



GIS modeling of bison habitat in southwestern Montana : a study in ranch management and conservation
by Linda Bowers Phillips

A thesis submitted in partial fulfillment Of the requirements for the degree of Master of Science in Earth Sciences
Montana State University
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Abstract:

Since the near extinction of American bison (*Bison bison*) at the turn of the century free-ranging herds exist in only a few locations. However, bison ranching has become increasingly common on fenced private lands. An example, is a privately owned bison ranch located in southwestern Montana that maintains their herd using a minimal management approach. The ranch manager's intent is to allow the bison operation to be largely defined by natural processes. Selective range utilization by bison, however, has affected range quality resulting in overutilization and underutilization. The objectives of this research were to determine if biophysical differences existed between areas of bison overutilization and underutilization, and to provide ranch managers with information regarding whether more intensive management could alleviate impacts associated with differential bison utilization. The methods employed were to (1) determine and collect data regarding bison utilization, (2) to develop a database of biophysical variables that could be measured and that might influence bison habitat selection, (3) to perform an exploratory data analysis using Classification and regression tree analysis, (4) to analyze nutritional, physical environmental, and behavioral variables independently using Bayesian probability analysis, and (5) to model the results of the analysis geographically for the ranch. Classification and regression tree analysis and Bayesian probability analysis were used to identify differences in biophysical variables and to produce bison habitat use models. Of the 14 variables studied, significant differences existed in areas underutilized and overutilized for 5 nutritional variables (forage type, forage productivity, soil mineralogy, soil pH, and soil salinity), 3 physical environmental variables (elevation, slope, and surface soil texture), and 2 behavioral variables (nearest neighbor distance and viewshed). The digital database, analysis and results were intended to provide ranch managers with information regarding the characteristics of the sites utilized and not utilized by bison throughout the ranch.

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APPROVAL

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Linda Bowers Phillips

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.

Dr. Richard Aspinall

Richard Aspinall

4-17-00

Chairperson, Graduate Committee

Date

Approved for the Department of Earth Sciences

Dr. James Schmitt

James Schmitt
Head, Major Department

4-17-00

Date

Approved for the College of Graduate Studies

Dr. Bruce R. McLeod

Bruce R. McLeod
Graduate Dean

4-24-00

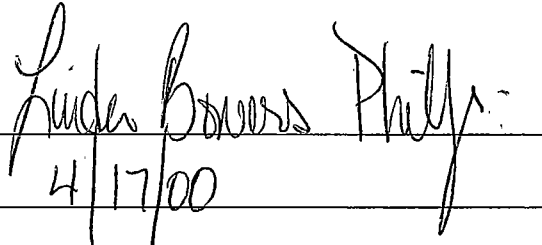
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ABSTRACT

Since the near extinction of American bison (*Bison bison*) at the turn of the century free-ranging herds exist in only a few locations. However, bison ranching has become increasingly common on fenced private lands. An example, is a privately owned bison ranch located in southwestern Montana that maintains their herd using a minimal management approach. The ranch manager's intent is to allow the bison operation to be largely defined by natural processes. Selective range utilization by bison, however, has affected range quality resulting in overutilization and underutilization. The objectives of this research were to determine if biophysical differences existed between areas of bison overutilization and underutilization, and to provide ranch managers with information regarding whether more intensive management could alleviate impacts associated with differential bison utilization. The methods employed were to (1) determine and collect data regarding bison utilization, (2) to develop a database of biophysical variables that could be measured and that might influence bison habitat selection, (3) to perform an exploratory data analysis using Classification and regression tree analysis, (4) to analyze nutritional, physical environmental, and behavioral variables independently using Bayesian probability analysis, and (5) to model the results of the analysis geographically for the ranch. Classification and regression tree analysis and Bayesian probability analysis were used to identify differences in biophysical variables and to produce bison habitat use models. Of the 14 variables studied, significant differences existed in areas underutilized and overutilized for 5 nutritional variables (forage type, forage productivity, soil mineralogy, soil pH, and soil salinity), 3 physical environmental variables (elevation, slope, and surface soil texture), and 2 behavioral variables (nearest neighbor distance and viewshed). The digital database, analysis and results were intended to provide ranch managers with information regarding the characteristics of the sites utilized and not utilized by bison throughout the ranch.

Chapter 1

INTRODUCTION

American bison (*Bison bison*) historically occupied a variety of habitats from prairies to upland mountains (Roe 1972). Since their near extinction at the turn of the century, however, free-ranging herds exist on just a few locations in the U.S. and Canada. Cattle have been introduced and have occupied most historical bison rangelands, except where bison populations have since been restored on public and private lands. Bison herds on private lands are managed on fenced ranges. While efforts to sustain bison populations have been successful, having this species on fenced ranges can create ecological problems associated with overgrazing, overrest, overuse, bison-elk conflict, bison health, and noxious weeds (Sindelar and Ayers 1999).

In 1989 the Flying D Ranch (FDR), a 53,825 ha (133,000 acre) ranch located in southwestern Montana, began bison ranching using a minimal management approach. This approach included the removal of internal fences, allowing bison to range freely within the confines of the fenced FDR exterior boundary (pers comm Bud Griffith, FDR manager). The intent was to allow the bison operation to be largely defined by natural processes. Over the years, FDR personnel and range habitat assessors observed that bison utilized certain areas of the FDR intensively, while other areas were unutilized. This

pattern of use has affected range quality, resulting in poor habitat where parts of the FDR were being overgrazed and less than ideal habitat in areas characterized by severe underutilization (Sindelar 1997). Recently, FDR managers have questioned whether more intensive management could promote a more widespread distribution of bison on the range and thus alleviate problems resulting from this selective grazing behavior.

Objectives

The overall objective of this research was to determine if Geographic Information Systems (GIS) are useful for ranch management activities on the FDR. The first part of the research entailed a GIS User Needs Assessment (Aspinall and Phillips 1998). The assessment and discussions with ranch employees indicated the need to explore the geography of bison habitat of the FDR bison herd. The specific objectives of the bison investigation were:

- (a) to identify biophysical differences, if any, between areas receiving different levels of utilization; and
- (b) to explore the physical geography of bison habitat so to better understand how management might result in better bison distribution on the FDR.

GIS and spatial analysis techniques allow quantitative analysis of spatial use patterns over large areas (Herr and Queen 1993, Hepinstall *et al.* 1996, Bian and West 1997, Pearson *et al.* 1995, Turner *et al.* 1994). These techniques were used to assess bison habitat requirements and apply this knowledge to understanding bison spatial patterns of use to facilitate management and conservation of bison rangeland for the FDR.

Bison habitat use has been studied extensively (Reynolds *et al.* 1978, Meagher and Shaw 1999, Meagher 1973), and reliable knowledge of habitat requirements is necessary for development of successful conservation and management strategies (Otis 1998). Two general approaches to study habitat use by wildlife have been used, depending on the objectives and data availability (Stoms *et al.* 1992). The first, a deductive approach, determines geographic areas used by a species based on rules applied to biophysical characteristics of an area. These rules are derived from known general relationships and data overlay techniques, and the approach is ultimately descriptive (Aspinall 1992). The second, an inductive approach, is used when specific biophysical characteristics are not known, and a GIS and spatial analysis are used to induce the characteristics from known animal species' locations. More recently the inductive approach has been used for wildlife habitat studies (Aspinall 1992, Walker and Moore 1998).

Habitat Variable Selection

Based on previous literature and discussions with bison ecologists, biophysical variables that were directly or indirectly associated with bison habitat selection were identified and a digital database was created. While many aspects of bison ecology have been studied, bison research conducted in other geographic areas or research conducted on herds subject to different management strategies does not necessarily apply to the FDR. As a result, this research employs the inductive approach to habitat variable selection to account for differences in habitat requirements from one geographic area to another.

Knowledge of bison ecology allows for an investigation of bison habitat selection on a specific study area, incorporating biophysical variables.

Previous Literature

Male and female bison select similar foraging sites (Larter and Gates 1991), however the composition of their diets shows significant differences. This suggests that males and females use their habitat in different ways, choosing different plants or plant parts, the females being more selective than the males (Larter 1988).

Male and female bison repeat similar movements between summer and winter ranges (Meagher 1986, Van Vuren 1983), using mostly open rangelands and sometimes using wooded areas when available (Fuller 1960, McHugh 1958). Bison are large mammals, females averaging 1760 kg and males averaging 4400 kg (Meagher 1973), requiring large quantities of forage (Houston 1982). Bison have adapted to a diet of low quality and high quantity forage (Houston 1982). They are generalist foragers and eat grasses and sedges proportionate to their availability in some habitats (Reynolds *et al.* 1978). The diet of bison in the Henry Mountains, Utah consisted of approximately 90% grasses and sedges, 5% forbs, and 1% browse (VanVuren 1979). The food habits in the Yellowstone National Park bison herd were found by Meagher (1973) to be similar to those in the Henry Mountains. Grasses and grass-like plants composed 91-99% of their diet, sedges constituted more than half of the main food source for all seasons, forbs constituted 3% and browse constituted 1% of their diet (Meagher 1973). It has been suggested that soil

salinity and soil pH (pers comm Dennis Cash) might influence plant absorption of minerals that subsequently become available to bison during digestion.

Bison are strongly attracted to recently burned areas (Shaw and Carter 1990, Turner *et al.* 1994), possibly resulting from the short-term increase in forage quality (Coppock *et al.* 1986) and quantity (Wallace *et al.* 1995). When bison were allowed access to an area that was previously unavailable and recently burned, females over two years old tend to consistently move on to the area in winter and repeat that movement in subsequent years (Shaw and Carter 1990).

Since cattle replaced bison throughout much of North America over the last century, comparative studies between domestic cattle and bison have been conducted. In the shortgrass plains of Colorado, cattle prefer foraging in swales and shallow depressions, whereas bison prefer foraging in upland areas (Peden *et al.* 1974). Bison spent an average of 1.9 days at any location in the Henry Mountains, Utah (Van Vuren 1981). The foraging behavior resulted in a more uniform distribution of grazing pressure by bison than by cattle in the Henry Mountains.

In the Henry Mountains of Utah, bison have been observed grazing at elevations greater than 3080 m, frequently at elevations up to 3260 m, and almost half of all bison observations were recorded above 3000 m (Van Vuren 1979). In another study, bison typically spent summer months at elevations of 2500-3500 m and spent winter months at elevations of 1700-2100 m (Van Vuren and Bray 1986). Comparative studies have been conducted on bison foraging behavior at various elevations and slopes in the Henry Mountains of Utah (Van Vuren 1983), and bison utilized areas at higher elevations than

cattle. Bison were observed grazing on slopes exceeding 25 degrees frequently, one third of slopes in the area exceeded 25 degrees (Van Vuren 1979) and bison consistently utilized steeper slopes than cattle (Peden *et al.* 1974). Distance to water was not important for bison habitat selection in bison herds in the Henry Mountains of Utah (VanVuren 1983). Bison preferred grazing at a farther distance to a water source than cattle, with only 18% of bison observations located within 200 m of a water source (Van Vuren 1979).

Bison wallows are prevalent in areas of bison use and are often permanent features in the landscape that are used year after year (Meagher 1973). Wallows are created most commonly by bulls, and wallowing increases during the rut (Meagher 1986).

