush. In fact, low adjusted R^2 values for this variable are the case in each of the high use taxa studied (Tables 6, 8, and 10).

The addition of AS did not improve the model for ATVH. A comparison of Tables 3 and 4 reveals that AS did not enter into the model for ATVH.

Low Use Wyoming Big Sagebrush (ATWL)

Group 1 variables produce the highest adjusted R^2 models for this taxon and form class combination (Table 3). All 3 variables in the best model (Table 7) are significant at the *P*<.05 level. Adjusted R^2 value is high and the root MSE is fairly low. The best model for ATWL is similar to the best models for mountain big sagebrush in both form classes. Indeed, the same variables, MJ, AC, and C1 are in the prediction equation. This simplifies matters in that the collection of relatively simple measurements will produce models that work well for ATVL, ATVH, and ATWL.

Table 7. Group 1 models for low use Wyoming big sagebrush (ATWL).

	ADJ R^2	R^2	ROOT MSE
Best model			
$\ln(F)=.322+.048(MJ)+.017(AC)-.0003(C1)$	.88	.90	.24
2 Variable models			
$\ln(F)=.270+.060(MJ)-.0003(C1)$	.85	.86	.27
$\ln(F)=1.44+.016(MJ)+.017(AC)$	.84	.86	.27
1 Variable models			
$\ln(F)=1.43+.027(MJ)$	.81	.82	.30
$\ln(F)=1.73+.038(AC)$	.78	.78	.32
Model with AS included			
$\ln(F)=.41+2.76(AS)+.041(MJ)+.015(AC)-.0002(C1)$	.92	.93	.18

Equation abbreviations; F-Forage (g), MJ-Major axis (cm), HT-Height (cm), AC-Average cover (cm), CD-Crown depth (cm), C1-Circular areal (cm^2), AS-Average seedhead weight (g). Root MSE=$MSE^{1/2}$.

This 3 variable "best model" shows some improvement over the model of Dean et al. (1981) for Wyoming big sagebrush. The 4 variable model they reported included crown denseness and resulted in an R^2 =0.86. For this study, a 3 variable model has R^2=0.90, and when AS is added to the best model in Table 9, the R^2=0.93.

The 2 variable models are very close in terms of reliability, and the measure of MJ with a subsequent calculation for C1 results in a very functional model. The additional measure of AC does not seem necessary as no improvement in R^2 is noted for a 2 variable model.

One variable models explain much of the variation for ATWL. MJ alone accounts for 81%, and AC accounts for 78%. Rittenhouse and Sneva (1977) accounted for 88% of the photosynthetic biomass of Wyoming big sagebrush with the variable, log(MJ). Even though the sampling techniques and the transformations are different, these results seem to be in close agreement.

The addition of the variable AS results in some improvement in the prediction of forage production for ATWL. All variables are significant at $P<.05$. This equation is very similar to the prediction equation for ATVL with AS included, probably because of similar growth forms for these 2 subspecies in low use form classes. The same variables are used in each prediction equation, but the coefficients are quite different so it is necessary to identify plants to subspecies in order to select the appropriate equation.

High Use Wyoming Big Sagebrush (ATWH)

The highest adjusted R^2 model for ATWH (Table 3) includes the variable CD which is not significant at $P<.05$. When this variable is excluded from the model, there is no reduction in adjusted R^2, R^2, or root MSE. The best model for ATWH (Table 8) has 3 variables, MJ, AC, and HT. These 3 variables are significant at $P<.01$. The variable HT is an important variable for ATWH, but did not enter into any of the best models for the previous 3 taxa and form class combinations investigated. This variable is included in both of the highest adjusted R^2 models with 2 variables along with AC and MJ.

Table 8. Group 1 models for high use Wyoming big sagebrush (ATWH).

Best model	ADJ R^2	R^2	ROOT MSE
$\ln(F)=.669+.008(MJ)+.029(AC)+.028(HT)$	.84	.86	.26
2 Variable models			
$\ln(F)=.716+.034(HT)+.036(AC)$	.82	.83	.28
$\ln(F)=.940+.035(HT)+.014(MJ)$	.73	.75	.34
1 Variable models			
$\ln(F)=1.18+.051(HT)$	.61	.62	.41
$\ln(F)=1.41+.054(AC)$	.61	.62	.41
$\ln(F)=1.64+.024(MJ)$	.53	.55	.45
Model with AS included			
$\ln(F)=.68+.86(AS)+.009(MJ)+.026(AC)+.043(HT)$	.87	.89	.24

Equation abbreviations; F-Forage (g), MJ-Major axis (cm), HT-Height (cm), AC-Average cover (cm), CD-Crown depth(cm), C1-Circular areal (cm^2), AS-Average seedhead weight (g). Root $MSE=MSE^{1/2}$.

The differences between the best model, with 3 variables, and the 2 variable model that includes HT and AC are very small. So forage production for high use Wyoming big sagebrush can be reliably and easily determined by a 2 variable model that includes AC and HT.

Height alone accounts for 62% of the variation in forage for ATWH as does AC. The variable MJ accounts for 55% for the high use form class as compared to 82% for the low use form class of the same subspecies.

The addition of AS improves the model from adjusted $R^2 = 0.84$ to adjusted $R^2 = 0.89$. This improvement is small, so the increased sampling time may not justify the measure of this variable for ATWH. Combining AS with other single variables does not improve the adjusted R^2 values from the values for 2 variable models presented in Table 8.