Bison are gregarious animals (Roe 1970), and therefore bison habitat selection studies must incorporate habitat variables that allow bison to maintain required natural behaviors. Bison herds are fluid aggregations. Individuals and juvenile groups change membership frequently and group size varies from a few to hundreds of animals (Van Vuren 1983, Lott and Minta 1983). These mixed groups maintained closer contact in smaller groups than when they are farther from neighboring groups (Green 1992). Non-mother females are more often found in adult groups containing males. These adult groups more often occur before the rut (Komers *et al.* 1993, Fuller 1960, Reynolds *et al.* 1982).

Females appear to have larger home ranges than males, and larger groups are found in more open habitats (Van Vuren 1981) and on more gentle slopes (Rutberg 1984). This may result from a larger foraging area required for the larger number of animals (Larter and Gates 1990).

Forested areas are not used frequently for foraging (Meagher 1973) and wooded areas are used only to seek relief from the sun, during rutting activity, travel, and escape from insects (Robert Garrott pers comm, Meagher 1973). It has been theorized (pers comm Margie Taylor) that more convoluted patch shapes might minimize bison comfort as a result of historic gray wolf (*Canis lupus*) predation of bison (Fuller 1960). Bison are gregarious animals, forming herds according to sex, age, season, foraging conditions and habitat (Meagher 1986). Travel routes are usually well defined in mountainous areas, and travel is usually in a line lead by an adult female (McHugh 1958). Bison principally utilize open areas and prefer to maintain visual contact for communication.

Thesis Structure

The remainder of this thesis is structured with 6 chapters and 4 appendices. Chapter 2 describes the physical geography of the study area. Chapter 3 describes the methodology employed, including the specifics of the biophysical data, and a description and justification of the statistical analysis and sensitivity analysis. Chapter 4 explains the results of the statistical analysis and sensitivity analysis, from both a statistical and geographical perspective. Chapter 5 discusses the inferences drawn from the statistical and sensitivity analysis. Chapter 6 discusses implications of the research for FDR management activities and suggestions for future research.

Chapter 2

STUDY AREA

The research was conducted on the FDR, located in southwestern Montana, southwest of Bozeman, MT (Figure 1). The FDR is 53,825 ha (133,179 acres) in area and supports approximately 3000 bison. The FDR is within the Madison River basin and the Gallatin River basin, north of the Spanish Peak Mountains on the Madison Range, and south of Gallatin Gateway, MT .

The FDR consists of open rangeland, foothills, and mountains ranging in elevation from approximately 1300 m to 2590 m. The lower elevations are found along the Madison River basin and the higher elevations are in the southern portion of the FDR approaching the Spanish Peak Mountains. Slopes range from 0 degrees to 46 degrees with the flatter areas in the northwestern region along the Madison River. Precipitation ranges from 356 mm/year (14 inches/year) in the lower elevations to 1524 mm/year (60 inches/year) in the higher elevation southern region (The Nature Conservancy 1989). Geologically, the lower elevations are on a syncline composed of gently folded sedimentary rocks (The Nature Conservancy 1989). Soils in this region are deep and consist mostly of silty and clayey loams. The mountains in the southern region of the FDR are uplifted metamorphic rocks

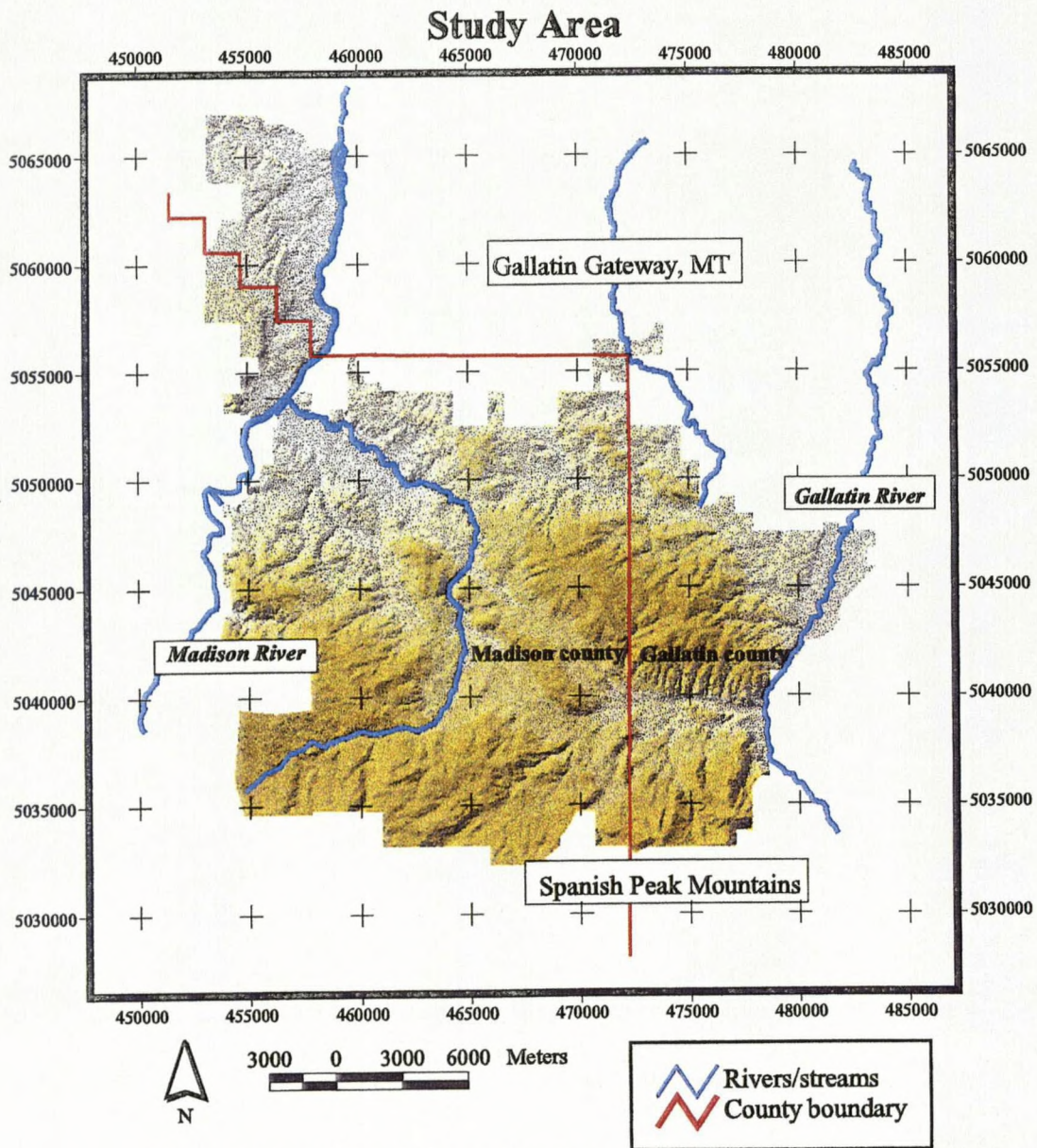
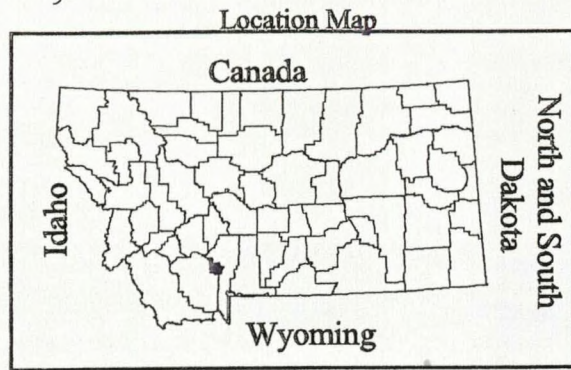


Figure 1. Location of the study area.

with many outcrops (Nature Conservancy 1989). Soils in these upper elevations are shallow and derived from granite and gneiss.

soil pH of the rangelands averaged 7.3, and soil pH of the southeastern and northeastern areas of the FDR is 7.8. The lower elevations along the Madison River and lower Cherry Creek have the highest soil pH levels of 8.4. The mineralogy of the soil within the rangelands is mixed. Areas in the central and southeastern corner are carbonatic while montmorillonitic soils are prevalent in the large basin area in the central region.

The southern portion of the FDR is largely covered by conifer forest. This is predominantly lodgepole pine (*Pinus contorta*), Douglas-fir (*Pseudotsuga menziesii*), and subalpine fir (*Abies lasiocarpa*). The ranch has nine distinct bison foraging areas that have been defined by a range consulting firm (Sindlear and Ayers 1989). Thirteen forage types have been mapped, and documented in the Grazing Plan and Resource Base for the FDR (Sindelar and Ayers 1999). Individual species composition for these forage types is not known, as a consensus view of forage types was employed. These forage types are deep upland bench grass, moist foothills grass, wet meadow grass, dry meadow grass, improved pasture, basin timothy, dry foothills grass, shallow upland bench grass, moist mountain browse, dry mountain browse, aspen woodland, willow riparian, and conifer forest.

Chapter 3

METHODS

Database Development

A database was developed to analyze variables that could reasonably be measured and related to bison range utilization. The landscape variables were represented in the database by biophysical variables that were collected and converted to digital format, acquired in digital format, or derived in a GIS from an existing spatial dataset.

The database consisted of 14 biophysical variables and one response variable. These variables representing the biophysical landscape, were grouped into three categories: 1) nutritional variables, 2) physical environmental variables, and 3) social/behavioral variables. The response variable was the level of bison utilization. Database details regarding data source, method of derivation, and data values are provided in Appendix A.

Biophysical Variable Selection/Representation

Nutritional Variables. Nutritional variables were included because they contribute calories and minerals to bison through forage and soils. The 5 nutritional variables selected based on previous literature included:

- (1) forage productivity (forage quantity and species composition),

- (2) forage type (forage quality),
- (3) soil mineralogy (trace minerals),
- (4) soil pH (potential mineral absorption), and
- (5) soil salinity (potential mineral absorption).

Forage productivity represented the forage quantity and forage type represented forage quality and species composition. Soil salinity and soil pH were included because they dictate plant composition and might influence mineral absorption through plants during digestion. The FDR bison herd might be deficient in trace minerals so the herd is supplemented with mineral blocks (pers comm Bud Griffith). Therefore mineralogy was included to represent availability of trace minerals.

Physical Environmental Variables. Physical environmental variables were included because they can limit bison utilization (i.e., physical barriers) of range. The 4 physical environmental variables were chosen based on previous literature and included:

- (6) distance from water,
- (7) elevation,
- (8) slope, and
- (9) surface soil texture.

Distance to water is important during the summer months. Bison do not obtain sufficient amounts of water from vegetation in the summer months and, thus must have drinking water available (pers comm Mary Meagher). Bison use of habitat as it relates to elevation and slope has not been studied for the FDR bison herd, so elevation and slope

were included as potential contributors to bison habitat selection. The creation of wallows has been noted (Meagher 1986, Meagher 1973), although research on wallowing has not been extensively studied. Surface soil texture was included as a measure of potential for bison to create wallows; relationships between wallow sites and soil texture have not previously been reported.

Social/Behavioral Variables. Biophysical variables representing aspects of bison social behavior were included in the study. Five datasets representing bison social behavior attempted to incorporate bison behavior with digital landscape representation. These 5 datasets based on previous literature included:

- (10) nearest neighbor distance (forage area connectivity),
- (11) patch area (forage area size),
- (12) patch shape (forage area shape),
- (13) proximity (forage area connectivity), and
- (14) viewshed (visual contact).