Low Use Basin Big Sagebrush (ATTL)

This taxon and form class combination resulted in the lowest adjusted R^2 in all 3 variable groups. This is probably due to a difference in overall growth form from the other subspecies of big sagebrush. Group 1 variables provided the highest adjusted R^2 values of the 3 variable groups investigated (Table 3).

Neither HT or CD in the Group 1 model for this taxa and form class combination (Table 3) is significant at $P<.05$ (both are significant at $P<.10$). If these variables are dropped from the model, the 2 variable model in Table 9 is the result and becomes the best model.

This 2 variable model has adjusted $R^2=0.77$ which is essentially equal to the highest adjusted R^2 model. The 2 variables in this model also appear as the best single variable models for ATTL. The variable AC accounts for 69% of the variation by itself, and MJ alone accounts for 65%.

Table 9. Group 1 models for low use basin big sagebrush (ATTL).

Best model	ADJ R^2	R^2	ROOT MSE
$\ln(F)=2.37+.008(MJ)+.020(AC)$	.77	.78	.37
1 Variable models			
$\ln(F)=2.54+.032(AC)$	.69	.70	.42
$\ln(F)=2.72+.016(MJ)$	.65	.66	.45
Model with AS included			
$\ln(F)=1.95+1.00(AS)+.008(MJ)+.023(AC)$	.89	.90	.25

Equation abbreviations; F-Forage (g), MJ-Major axis (cm), HT-Height (cm), AC-Average cover (cm), CD-Crown depth(cm), C1-Circular areal (cm^2), AS-Average seedhead weight (g). Root $MSE=MSE^{1/2}$.

The addition of AS to the 2 variable model results in a dramatic improvement both in adjusted R^2 values and root MSE values. The increase in field time for collection of AS data therefore is justified in the case of ATTL.

High Use Basin Big Sagebrush (ATTH)

The highest adjusted R^2 model for ATTH has 4 variables including MJ, AC, HT, and C1. The variable C1 is not significant and should be omitted. This results in the 3 variable model presented in Table 12. There are no changes in adjusted R^2, R^2, or root MSE for this 3 variable model and all variables are significant at $P<.05$.

The 2 variable models in Table 12 both include AC and either HT or MJ. The adjusted R^2, R^2, and root MSE values are identical for these 2 models. All variables are significant at $P<.01$.

Average cover alone results in a very reliable model with an adjusted $R^2=0.84$. The variable MJ alone accounts for 59% of the variation for ATTH.

Table 10. Group 1 models for high use basin big sagebrush (ATTH).

Best model	ADJ R^2	R^2	ROOT MSE
$\ln(F)=2.18+.004(MJ)+.027(AC)+.004(HT)$	.88	.89	.21
2 Variable models			
$\ln(F)=2.24+.032(AC)+.005(HT)$	.86	.87	.22
$\ln(F)=2.41+.029(AC)+.005(MJ)$	.86	.87	.22
1 Variable models			
$\ln(F)=2.52+.035(AC)$	.84	.84	.24
$\ln(F)=2.77+.016(MJ)$	.59	.60	.38

Equation abbreviations; F-Forage (g), MJ-Major axis (cm), HT-Height (cm), AC-Average cover (cm), CD-Crown depth (cm), C1-Circular areal (cm^2), Root MSE=$MSE^{1/2}$.

SUMMARY AND CONCLUSIONS

Difficulties in identifying the big sagebrushes to the subspecific level are well known (Winward and Tisdale 1977). Nevertheless, differentiation of big sagebrush subspecies is important in analyzing site potential, site condition (Dean et al. 1981), identifying animal preferences (Welch et al. 1981, Personius et al. 1987), and predicting treatment response. Even though the prediction equations for low use Wyoming big sagebrush and low use mountain big sagebrush use the same variables, the y-intercept and the associated coefficients in each equation are quite different. Identification to the subspecific level is necessary to predict forage production as separate regression equations in this study have proven to greatly increase precision.

Heavy previous use can be considered a treatment that affects growth form (Patton and Hall 1966). Hughes et al.(1987) found that while range site did not affect prediction equations, mechanical treatment (shredding) did. They concluded that treatments which greatly modify plant form will probably require regression equations different from those of undisturbed vegetation. Our findings are consistent with this premise as separate prediction equations were developed for each form class with a consequent increase in precision.

The relationship studied is between big sagebrush annual winter forage production and the independent variables (big sagebrush parameters). It is expressed with a natural logarithmic transformation of the dependent variable in the regression equation for the 6 combinations of subspecies and form classes studied. This transformation was necessary to stabilize nonconstant variance of the error term as exhibited in the initial scatter plots of residual error vs predicted values. The nonconstant variance is a direct result of the sampling strategy employed: stratified random sampling. If a strict random sampling technique can be applied, this transformation may be avoided as the error terms would also be randomly distributed. But a stratified sample is often desirable when there are risks that a random sample may not satisfactorily represent the population of interest because of time or financial constraints. This is the case with determination of annual winter forage production for big sagebrush taxa as sampling time is limited to the rather short period between ephemeral leaf drop and winter.

Other researchers have developed log-log equations for predicting various components of big sagebrush (Rittenhouse and Sneva 1977, and Dean et al. 1981, Hughes et al. 1987). Tausch (1989) determined that systematic bias from log-log transformations with a specified nonlinear model is an important factor to consider in biomass estimation. In this study, linear regression was justified by the fact that nonlinear relationships were not indicated in the scatter plots of dependent versus independent variables.

Colinearity analysis indicated that the variables "major axis (MJ)", "minor axis (MN)", and "elliptical area (E)" could not be legitimately used in the same equation. This resulted in somewhat different final equations than those reported by other researchers. Rittenhouse and Sneva (1977) combined these variables in some of their higher R^2models. Dean et al. (1981) also used measures of maximum and minimum diameters together in the best fit equations that they reported. These studies do not mention colinearity tests. If colinearities among maximum diameter, minimum diameter, and elliptical areas were not indicated for their data, then it would seem that the overall shape of big sagebrush is more variable from site to site than previously thought. A test for colinearity is imperative then to determine the appropriateness of including different variables in the same regression equation.

Three variable groups were considered in this study. Group 1 was based on the measure of the major axis, group 2 was based on the measure of the minor axis and group 3 was based on the elliptical crown area, and included various measures of shrub and crown volume. All 3 variable groups yield very similar results in terms of adjusted R^2 values (Tables 3 and 4). Group 1 variables were less time consuming to collect in the field and were used to determine the best models.

The resulting models have adjusted R^2 values that range from 0.78 for low use basin big sagebrush (Table 9) to adjusted R^2=0.90 for high use mountain big sagebrush (Table 6). Major axis (MJ), average cover (AC), crown depth (CD), height (HT) and circular areal (C1), were the most useful shrub characteristics in forage prediction. These are well defined and easily measured variables. The addition of the variable "average seedhead weight (AS)" improved the adjusted R^2 values of some subspecies and form class combinations (Table 4), but not all. This variable is more time consuming to collect but may be justified in predicting forage production for low use form classes where sizeable increases in adjusted R^2 values occur. "Average seedhead weight (AS)" may not improve the adjusted R^2 values enough to justify the increased field time for forage prediction of high use plants.

Uresk et al. (1977) found the poorest relationship when predicting the phytomass of flowering stalks compared to other fractions of big sagebrush (R^2=0.52). Mack (1971) and Murray (1977) (in Murray and Jacobson 1982) were unable to develop satisfactory relationships between inflorescence weight and canopy volume for big sagebrush plants. In this study, "average seedhead weight (AS)" alone accounts for less than 10% of the variation in forage production in each of the low use form classes. But when included with other independent variables, "average seedhead weight (AS)" becomes a useful measurement for predicting annual winter forage production. Including this variable increases precision by 2 % for low use mountain big sagebrush (Table 5), 4 % for low use Wyoming big sagebrush (Table 7), and 12 % for low use basin big sagebrush (Table 9).

In most cases, combining "major axis (MJ)" and "average cover (AC)" resulted in reliable and accurate prediction equations. Adjusted R^2 values range from 0.77 for low use basin big sagebrush (Table 9), to 0.86 for high use basin big sagebrush (Table 10). High use Wyoming big sagebrush was the exception. For this subspecies and form class combination, the 2 variable model with the highest adjusted R^2 value (0.82) includes height (HT) and average cover (AC) (Table 8).

Rittenhouse and Sneva (1977) noted good results in estimating big sagebrush production with 1 variable. They reported $R^2=0.88$ for the longest measure of crown width for Wyoming big sagebrush. This study also found a strong relationship (adjusted $R^2=0.81$) between "forage (F)"and the "major axis (MJ)" for low use Wyoming big sagebrush (Table 7). However, this variable was not a reliable predictor of forage for other subspecies of big sagebrush. Adjusted R^2 values ranged from a high value of adjusted $R^2=0.81$ for low use Wyoming big sagebrush (Table 7) to a low value of adjusted R^2 $=0.48$ for high use mountain big sagebrush (Table 6). Adjusted R^2 values for prediction equations with this single variable were consistently low for plants in the high use form classes (Tables 6, 8, 10).

Average cover (AC) was also considered in a single variable model and found to be reliable for all subspecies and form classes.This variable is well defined, consistent and easy to collect. Adjusted R^2 values range from 0.61 for high use Wyoming big sagebrush (Table 8) to adjusted $R^2=0.84$ for high use basin big sagebrush (Table 10). Weaver (1986) speculated that a strong relationship between shrub cover and browse mass would allow a wildlife manager to use aerial photographs to estimate available browse. Our study suggests that line intercept canopy cover (Canfield 1941) may be used to estimate annual winter forage production for big sagebrush subspecies from aerial photographs. Further study is required to develop a technique to apply these findings. This may involve reading intercepts directly from a photograph.

It is important to remember that regression models are merely useful approximations. The true relationships and important variables may be difficult if not impossible to identify. Models must then be based on variables that can be measured easily and accurately. The data examined in this study have shown that several easily measured variables can be used in different regression equations to accurately predict annual winter forage production for 3 subspecies of big sagebrush in both low and high use form classes.

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APPENDICES

APPENDIX A

SIMPLE STATISTICS FOR EACH SITE

Table 11. Simple statistics for low use mountain big sagebrush (ATVL).