Four of these datasets were generated by performing a spatial pattern analysis of the FDR. The spatial objects (patches) in this research were the generalized vegetation types: wet grassland, dry grassland, riparian vegetation, conifer forest and non-vegetation.

Patch connectivity was addressed due to the need for an appropriate level of comfort for animals traveling from patch to patch. Nearest neighbor distance and proximity were included to represent the connectivity of patches as foraging areas that are insufficiently connected within the landscape since these might influence bison utilization of these

areas. Nearest neighbor distance indicates the similarity of forage types next to, and adjacent to, one another. Proximity indicates the similarity of forage types at a smaller scale, and incorporates the size of the neighboring forage patch. The size of foraging areas is represented by patch area, as the size of foraging areas is potentially important due to the social group requirements of bison. Areas that are not of adequate size to enable the social group to forage might be avoided.

Patch shape was included to represent the potential importance of the shape of the foraging area.

The fifth dataset that represented bison sociality was viewshed. A viewshed analysis was performed to address the need for bison to maintain visual contact with other bison.

Response Variable – Bison Utilization. The response variable was the historic pattern of utilization by bison on specific areas throughout the FDR during the months of April through September. A range assessment of the FDR categorized utilization into three distinct levels of use (Sindelar and Ayers 1999): overgrazed, moderately utilized, and underutilized. This pattern of utilization has been collected as expert knowledge by the ranch manager (pers comm Bud Griffith). The bison utilization observations by the ranch manager were independently confirmed by a range consulting firm (pers comm Brian Sindelar). Bison utilization of the range was known for 19 specific grazing sites, represented in the GIS by 19 polygons (Figure 2).

The 19 areas of known utilization constituted 18,267 ha (45,138 acres). Areas were noted overgrazed when foraging plants were regrazed before they recovered from a

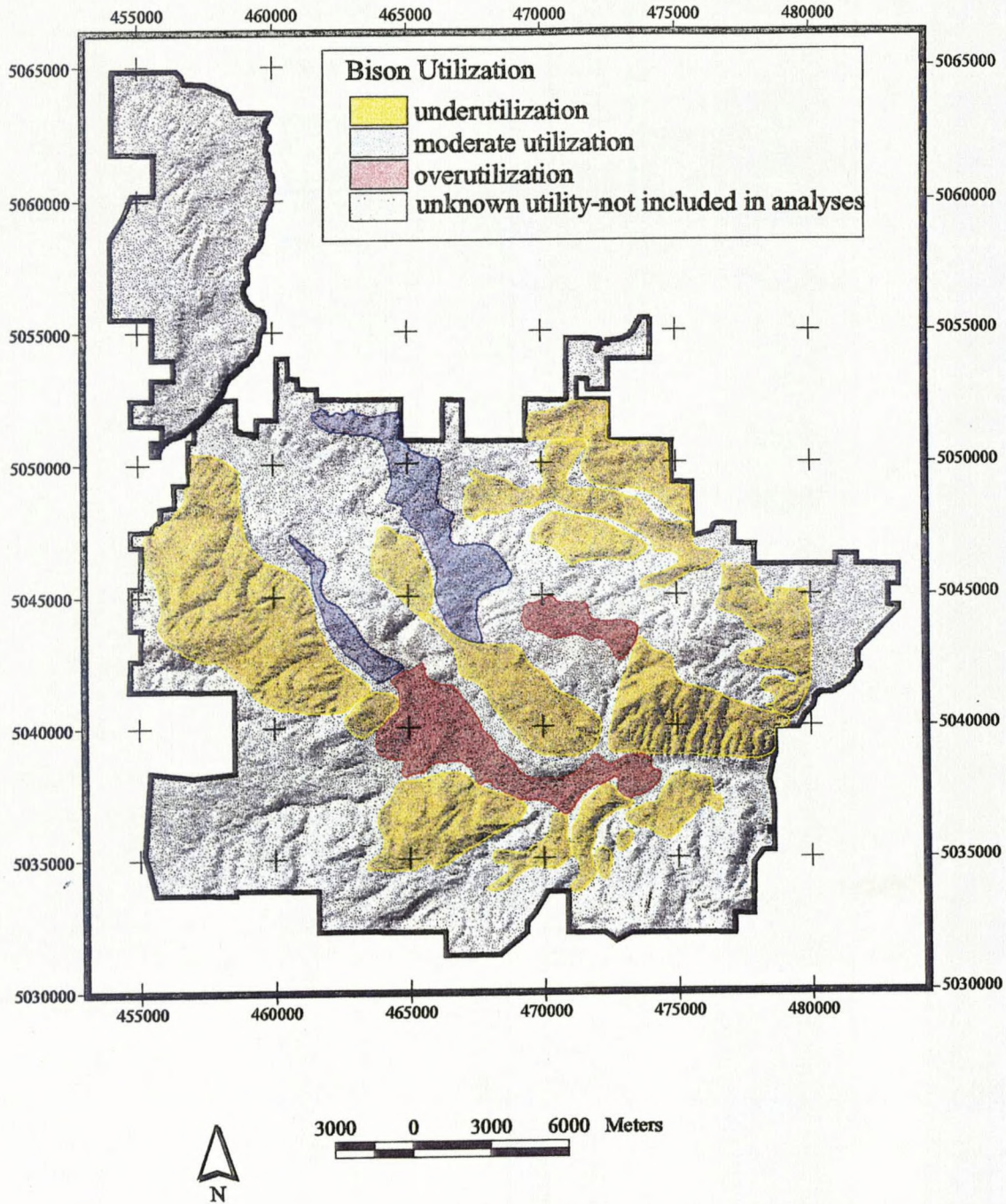


Figure 2. Areas of the ranch characterized by underutilization, moderate utilization and overutilization by bison, collected by expert knowledge from the ranch manager.

previous grazing event. The overutilized areas constituted 2488 ha (6150 acres). This was 14% of the total area of known utilization. Moderate utilization were labeled such when foraging plants received an appropriate amount of grazing, allowing recovery without old tissue accumulation. Areas of moderate utilization constituted 2091 ha (5168 acres), or 11% of the total area of known utilization. Underutilized areas had not been stimulated and old tissue had not been removed, allowing tissue to accumulate and restrict growth of new palatable forage. Areas of underutilization constituted 13,419 ha (33,158 acres), or 75% of the area of known utilization. Therefore, areas supporting an undesirable level of use, underutilized or overutilized, constituted 89% of the area that bison were known to forage.

Areas outside these areas of known bison utilization were of unknown utilization and were therefore not considered when exploring the geography of bison habitat selection. Areas of undesignated utility however were modeled for all areas designated as potential bison range on the FDR (Sindelar and Ayers 1999).

Data Structure

All datasets were represented as GRIDs for ArcInfo and ArcView. The GRID structure was used because it was conceptually and mathematically suitable for analysis (Turner and Gardner 1991). All analyses were performed using 900 m² grid cells (30m x 30m pixels), as this was the smallest resolution data available for all datasets.

All geographic data were in the Universal Transverse Mercator projection Zone 12 using North American Datum 27 with distance units in meters. All data were clipped to

the FDR boundary after modeling was performed to minimize edge effects. Biophysical variables included in the research are described according to data source and spatial resolution (Table 1 and Appendix A).

Statistical Analysis of the Database

The response variable was represented by 3 ordinal classes of bison habitat use, therefore logistic regression analysis, discriminant analysis, and classification and regression tree analysis (CART) were suitable modeling techniques (Pereira and Itami 1991). However, because three of the biophysical (predictor) variables (forage type, soil mineralogy, and surface soil texture), were not continuous, logistic regression and classification and regression tree analyses were considered the most appropriate. The relationships between biophysical variables in this research were complex. For example, previous research suggests that bison utilization of an area is dependent on the interaction of many biotic and abiotic variables. The hierarchical interactions of the independent variables regarding landscape characteristics that might influence bison utilization indicated that CART was the most appropriate analysis. CART analysis is a relatively new technique but has been employed in ecological research (Michaelsen *et al.* 1987, Borchert *et al.* 1989, Grubb 1991, Lawrence in press). In this research CART is used to predict three categorical levels of utility from the values of the 14 biophysical variables. The results of the CART analysis allowed for additional analyses to identify biophysical differences in areas of various levels of bison utilization.

Table 1. Biophysical variable datasets, and data source for analyzed variables.

Biophysical Variable	Data Source
<u>Nutritional Variables</u>	
forage productivity	Rangehands, Inc., Consulting
forage type	Rangehands, Inc., Consulting
soil mineralogy	US Department of Agriculture, Natural Resources Conservation Service, Soil Survey Geographic Data Base (SSURGO)
soil pH	SSURGO
soil salinity	SSURGO
<u>Physical Environmental Variables</u>	
water distance	derived from Montana Natural Resources Information System hydrography dataset
elevation	US Geological Survey digital elevation model
slope	derived from US Geological Survey digital elevation model
soil surface texture	SSURGO
<u>Behavioral Variables</u>	
nearest neighbor distance	FRAGSTATS software and Landsat TM satellite image, July 1990
patch area	FRAGSTATS software and Landsat TM satellite image
patch shape	FRAGSTATS software and Landsat TM satellite image
proximity	FRAGSTATS software and Landsat TM satellite image
viewshed	derived from US Geological Survey digital elevation model at Landsat TM satellite image
<u>Response Variable</u>	
bison habitat use	expert knowledge, Bud Griffith, FDR ranch manager

A Bayesian probability analysis was used to acquire more information regarding biophysical predictors of bison utilization. The results of the CART analysis and the Bayesian probability analysis were mapped for all bison range on the FDR to help interpret existing patterns of use as well as potential patterns. The conceptual structure of the research was illustrated (Figure 3).

Classification and Regression Tree Analysis

Classification and regression trees (CART) are used to predict membership probabilities for categorical response variables. This technique is especially informative when relationships between the response variables and some predictor variables are conditional on the values of other predictors (Michaelsen 1994).

The result of CART analysis was a binary tree constructed by repeatedly splitting the data into subsets, each split based on a single predictor variable. The tree begins with the full data set. Splits were determined using analysis of variance for continuous datasets and goodness of fit tests for categorical datasets. Predictor variables that provide the greatest reduction in deviance were used for the split. Each split in the tree resulted from the previous dataset split, therefore each split was dependent on previous splits. If there was no limit placed on the number of nodes, splitting continued until terminal nodes were composed entirely of the single predictor response variable.