Variable	Minimum	Maximum	Range	Mean
MJ	22.860	182.880	160.020	86.868
MN	10.160	132.080	121.920	54.568
HT	30.480	86.360	55.880	62.907
AC	14.605	112.395	97.790	42.037
CD	11.853	26.670	14.817	17.685
HT^2	929.030	7458.050	6529.019	4239.884
E	182.415	18971.172	18788.757	4658.806
CV	2780.006	505961.167	503181.161	91567.065
SV	5560.013	1614257.058	1608697.045	344278.590
C1	410.434	26267.777	25857.343	7300.996
C2	81.073	13701.402	13620.329	3059.971
AS	0.124	1.940	1.816	0.375
F	6.000	364.090	358.090	71.197
Ln(F)	1.792	5.897	4.106	3.799

Variable	Variance	Std Dev	Std Error
MJ	1810.185	42.546	7.768
MN	950.107	30.824	5.628
HT	292.295	17.097	3.121
AC	541.626	23.273	4.249
CD	11.672	3.416	0.624
HT^2	4233013.843	2057.429	375.633
E	21397644.711	4625.759	844.544
CV	11426524665	106894.923	19516.254
SV	150109490664	387439.661	70736.481
C1	45145666.906	6719.053	1226.726
C2	10623998.372	3259.448	595.091
AS	0.139	0.373	0.068
F	6084.985	78.006	14.242
Ln(F)	1.025	1.013	0.185

Variable abbreviations; F-Forage(g), MJ-Major axis(cm), MN-Minor axis (cm), HT-Height (cm), AC-Average cover (cm), CD-Crown depth (cm), C1-Circular area1(cm^2), C2-Circular area2 (cm^2), SV-Shrub vol. (cm^3), AS-Average seedhead weight(g), E-Elliptical area (cm^2), CV-Crown volume (cm^3). N=30.

Table 12. Simple statistics for high use mountain big sagebrush (ATVH).

Variable	Minimum	Maximum	Range	Mean
MJ	21.590	135.890	114.300	65.024
MN	12.700	104.140	91.440	41.995
HT	25.400	66.040	40.640	42.460
AC	15.875	68.898	53.023	38.989
CD	9.525	20.743	11.218	14.217
E	215.351	11114.655	10899.303	2481.648
CV	2826.125	128178.459	125352.334	36267.057
SV	7110.896	451699.561	444588.665	115423.196
C1	366.097	14503.269	14137.172	3930.961
C2	126.677	8517.773	8391.095	1704.906
AS	0.000	0.660	0.660	0.193
F	8.250	123.280	115.030	44.748
Ln(F)	2.110	4.814	2.704	3.550

Variable	Variance	Std Dev	Std Error
MJ	803.714	28.350	5.176
MN	421.238	20.524	3.747
HT	120.877	10.994	2.007
AC	209.513	14.475	2.643
CD	9.568	3.093	0.565
E	5358858.849	2314.921	422.645
CV	1151734906.400	33937.220	6196.060
SV	14880940062.000	121987.459	22271.761
C1	12598287.242	3549.407	648.030
C2	3293926.227	1814.918	331.357
AS	0.023	0.152	0.028
F	981.887	31.335	5.721
Ln(F)	0.569	0.754	0.138

Variable abbreviations; F-Forage(g), MJ-Major axis(cm), MN-Minor axis (cm), HT-Height (cm), AC-Average cover (cm), CD-Crown depth (cm), C1-Circular area1(cm^2), C2-Circular area2 (cm^2), SV-Shrub vol. (cm^3), AS-Average seedhead weight(g), E-Elliptical area (cm^2), CV-Crown volume (cm^3). N=30.

Table 13. Simple statistics for low use Wyoming big sagebrush (ATWL).

Variable	Minimum	Maximum	Range	Mean
MJ	35.560	127.000	91.440	72.856
MN	25.400	101.600	76.200	54.102
HT	20.320	73.660	53.340	50.927
AC	18.415	79.692	61.277	43.487
CD	9.652	24.130	14.478	15.560
E	851.271	10134.173	9282.903	3410.234
CV	8803.354	147294.579	138491.225	54774.570
SV	18533.376	617779.203	599245.827	187751.144
C1	993.149	12667.717	11674.568	4581.533
C2	506.709	8107.339	7600.630	2618.924
AS	0.000	0.231	0.231	0.085
F	6.000	84.600	78.600	35.685
Ln(F)	1.792	4.438	2.646	3.372

Variable	Variance	Std Dev	Std Error
MJ	543.545	23.314	4.257
MN	421.534	20.531	3.748
HT	180.350	13.429	2.452
AC	260.953	16.154	2.949
CD	13.194	3.632	0.663
E	5141431.812	2267.473	413.982
CV	1511613175.300	38879.470	7098.388
SV	20864962072.000	144447.091	26372.310
C1	8185633.829	2861.055	522.355
C2	3838200.390	1959.133	357.687
AS	0.003	0.051	0.009
F	465.973	21.586	3.941
Ln(F)	0.472	0.687	0.125

Variable abbreviations; F-Forage(g), MJ-Major axis(cm), MN-Minor axis (cm), HT-Height (cm), AC-Average cover (cm), CD-Crown depth (cm), C1-Circular area1(cm^2), C2-Circular area2 (cm^2), SV-Shrub vol. (cm^3), AS-Average seedhead weight (g), E-Elliptical area (cm^2), CV-Crown volume (cm^3). N=30.

Table 14. Simple statistics for high use Wyoming big sagebrush (ATWH).

Variable	Minimum	Maximum	Range	Mean
MJ	22.860	93.980	71.120	59.605
MN	15.240	66.040	50.800	38.777
HT	15.240	55.880	40.640	36.745
AC	13.335	56.515	43.180	30.586
CD	3.810	15.240	11.430	7.382
E	334.428	4611.049	4276.621	1978.866
CV	1853.338	44910.342	43057.004	14786.432
SV	5096.678	210817.153	205720.475	80164.788
C1	410.434	6936.842	6526.408	3111.529
C2	182.415	3425.351	3242.935	1323.861
AS	0.000	0.600	0.600	0.129
F	3.550	60.540	56.990	25.335
Ln(F)	1.267	4.103	2.836	3.050

Variable	Variance	Std Dev	Std Error
MJ	423.017	20.567	3.755
MN	188.179	13.718	2.505
HT	103.441	10.171	1.857
AC	92.855	9.636	1.759
CD	4.566	2.137	0.390
E	1477730.225	1215.619	221.941
CV	99284818.814	9964.177	1819.201
SV	3712485688.400	60930.171	11124.276
C1	3781880.513	1944.706	355.053
C2	805581.344	897.542	163.868
AS	0.018	0.133	0.024
F	210.873	14.521	2.651
Ln(F)	0.430	0.656	0.120

Variable abbreviations; F-Forage(g), MJ-Major axis(cm), MN-Minor axis (cm), HT-Height (cm), AC-Average cover (cm), CD-Crown depth (cm), C1-Circular area1(cm^2), C2-Circular area2 (cm^2), SV-Shrub vol. (cm^3), AS-Average seedhead weight(g), E-Elliptical area (cm^2), CV-Crown volume (cm^3). N=30.

Table 15. Simple statistics for low use basin big sagebrush (ATTL).

Variable	Minimum	Maximum	Range	Mean
MJ	27.940	205.740	177.800	102.574
MN	25.400	149.860	124.460	70.019
HT	43.180	139.700	96.520	93.895
AC	23.495	95.885	72.390	56.780
CD	11.853	35.560	23.707	22.217
E	557.380	24215.607	23658.228	6391.708
CV	6606.805	599699.509	593092.703	146200.804
SV	24067.648	3013874.454	2989806.806	672828.693
C1	613.117	33245.155	32632.038	9391.381
C2	506.709	17638.529	17131.820	4517.646
AS	0.000	1.180	1.180	0.320
F	14.100	290.460	276.360	101.563
Ln(F)	2.646	5.671	3.025	4.359

Variable	Variance	Std Dev	Std Error
MJ	1485.613	38.544	7.037
MN	878.612	29.641	5.412
HT	514.563	22.684	4.142
AC	396.016	19.900	3.633
CD	20.095	4.483	0.818
E	26130377.940	5111.788	933.281
CV	15661259659	125144.955	22848.238
SV	427007895455	653458.411	119304.637
C1	50500695.728	7106.384	1297.442
C2	15349985.738	3917.906	715.308
AS	0.072	0.269	0.049
F	5459.109	73.886	13.490
Ln(F)	0.577	0.760	0.139

Variable abbreviations; F-Forage(g), MJ-Major axis(cm), MN-Minor axis (cm), HT-Height (cm), AC-Average cover (cm), CD-Crown depth (cm), C1-Circular area1(cm^2), C2-Circular area2 (cm^2), SV-Shrub vol. (cm^3), AS-Average seedhead weight(g), E-Elliptical area (cm^2), CV-Crown volume (cm^3). N=30.

Table 16. Simple statistics for high use basin big sagebrush (ATTH).

Variable	Minimum	Maximum	Range	Mean
MJ	25.400	144.780	119.380	84.159
MN	20.320	96.520	76.200	53.763
HT	45.720	129.540	83.820	79.968
AC	19.050	84.455	65.405	44.429
CD	7.239	27.093	19.854	16.294
E	405.367	9964.426	9559.059	3985.348
CV	10982.741	245865.091	234882.350	61383.257
SV	26770.432	1151588.699	1124818.267	343939.026
C1	506.709	16462.964	15956.256	6216.302
C2	324.294	7316.873	6992.580	2661.149
AS	0.000	0.890	0.890	0.147
F	19.180	191.820	172.640	69.943
Ln(F)	2.954	5.257	2.303	4.082

Variable	Variance	Std Dev	Std Error
MJ	860.836	29.340	5.357
MN	514.941	22.692	4.143
HT	468.462	21.644	3.952
AC	239.161	15.465	2.823
CD	34.654	5.887	1.075
E	7514557.734	2741.269	500.485
CV	2551531520.8	50512.687	9222.313
SV	87862201339	296415.589	54117.835
C1	15903121.177	3987.872	728.082
C2	4441533.149	2107.495	384.774
AS	0.035	0.188	0.034
F	1723.393	41.514	7.579
Ln(F)	0.350	0.591	0.108

Variable abbreviations; F-Forage(g), MJ-Major axis(cm), MN-Minor axis (cm), HT-Height (cm), AC-Average cover (cm), CD-Crown depth (cm), C1-Circular area1(cm^2), C2-Circular area2 (cm^2), SV-Shrub vol. (cm^3), AS-Average seedhead weight (g), E-Elliptical area (cm^2), CV-Crown volume (cm^3). N=30.

APPENDIX B

SCATTER DIAGRAMS FOR EACH TAXON

```
                MJ vs MN

  200 +
      |                    A A
MJ    |
      |            A  A
      |              D A
  100 +      AB     A
      |      BBA AA
      |    B  B
      |  AAA A
      |  B
    0 +
      -+-------+-------+-------+
       0      50     100     150

                 MN
```

```
               E vs MN²

  20000 +
        |                  A   A
E       |
        |
        |
  10000 +        A
        |      ACA A
        |      A
        |  BAA A
        | BH
      0 +DA
       -+----------+----------+
        0         10000    20000

                 MN²
```

~ ~

```
                 E vs MJ²

  20000 +
        |                  B
E       |
        |
        |
  10000 +           A
        |       AACA
        |     A
        |    CB
        | CBBBA
      0 +BC
       -+----------+----------+
        0         20000    40000

                  MJ²
```

```
              E vs (MJ x MN)

  20000 +
        |               A A
E       |
        |
        |
  10000 +        A
        |       EA
        |     A
        |   DA
        | CEB
      0 +CB
       -+------+------+------+-
        0    10000  20000 30000

               MJ x MN
```

Variable abbreviations: MJ-Major axis (cm), MN-Minor axis (cm), E - Elliptical area (cm^2), For data points: A=1, B=2, C=3, etc. N=30.