The tree grown to node homogeneity was not necessarily realistic, but rather reflects overfitting the data. Therefore, to determine the best predictors of the response variable, and to minimize overfitting of data, pruning of the tree is required. The

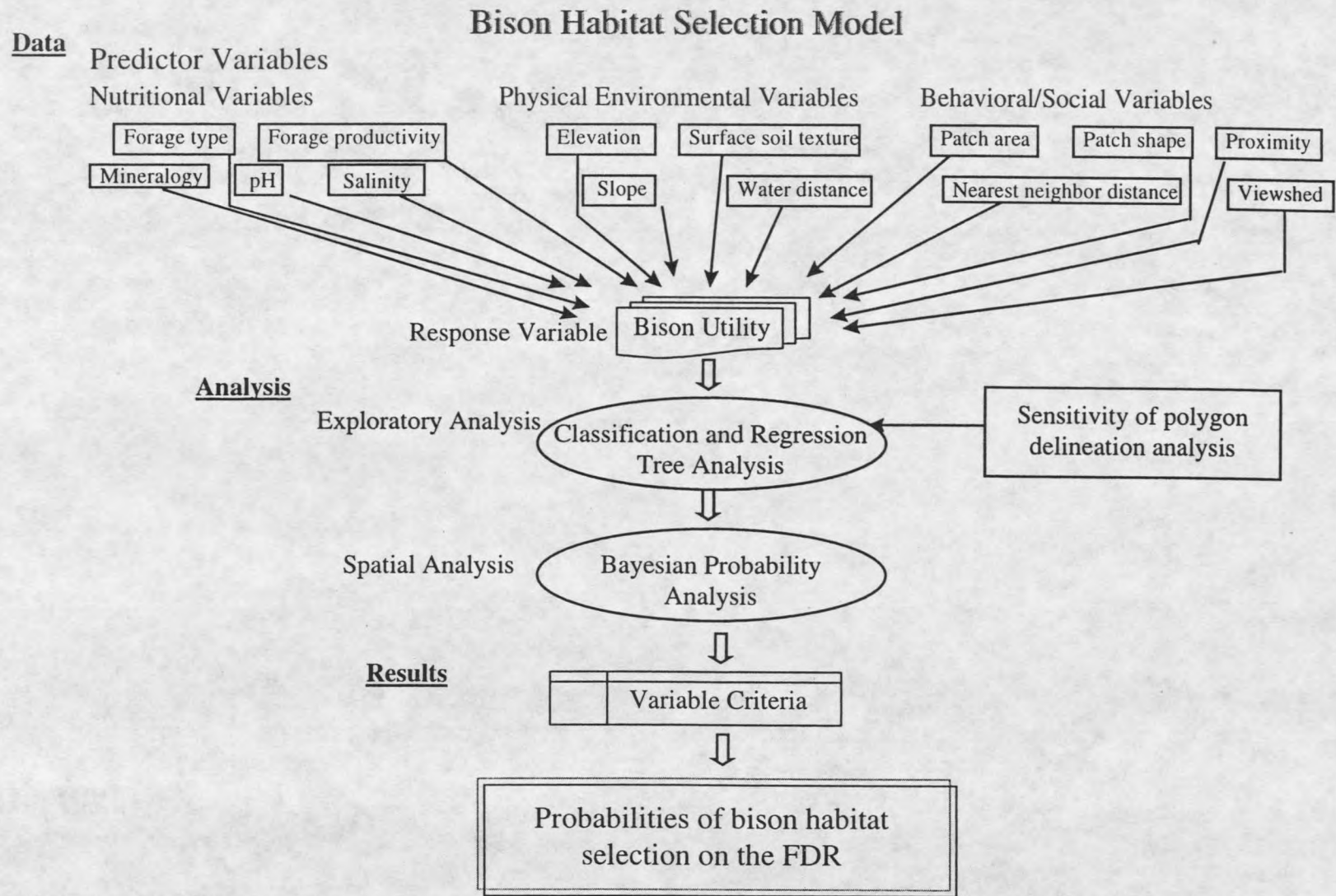


Figure 3. The conceptual structure of the bison habitat selection research on the FDR.

pruned tree determines the best approximating model, including predictors that contribute information and eliminating predictors that fail to have substantial explanatory value.

The results of the CART analysis produce numerous statistics (Figure 4). The splitting variable is the biophysical variable used to split the data into two groups. The split is made using specific criteria to divide the splitting variable into two groups. The y-probabilities are the estimated probability of the sites in that node being classified as receiving underutilization, moderate utilization, or overutilization (represented by 1, 2, 3, respectively).

Bayesian Probability Analysis

The results of the CART analysis indicated that underutilized areas and moderately utilized areas are similar. This allowed for the creation of a binary response variable, grouping underutilization and moderate utilization as one response. The creation of a binary response variable allowed the Bayesian analysis.

Bayesian probability analysis was used to predict the probable distribution of bison from the 14 biophysical variables and known bison utilization. Bayesian probability analysis has been employed for wildlife habitat research (Aspinall 1992, 1994; Pereira and Itami 1991). The output were maps of the probability of bison utilization. To implement the Bayesian analysis, a four step statistical process was required.

The first step was the calculation of conditional probabilities. Conditional probabilities were proportionally calculated as the total area of presence or absence in each class of

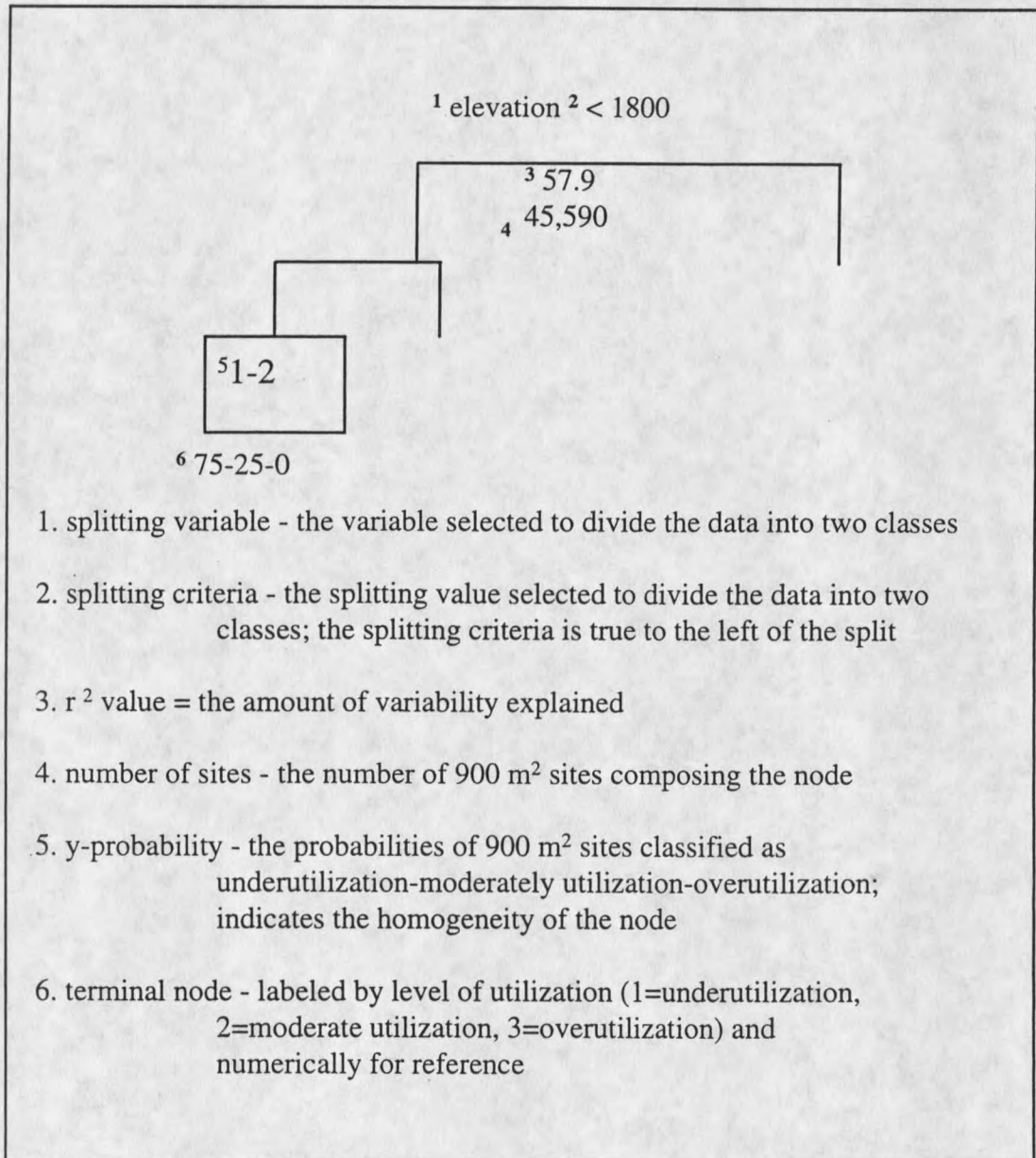


Figure 4. A description and illustration of the resulting statistics from the statistical CART analysis.

each biophysical variable. The conditional probability was expressed as relative frequencies of occurrence (bison overutilization/underutilization compared with the area of presence/absence of a biophysical variable).

The second step was testing the significance of the probability relationships using a chi square analysis of discriminatory significance. The chi square analysis compares observed frequencies of a single variable with an expected distribution of frequencies allocated over the same categories (McGrew and Monroe 1993). If observed and expected frequencies were significantly different, the chi square values provided a measure of the difference. Only predictor variables found to have significant ($p \leq 0.01$) associations with bison utilization were used for modeling.

The third step was testing conditional probabilities for presence and absence for significant ($p \leq 0.05$) variation between the specific biophysical variable values (ie. specific forage types, specific surface soil textures) using a binomial test for difference in proportions. However, due to test assumptions, some differences in proportions can result in statistically invalid tests that could provide ecologically important information. This occurs when there are too few values in presence or absence ($n_{pa} \leq 9$) to perform a statistically valid test. Invalid tests are often a result of inadequate samples collected. However, in this research, all known areas of bison utilization were included in the analyses. Therefore, when bison did not utilize an area that was characteristic of a biophysical variable, then this might provide important information rather than result from an invalid test. Therefore, all binomial test results (valid and invalid) were evaluated regarding ecologically important information.

The fourth step in the Bayesian analysis is the combination of conditional probabilities using Bayes' theorem. The equation for Bayes' theorem is:

$$P_p = \frac{(P_{pp} * P_{cp})}{(P_{pp} * P_{cp}) + (P_{pa} * P_{ca})}$$

where P_{pp} = probability of bison overutilization; P_{pa} = the a priori probability of bison underutilization; P_{pp} = the a priori probability of bison overutilization; P_{cp} = the product of conditional probabilities of bison overutilization for each input; P_{ca} = the product of conditional probabilities of bison underutilization for each input

The priori probability value was .5, therefore eliminating this influence. The implementation of Bayes theorem produces estimates of presence from the probability ratios of presence and absence, rather than from the magnitude of the conditional probabilities (Aspinall 1994). This aspect of Bayes theorem allows for important biophysical variables that constitute a small proportion of the landscape (e.g. montmorillonitic soils) to be recognized as important if bison are proportionally using these sites more intensively. The Bayesian model provides a single probability value representing the probability of bison utilization given the particular combination of attributes of all biophysical datasets included. This value represents a measure of the quality of the sites for each predictor dataset (Aspinall 1992), in this research the probability of bison utilization with respect to biophysical variables.

Sensitivity Analysis of Known Use Delineations

The utility data were represented by polygons and therefore had discrete boundaries rather than continuous. However, bison utilization of habitat is probably not so abruptly defined in geographic space. To address the problem of the potential lack of discrete

bison utilization in definition of the utilization boundaries, a sensitivity analysis was performed on all known utility boundaries.

Utilization areas were buffered 100 meters to the interior and 100 meters to the exterior. When creating the new exterior polygon boundaries many polygons overlapped other polygons of different levels of utility. Therefore new utility designations (data values) were assigned to these newly created polygons. For example, a small polygon created as a result of overutilized and underutilized overlapping polygons was assigned a new value of utility.

After creating these new data boundaries, the CART analysis was performed for each of the interior polygons, original known use polygons, and exterior polygons separately. This analysis determined if biophysical data outside the designated boundary, or data inside the designated use boundary influenced bison habitat selection and the CART model produced. Additionally, if the results of the sensitivity analysis differed from the results of the analysis of designated polygons, then the analysis was sensitive to the polygon boundaries and limitations on inferences drawn would be noted.

The CART analysis was performed using S-Plus Statistics software (Mathsoft, Inc., 1989). There were small areas within some datasets that did not contain data values. Additionally, forage type and forage productivity data were collected only for areas defined as bison range (Sindelar and Ayers 1998). Analysis was performed only for sites that contained data values for all biophysical variables, and was therefore limited to areas within bison range. The Bayesian analysis was performed in ArcView GIS using a Bayesian extension written by Richard J. Aspinall. J

Chapter 4

RESULTS

Introduction

The statistical analyses produced models that were interpreted quantitatively and spatially. First, this chapter discusses the statistical and geographic CART analysis results regarding each of the biophysical variables, and the results of the sensitivity analysis are discussed with respect to the interior use boundary and exterior use boundary. Second, the rationale for additional analysis is provided. Finally, the results of the Bayesian analysis are discussed, including the chi square analysis, binomial difference in proportions tests, conditional probabilities and geographic Bayesian model.

Statistical CART Results

The full tree grown with the 14 biophysical variables resulted in 66 homogeneous terminal nodes. The full tree had a misclassification error rate of 0.075, residual mean deviance of 0.38, and $r^2 = 79\%$.

The root node contains all biophysical variable datasets, consisting of 211,629 observations (19,046 ha). Based on the results of the misclassification error rate,

residual mean deviance (Figure 5), and location of terminal nodes, the final tree was pruned to 9 terminal nodes (Figure 6).

Pruning the tree to 9 terminal nodes resulted in a reduction of half of the tree deviance, a misclassification error rate of 0.13, a residual mean deviance of 0.71, and $r^2 = 51\%$. The pruned tree allowed a decision to reject or fail to reject each of the H_0 (Table 2).

Table 2. Hypotheses of this research, and decision to reject or fail to reject the H_0 as a result of the CART analysis

H_0 - There is no difference in underutilized, moderately utilized and overutilized areas for the following biophysical variables:	Reject	Fail to Reject
<u>Nutritional Variables</u>		
forage productivity	✓	
forage type	✓	
soil mineralogy	✓	
soil pH		✓
soil salinity		✓
<u>Physical Environmental Variables</u>		
distance from water		✓
elevation	✓	
slope		✓
surface soil texture	✓	
<u>Behavioral Variables</u>		
nearest neighbor distance		✓
patch area		✓
patch shape		✓
proximity		✓
viewshed		✓

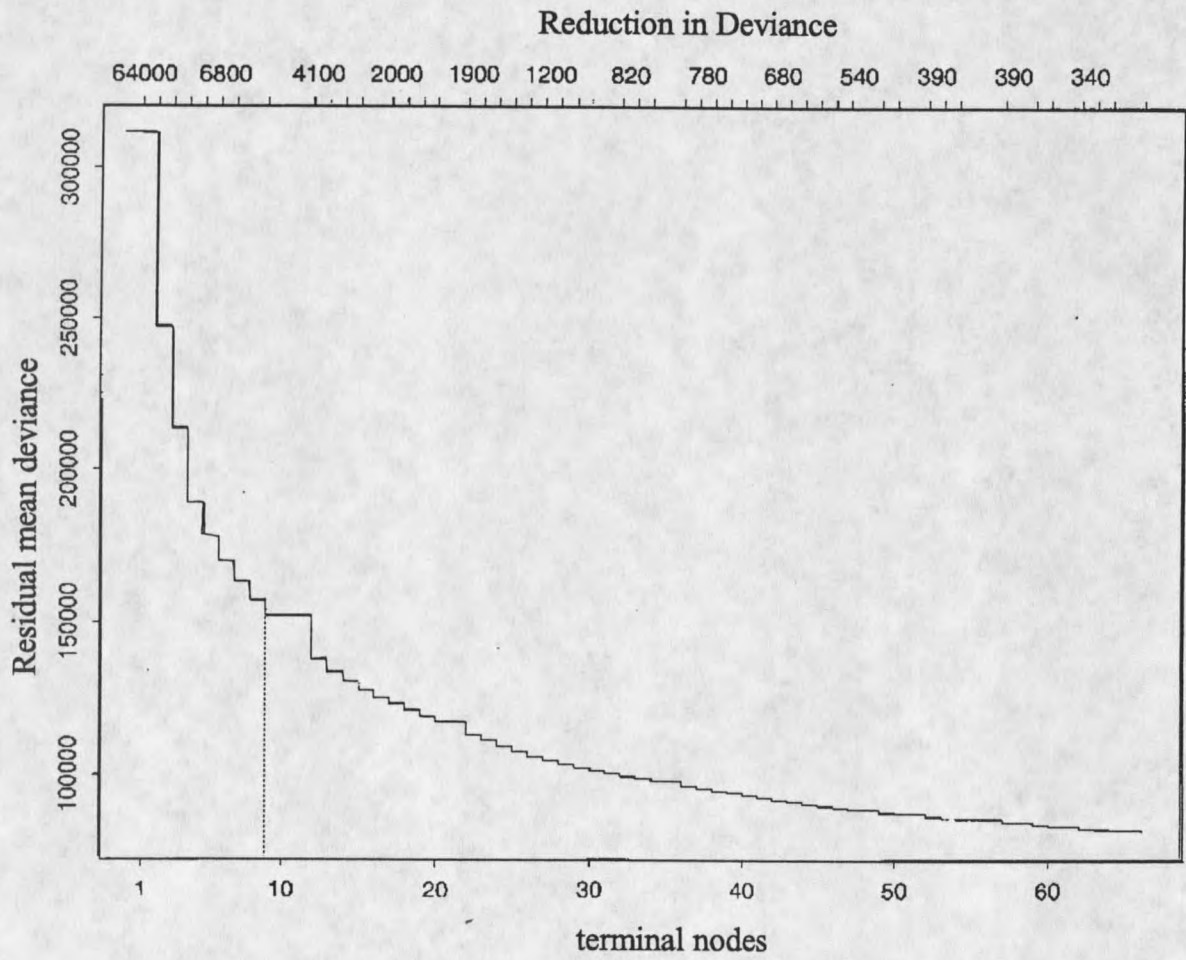


Figure 5. Graph of residual mean deviance as the number of terminal nodes increases.

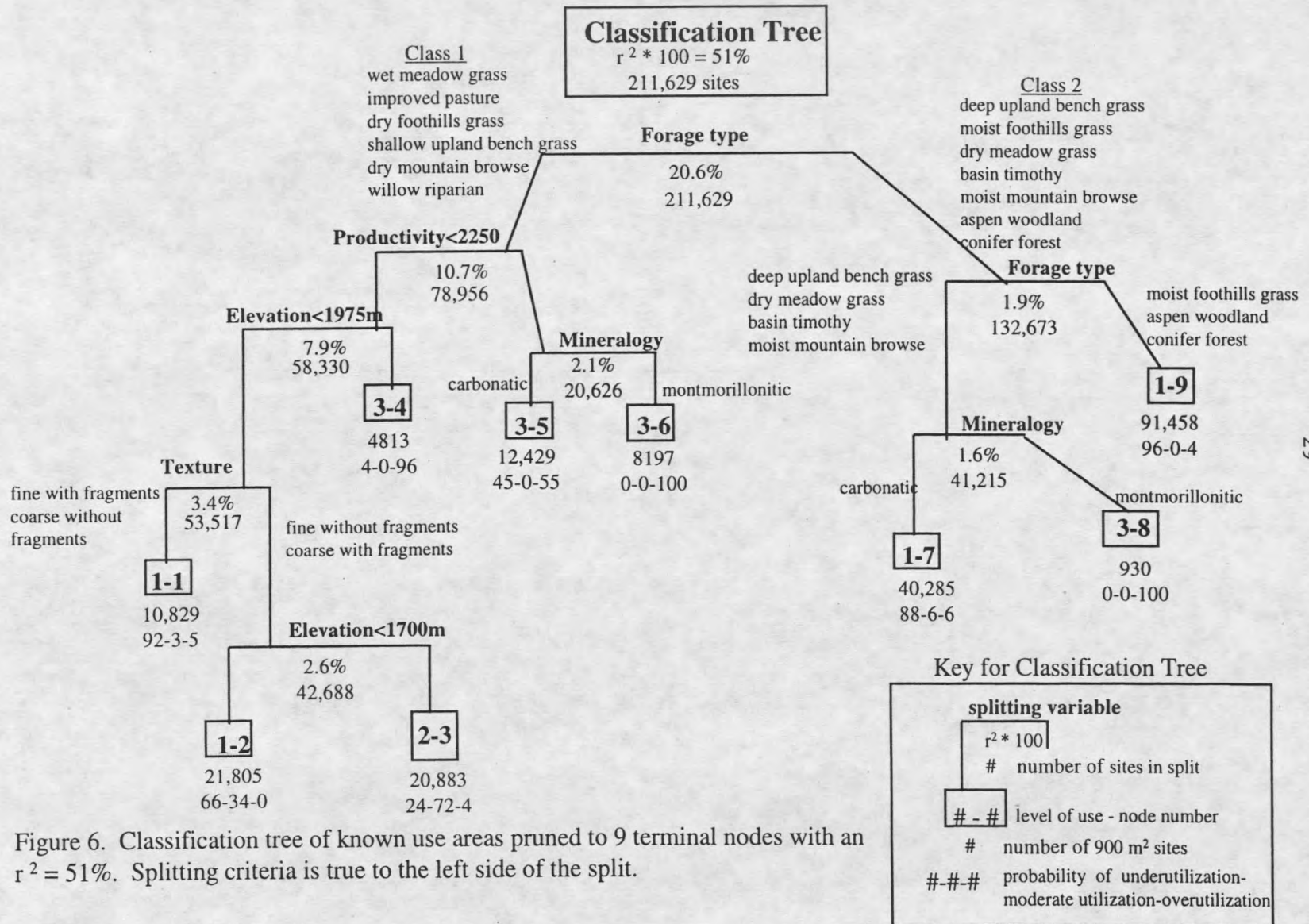


Figure 6. Classification tree of known use areas pruned to 9 terminal nodes with an $r^2 = 51\%$. Splitting criteria is true to the left side of the split.

Five of the null hypotheses were rejected as a result of the CART analysis. Three of these null hypotheses related to nutritional biophysical variables, and two related to physical environmental variables. None of the null hypotheses regarding behavioral variables were rejected as a result of the CART analysis.

Nutritional Variables

The categorical variable forage type was the first predictor of nutritional variables, explaining 20.6% of variability within the pruned tree. Forage type constituted the first split of the tree so that all other splits result from the differences between these two classes of forage. This initial split of forage type divided the 211,629 observations (19,046 ha) into 78,956 observations (7106 ha, class 1) and 13,673 observations (1230 ha, class 2). All three levels of bison utility were predicted by class 1, and underutilization and overutilization was predicted in class 2.

Within class 1, forage type was not a splitting variable again. However, within class 2 forage type was a splitting variable once further in the tree. The forage type split in class 2 ($r^2 = 1.9\%$) predicted underutilization in moist foothills grass, aspen woodland, and conifer forest (terminal node 1-9) with a y-probability of 96%.