Figure 3. Scatter diagrams for low use mountain big sagebrush (ATVL) showing linear relationships among variables as indicated by colinearity analysis.

```
                MJ vs MN

MJ    |
  150 +
      |       A         A
      |           A
  100 +      A    A  A
      |      AA A
      |    ABB B A
   50 +    BA A A
      |  A CBA
      |  A
    0 +
      -+-------+-------+-------+
       0      50     100     150

                MN
```

```
               E vs MN²

E       |
  15000 +
        |
        |               A
  10000 +
        |
        |       A  A
   5000 +   A   A
        |  B AB
        | GFAB
      0 +BB
        -+------+------+------+-
         0   5000   10000 15000

                MN²
```

```
~ ~ ~ ~ ~ ~ ~ ~ ~ ~ ~ ~ ~ ~ ~ ~ ~ ~ ~ ~ ~ ~ ~ ~ ~ ~ ~ ~ ~ ~ ~ ~ ~ ~ ~ ~
```

```
                E vs MJ²

E       |
  15000 +
        |
        |                    A
  10000 +
        |
        |          A   A
   5000 +            A     A
        |    AAAA  A
        | ADDDBA
      0 + CA
        -+----------+----------+
         0        10000    20000

                 MJ²
```

```
                E vs (MJ x MN)

E       |
  15000 +
        |
        |                    A
  10000 +
        |
        |           B
   5000 +        A A
        |    ACA
        |  IDC
      0 +AC
        -+------+------+------+-
         0   5000   10000 15000

              (MJ x MN)
```

Variable abbreviations: MJ-Major axis (cm), MN-Minor axis (cm), E - Elliptical area (cm²), For data points: A=1, B=2, C=3, etc. N=30.

Figure 4. Scatter diagrams for high use mountain big sagebrush (ATVH) showing linear relationships among variables as indicated by colinearity analysis.

```
                 MJ vs MN

      |
  150 +
MJ    |                A
      |          A  A
  100 +               A
      |      AA AD   BA
      |       B CA
   50 +    ADAB
      |     B
      |
    0 +
      -+-------+-------+-------+
       0      50      100    150

                 MN
```

```
               E vs MN²

  10000 +              A
E       |
        |
        |          AA
        |     A    B
   5000 +         A
        |    CA
        |  ACB
        | CC
        | EB
      0 +
        -+------+------+------+-
         0    5000  10000 15000

                  MN²
```

```
~ ~ ~ ~ ~ ~ ~ ~ ~ ~ ~ ~ ~ ~ ~ ~ ~ ~ ~ ~ ~ ~ ~ ~ ~ ~ ~ ~ ~ ~ ~ ~ ~ ~ ~
```

```
                      E vs MJ²

  10000 +                  A
        |
E       |
        |            A A
        |         B    A
   5000 +        A
        |       BB
        |     AD   A
        |   C AAA
        | AEA
      0 +
        -+----------+----------+
         0        10000     20000

                  MJ²
```