Mineralogy was the splitting variable once, within forage type class 1 ($r^2 = 2.1\%$), and once within forage type class 2 ($r^2 = 1.6\%$), splitting carbonatic and montmorillonitic soils. Within forage type class 1, carbonatic soils predicted overutilization (terminal node 3-5) with a y-probability of 55%, and montmorillonitic soils predicted overutilization (terminal node 3-6) with a y-probability of 100%.

Within forage class type 2, carbonatic soil predicted underutilization (terminal node 1-7) with a y-probability of 88%, and montmormillonitic soil predicted overutilization (terminal node 3-8) with a y-probability of 100%.

Forage productivity was the splitting variable once with an $r^2 = 10.7\%$. This split occurred within forage type class 1, with the split occurring at 0.252 kg/m^2 (2250 lbs/acre). Productivity greater than 0.252 kg/m^2 (2250 lbs/acre) was split further by mineralogy, but always predicted overutilization. Productivity less than 0.252 kg/m^2 (2250 lbs/acre) split further and predicted overutilization, moderate utilization, and underutilization.

Physical Environmental Variables

The biophysical continuous variables of distance from water, slope, and viewshed were not important under the null hypotheses and thus were not predictors of bison utilization of the range. Therefore the null hypotheses for these variables were not rejected.

Elevation and surface soil texture were found to be important predictors of bison utilization. Elevation was used to split the tree two times within forage type class 1. Elevation was split at 1975 m ($r^2 = 7.9\%$). Sites at elevations of greater than 1975 m predicted overutilization and constituted the remainder of predicted overutilized areas (terminal node 3-4) with a y-probability of 96%. Sites less than 1975 m were split further in the tree by surface soil texture and elevation of 1700 m ($r^2 = 2.6\%$). Sites at elevations greater than 1700 m predicted moderate utilization (terminal node 2-3) with

a y-probability of 72%. Sites at elevations of less than 1700 m predicted underutilization (terminal node 1-2) with a y-probability of 66%.

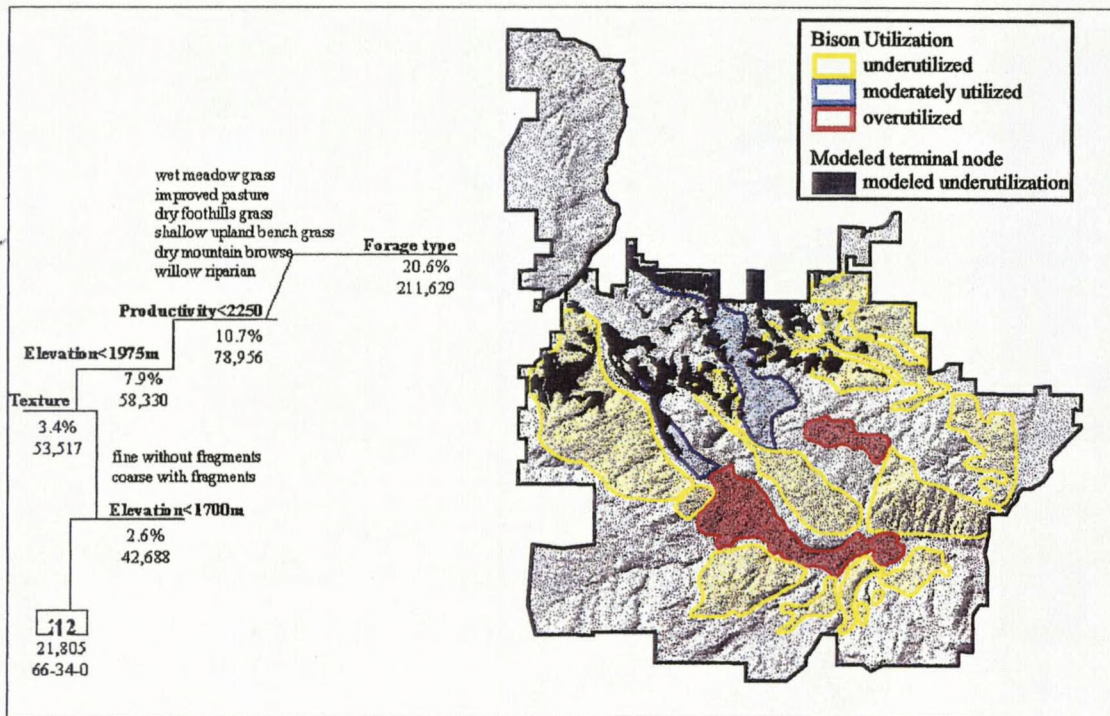
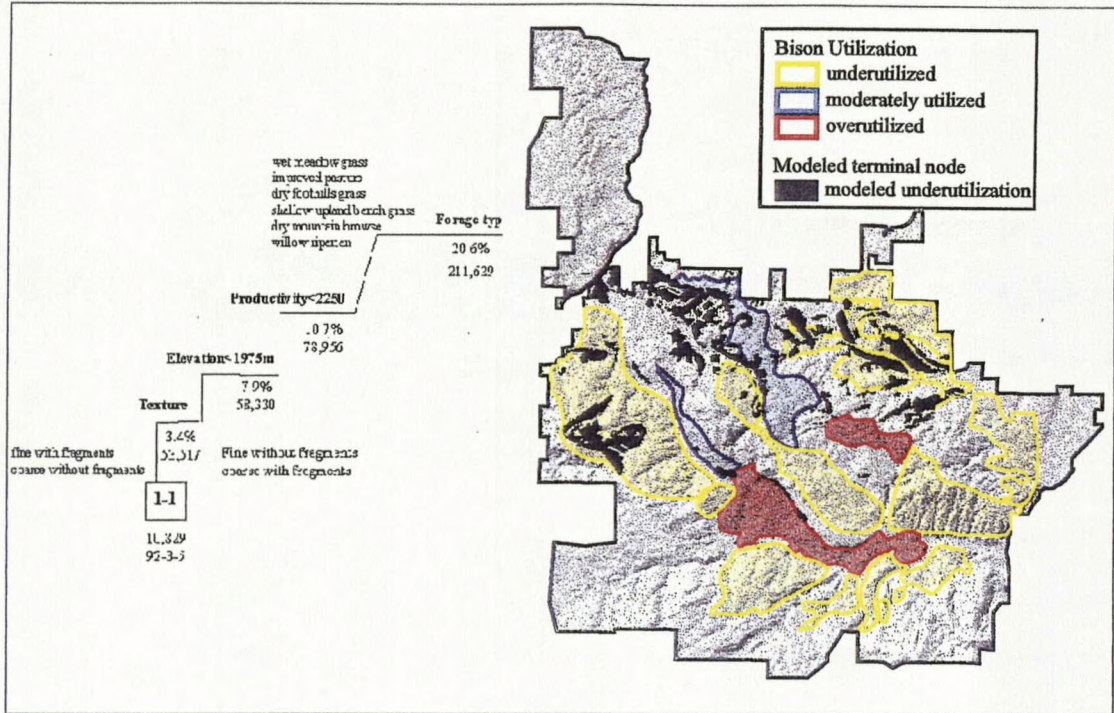
The categorical variable surface soil texture was also found to be an important predictor of bison utilization. Surface soil texture was a splitting variable once within forage type class 1. Surface soil texture split soil into two groups of (1) fine soil with rock fragments, and coarse soil without rock fragments and (2) fine soil without rock fragments and coarse soil with rock fragments ($r^2 = 3.4\%$). The first soil group predicted underutilization (terminal node 1-1) with an y-probability of 92%. The second surface soil texture group split further by elevation, predicting underutilization and moderate utilization.

Social/Behavioral Variables

None of the behavioral variables, nearest neighbor distance, patch shape, patch area, proximity, and viewshed, were found to be important under the null hypotheses from the CART analysis. The null hypotheses for these variables were not rejected.

Geographic CART Results

The results of the CART analysis were modeled for bison range throughout the ranch. Geographic areas modeled by the corresponding terminal node indicate that all of the biophysical information to create the node are characteristic of that geographic area (Figures 7-11). The full CART model incorporating all 9 terminal nodes is provided (Figure 11).



5000 0 5000 Meters



Figure 7. Geographic locations and statistical results of terminal nodes 1-1 and 1-2 from the classification and regression tree analysis.

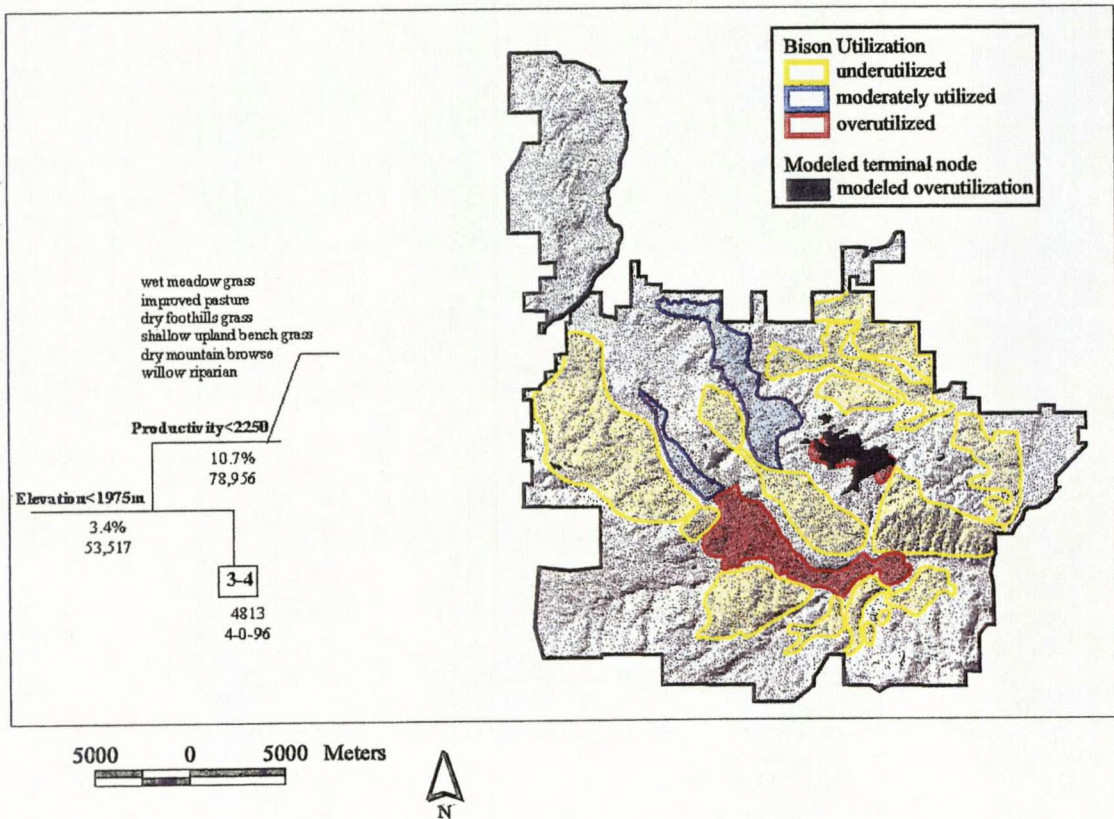
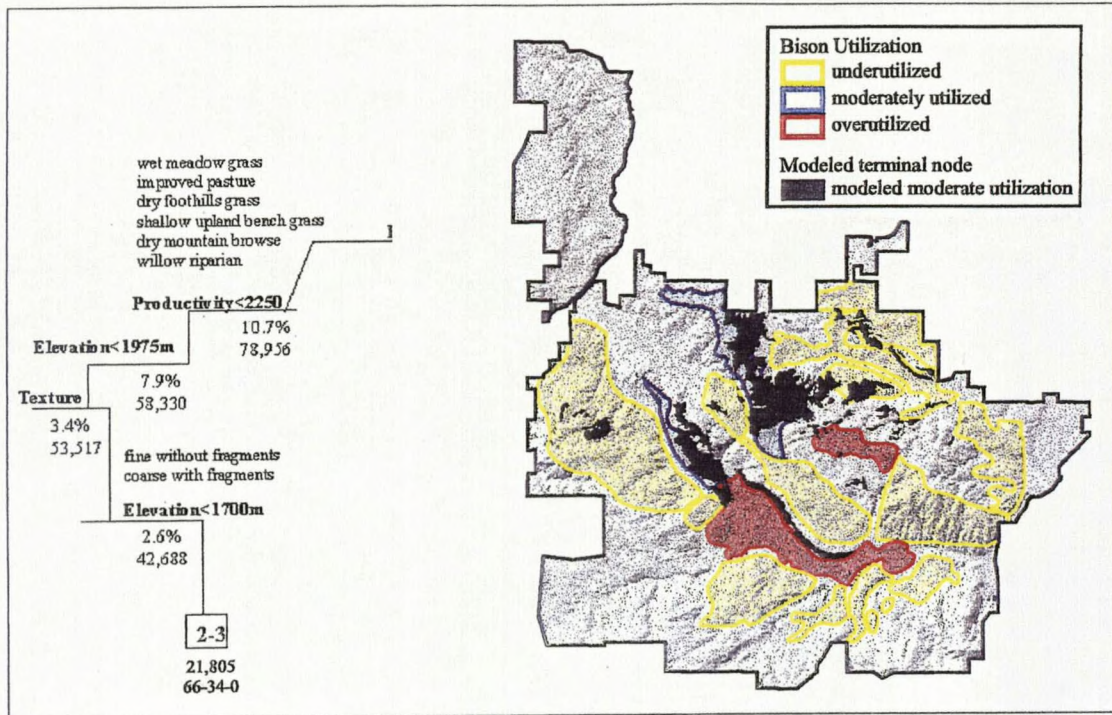
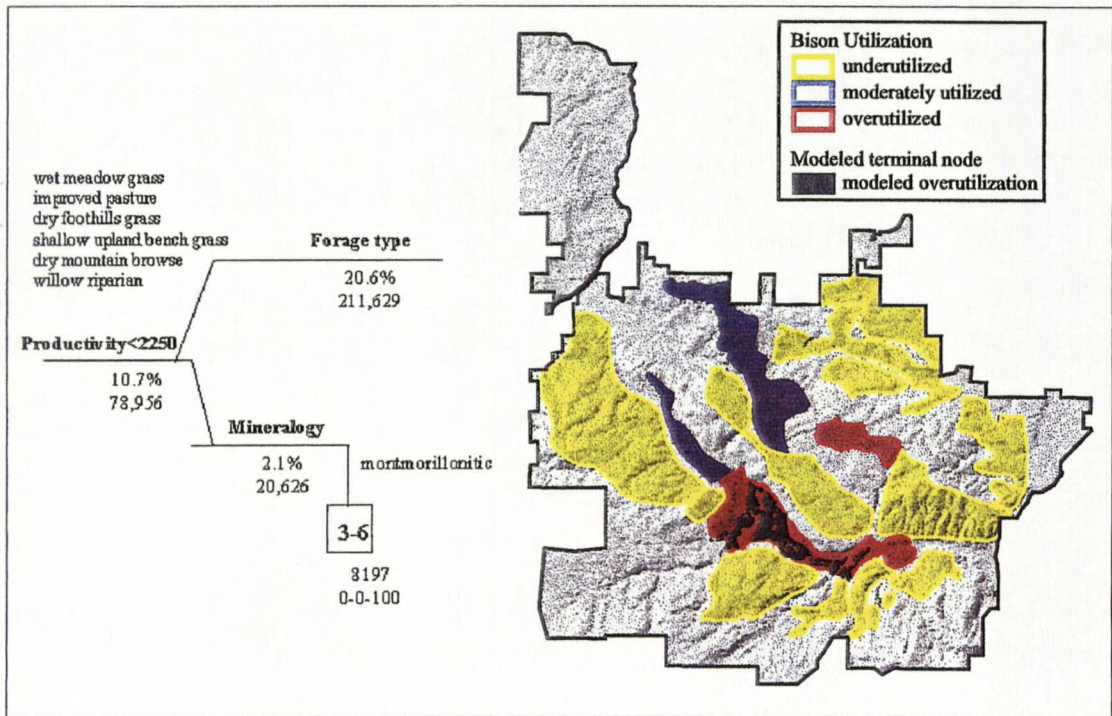
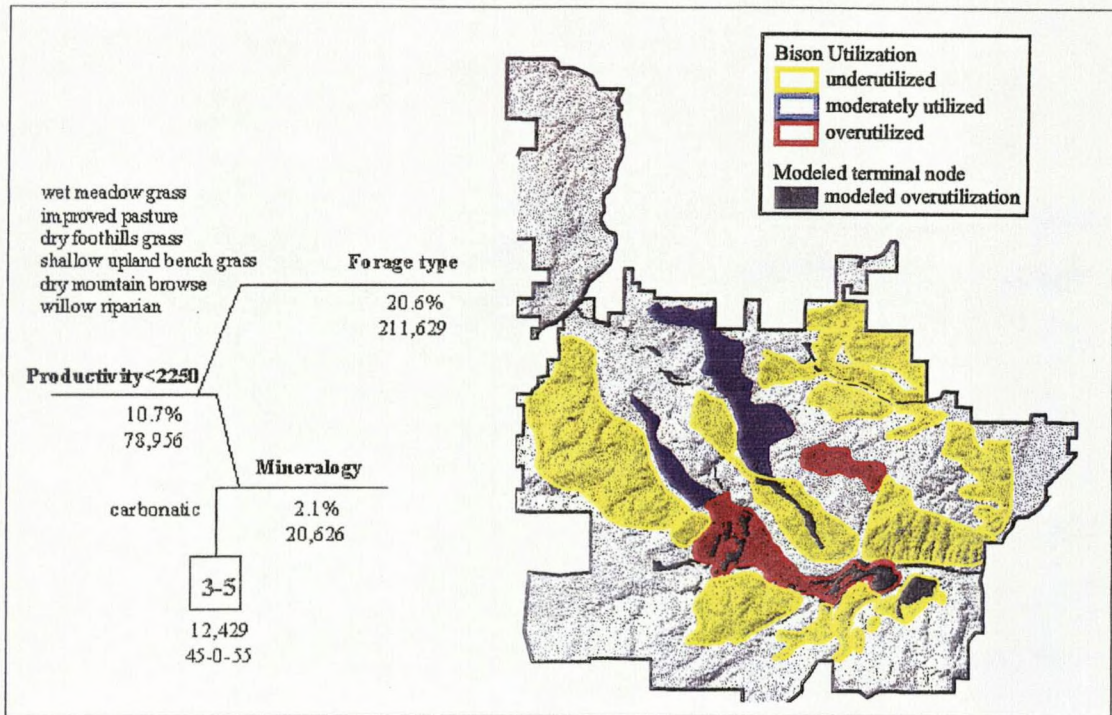


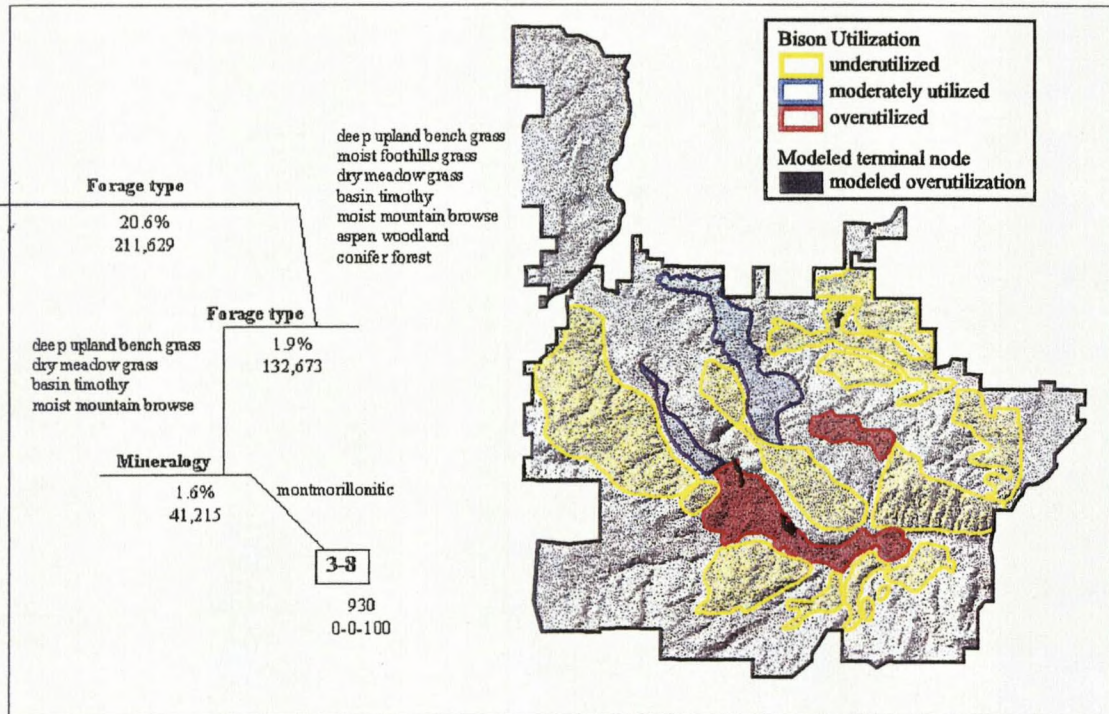
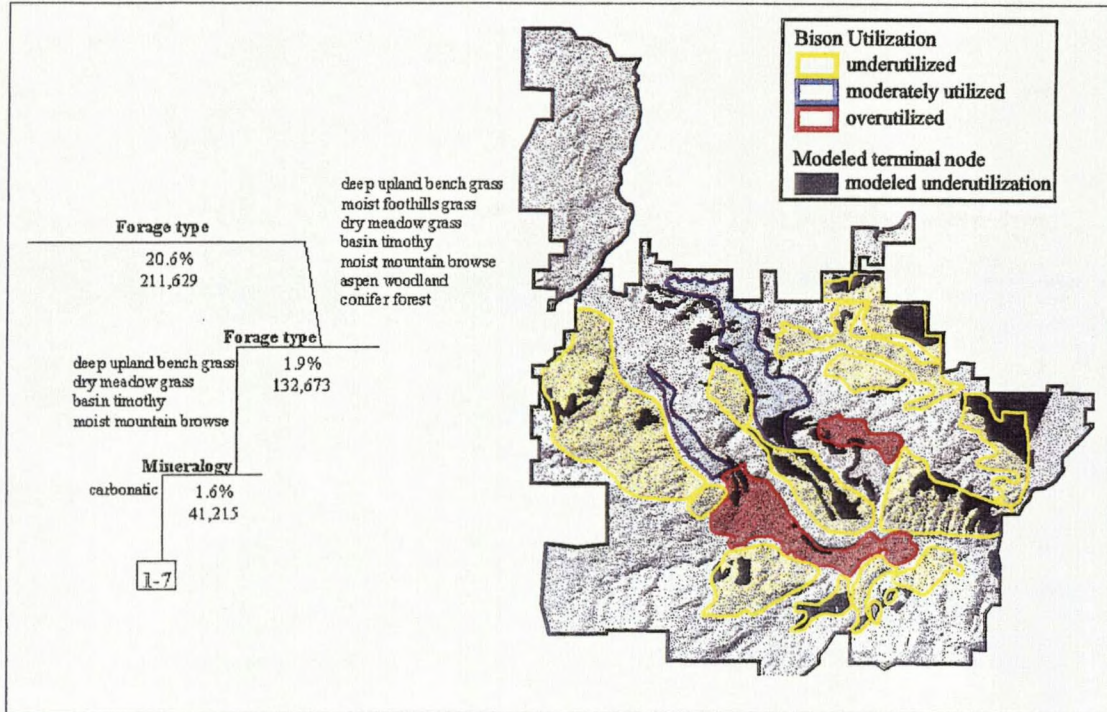
Figure 8. Geographic locations and statistical results of terminal nodes 2-3 and 3-4 from the classification and regression tree analysis.