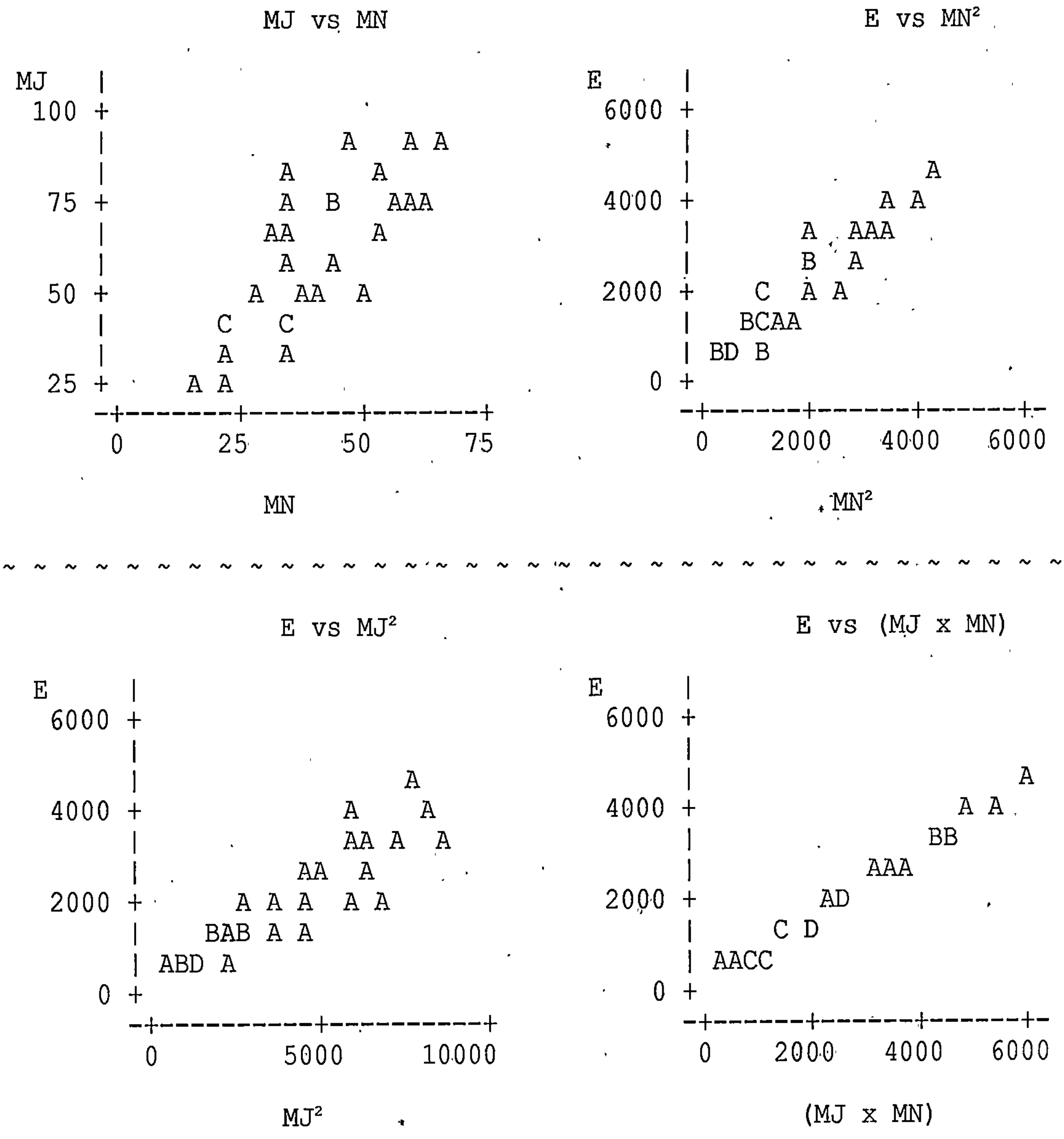
```
                 E vs (MJ x MN)

  10000 +                  A
        |
E       |
        |             B
        |          BA
   5000 +         A
        |       CA
        |     BD
        |   BD
        |  G
      0 +
        -+------+------+------+-
         0    5000  10000 15000

               (MJ x MN)
```

Variable abbreviations: MJ-Major axis (cm), MN-Minor axis (cm), E - Elliptical area (cm^2), For data points: A=1, B=2, C=3, etc. N=30.

Figure 5. Scatter diagrams for low use Wyoming big sagebrush (ATWL) showing linear relationships among variables as indicated by colinearity analysis.



Variable abbreviations: MJ-Major axis (cm), MN-Minor axis (cm), E - Elliptical area (cm²), For data points: A=1, B=2, C=3, etc. N=30.

Figure 6. Scatter diagrams for high use Wyoming big sagebrush (ATWH) showing linear relationships among variables as indicated by colinearity analysis.

MJ vs MN

```
  200 +                        A
      |               A
MJ    |                   A
      |       A      A AAAA
      |         A    A
  100 +      A  AA BA
      |       C CB
      |       BAA
      |
      |    A
    0 +
      -+-------+-------+-------+
       0      50      100    150
```

MN

E vs MN^2

```
        |
  30000 +
E       |
        |                A
  20000 +
        |
        |      A AAB
  10000 +     A A
        |  A BAA
        | GFC
      0 +A
        -+------+------+------+-
         0    10000  20000 30000
```

MN^2

~ ~

E vs MJ^2

```
E       |
  30000 +
        |
        |               A
  20000 +
        |
        |      ABA A
  10000 +      AA
        |   BAB
        | CGE  A
      0 +A
        -+------+------+------+-
         0    20000  40000 60000
```

MJ^2

E vs (MJ x MN)

```
E       |
  30000 +
        |
        |                 A
  20000 +
        |
        |        BBA
  10000 +      A A
        |    CAA
        | AJE
      0 +A
        -+----------+----------+
         0        20000    40000
```

(MJ x MN)

Variable abbreviations: MJ-Major axis (cm), MN-Minor axis (cm), E - Elliptical area (cm^2), For data points: A=1, B=2, C=3, etc. N=30.

Figure 7. Scatter diagrams for low use basin big sagebrush (ATTL) showing linear relationships among variables as indicated by colinearity analysis.

```
                 MJ vs MN                               E vs MN²

       |                               10000 +                 A
   150 +                     A               |                   AA
MJ     |                  A          E       |             AA   A
       |               A   A  AB             |                A
   100 +            AA A     A               |        A
       |       A CAAA B                 5000 +         A
       |    A   A AAA                        |      BA B
    50 +    A   A                            |    BCAA
       |    AAA                              |  AAA
       |                                     | CAA
     0 +                                   0 + A
      -+-----------+-----------+            -+----------+----------+
       0          50         100             0        5000     10000

                 MN                                   MN²

~ ~ ~ ~ ~ ~ ~ ~ ~ ~ ~ ~ ~ ~ ~ ~ ~ ~ ~ ~ ~ ~ ~ ~ ~ ~ ~ ~ ~ ~ ~ ~ ~ ~ ~ ~

                  E vs MJ²                     E vs (MJ x MN)

   10000 +               A             10000 +                  A
         |         AA                        |               B
E        |         A A A             E       |              BA
         |       A                           |            A
         |          A                        |          A
    5000 +      A                       5000 +        A
         |     CA A                          |      ACA
         |   ADAA                            |    AF
         |   AAA                             |   AB
         | BC                                | AD
       0 +A                                0 + A
         -+------+------+------+-            -+------+------+------+-
          0    10000  20000 30000             0    5000  10000 15000

                   MJ²                            (MJ x MN)
```

Variable abbreviations: MJ-Major axis (cm), MN-Minor axis (cm), E - Elliptical area (cm²), For data points: A=1, B=2, C=3, etc. N=30.

Figure 8. Scatter diagrams for high use basin big sagebrush (ATTH) showing linear relationships among variables as indicated by colinearity analysis.

APPENDIX C

PLANT SPECIES ON THE STUDY AREA

Table 17. Plant species identified on the Gardiner study area[1].

Graminoids

Agropyron cristatum *
A. smithii *
A. spicatum *
A. subsecundum *
A. trachycaulum *
Agrostis exarata *
A. stolonifera *
Bouteloua gracilis *
Bromus anomalus
B. inermis *
B. japonicus *
B. marginatus *
B. tectorum *
Calamagrostis canadensis
C. rubescens *
Carex festivella
C. filifolia *
C. geyeri *
Danthonia intermedia *
Distichlis stricta *
Elymus cinereus *
Festuca idahoensis *
Hordeum jubatum *
Juncus balticus *
Koeleria pyramidata *
Lolium perenne
Melica spectabilis *
Oryzopsis hymenoides *
Phleum pratense *
Poa ampla
P. cusickii
P. fendleriana
P. junctifolia
P. pratensis *
P. sandbergii *
Sitanion hystrix *
Stipa columbiana *
S. comata *
Trisetum spicatum *

Forbs, Ferns, Mosses, Vines, and Cactus

Achillia millifolium *
Actaea rubra
Agroseris glauca *
Allium brevistylum
A. textile *
Antennaria dimorpha
A. rosea *
A. umbrinella
Arabis holboellii
Arenaria congesta *
Arnica cordifolia *
Artemisia dracunculus
Aster canescens *
A. conspicuus
A. scopulorum
Astragalus cibarius
A. gilviflorus
A. miser
A. purshii
Balsamorhiza sagittata *
Campanula uniflora
Castelleja angustifolia
Cerastium arvense *
Cirsium arvense *
C. foliosum
Clematis columbiana
C. hirsutissima
Collinsia parviflora
Camandra pallida
Crepis acuminata
Delphinium bicolor *
D. occidentale *
Dodecatheon conjugans
Draba paysonii
Epilobium angustifolium
Equisetum arvense *
Erigeron compositus
E. corymbosus
E. glabellus
E. gracilis
E. ochroleucus
E. pumilus

Table 17. (Continued).

Eriogonum heracleoides *
E. ovalifolium
E. umbellatum
Erysimum asperum
Fragaria vesca
F. virginiana
Frasera speciosa
Frittilaria atropurpurea
F. pudica
Geranium richardsonii *
G. viscosissium *
Geum triflorum *
Grindelia squarrosa *
Haplopappus acaulis
Helanthella uniflora
Heracleum lanatum
Heterotheca villosa *
Hieracium cynoglossoides
Lathyrus bijugatus
Lesquerella alpina
Lewisia rediviva
Linaria dalmatica *
Linium lewisii
Lithospermin incisum
L. ruderale
Lomatium macrocarpum
L. triternatum
Lupinus sericeus *
Medicago sativa *
Meliotus officinalis
Mentha arvensis *
Mentzelia laevicaulis
Mertensia ciliata
Monotropa hypopithys
Myosotis alpestris
Oenothera caespitosa
Opuntia polycantha *
Oxytropis sericea *
Paronchia sessiliflora
Penstemon cyaneus
Phacelia sericea
Phlox caespitosa *
P. hoodii *
Plantago patagonica *
Polygonum bistoriodes
Potentillia glandulosa
P. gracillis
Peteridium aquilinum
Sedum stenopetalum *
Selagimella densa *
Senecio canus
S. serra
Sisymbrium altissium
Smilacina racemosa
S. stellata
Solidago canadensis *
Sphaeralcea coccinea *
Taraxacon officinale *
Thalictrum occidentale
Townsendia parryi
Tragopogon dubius
Trifolium haydenii
Viola adunca
V. purpurea
Zigadenus paniculatus *

Table 17. (Continued).

Shrubs, Half-Shrubs, and Trees

Abies lasiocarpa *
Acer glabrum *
Alnus tenuifolia *
Amelanchier alnifolia *
Arctostaphylos uva-ursi *
Artemisia frigida *
A. nova *
A. tridentata subsp. tridentata *
A. tridentata subsp. vaseyana *
A. tridentata subsp. wyomingensis *
Berberis repens *
Betula occidentalis *
Ceanothus velutinus *
Ceratoides lanata *
Chrysothamnus nauseosus *
C. viscidiflorus *
Cornus stolonifera *
Grayia spinosa *
Juniperus horizontalis *
J. scopulorum *
Leptodactylon pungens *
Physocarpus malvaceus *
Picea englmannii *
Pinus albicus
P. contorta *
P. flexilis *
Populus angustifolia *
P. tremuloides *
Prunus virginiana *
Pseudotsuga menziesii *
Rhus trilobata *
Ribes cereum *
R. setosum *
R. viscossissimum *
Rosa woodsii *
Rubus idaeus
R. parviflorus
Salix spp. *
Sambucus melanocarpa *
Sarcobatus vermiculatus*
Shepherdia canadensis
Symphoricarpos albus *
S. occidentalis *
Tetradymia canescens *
Vaccinium membranaceum
V. scoparium
Xanthocephalum sarothrae

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[1] Plants identified by McNeal (1984).
* Plants observed in 1989.