5000 0 5000 Meters



Figure 9. Geographic locations and statistical results terminal nodes 3-5 and 3-6 from the classification and regression tree analysis.



5000 0 5000 Meters

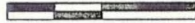


Figure 10. Geographic locations and statistical results of terminal nodes 1-7 and 3-8 from the classification and regression tree analysis.

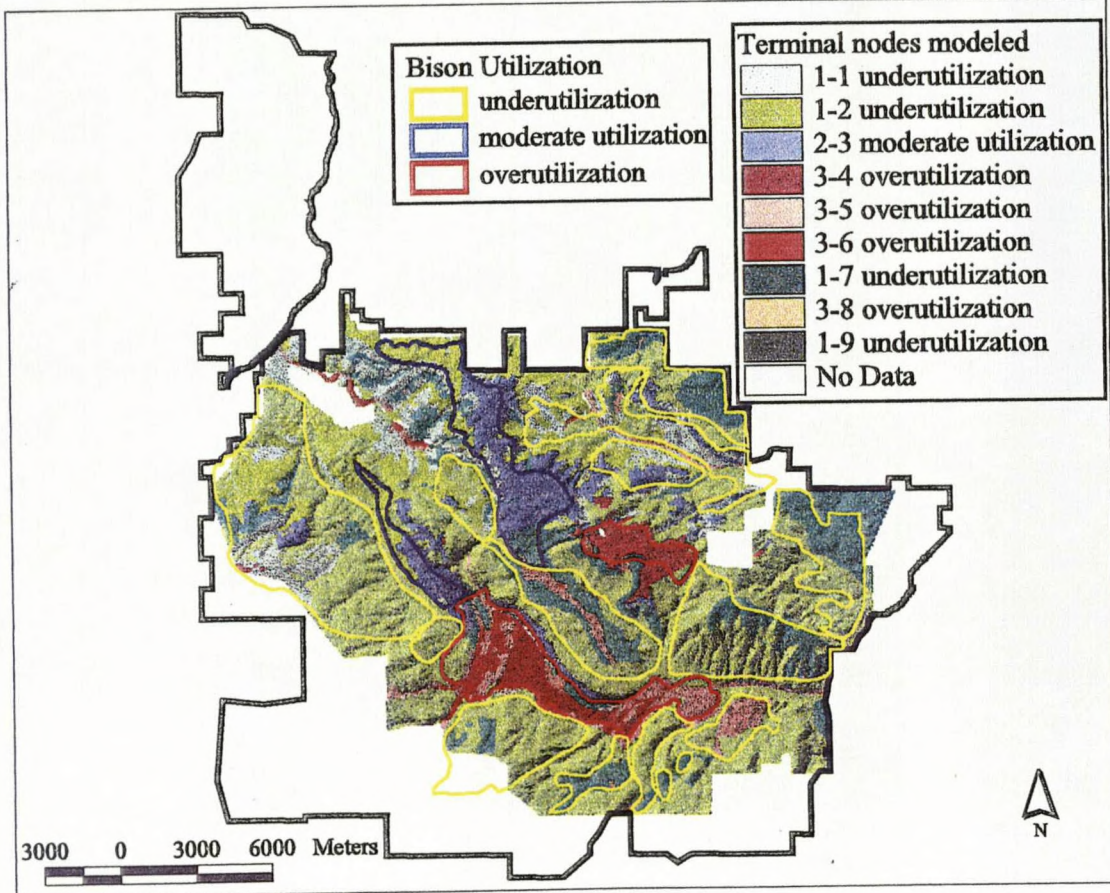
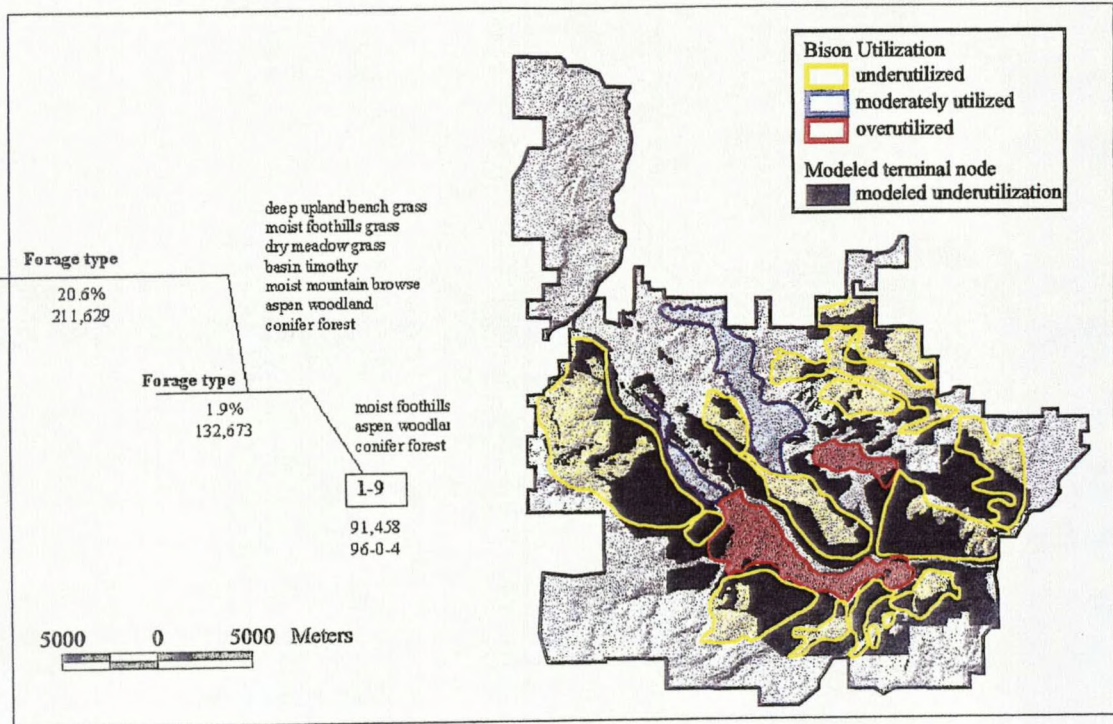


Figure 11. Geographic locations and statistical results of terminal node 1-9, and map of full CART model.

Overutilized Areas

Overutilized areas are predicted with four biophysical variables: forage type, forage productivity, mineralogy, and elevation. Forage type and productivity predicted 78% of the designated overutilized areas (1118 ha, terminal node 3-5) and (7371 ha, terminal node 3-6) and forage type, productivity, and elevation predicted 96% of the designated overutilized areas (22,289 ha, terminal nodes 3-4, 3-5, and 3-6) (Table 3). The remaining predicted overutilized sites are characterized by (1) forage types deep upland bench grass, dry meadow grass, basin timothy, and (2) moist mountain browse; and montmorillonitic soils (83 ha, terminal node 3-8) and constituted 3% of designated overutilized sites. Sites that were predicted overutilized constituted 9% of sites throughout bison range.

Underutilized Areas

Underutilization was predicted by five biophysical variables: forage type, forage productivity, mineralogy, elevation, and surface soil texture. Forage type class 1, productivity less than 0.252 kg/m^2 (2250 lbs/acre), elevation less than 1975 m, and surface soil textures fine with fragments and coarse without fragments (974 ha, terminal node 1-1) predicted 6% of underutilized sites within designated underutilized areas and 22% of sites throughout bison range. Forage type class 1, productivity less than 0.252 kg/m^2 (2250 lbs/acre), elevation less than 1975 m, and surface soil textures fine without fragments and coarse with fragments 1962 observations (176 ha, terminal node 1-2) predicted 13% of underutilized sites within designated underutilized areas and 3% of sites throughout bison

range. Forage types deep upland bench grass, dry meadow grass, basin timothy and moist mountain browse, and carbonatic soils (3625 ha, terminal node 1-7) predicted 24% of underutilized sites within designated underutilized areas and 15% of underutilized sites throughout bison range. Forage types moist foothills grass, aspen woodland, and conifer forest predicted 56% of underutilized sites (8231 ha, terminal node 1-9) within designated underutilized areas and 47% of underutilized sites throughout bison range.

Moderately Utilized Areas

Moderate utilization is predicted by four biophysical variables: forage type, forage productivity, elevation, and surface soil texture. Forage type class 1, productivity less than 0.252 kg/m^2 (2250 lbs/acre), elevations less than 1975 m, surface soil textures fine without fragments and coarse with fragments, and elevations greater than 1700 m (1879 ha, terminal node 2-3) predicted 100% of designated moderately utilized areas and 3% of moderately utilized areas throughout bison range.

Sensitivity Results

It was hypothesized that the interior boundary would reveal more distinct splits of utility. It was also assumed that the analysis of the exterior boundary would provide less discrete predictions.

Interior Boundary

The results of analysis on the interior use boundary indicated a very similar tree to the designated use tree (Appendix B). The classification tree of interior use pruned to 9 terminal nodes had an $r^2 = 55\%$.

Table 3. Percentages of sites within designated use areas, and modeled sites throughout bison range defined by Rangehands, Inc. (Sindelar and Ayers 1999).

Terminal node	% of sites within designated use areas	% of sites in bison range
<u>Overutilized</u>		
node 3-4	18	2
node 3-5	47	4
node 3-6	31	2
node 3-8	3	2
<u>Moderately Utilized</u>		
node 2-3	100	3
<u>Underutilized</u>		
node 1-1	6	22
node 1-2	13	3
node 1-7	24	15
node 1-9	56	47

The first two splitting variables, forage type and productivity, predicted 85% of overutilized sites, and splitting further by elevation constituted all of predicted overutilized sites within the interior use boundary. These are the same combination that predicted 96% of overutilized sites within the designated use boundary. Additionally, the two largest overutilized terminal nodes are predicted by the same variables and are generally found in the same location of each tree. The first four splitting variables are the same for both interior use and designated use: forage type, productivity, elevation, and mineralogy, therefore the boundary was not sensitive to the interior position of the utilization boundary.

Exterior Boundary

The results of analysis on the exterior use boundary also indicated a very similar tree to the designated use tree (Appendix C). The classification tree of exterior use pruned to 9 terminal nodes had $r^2 = 48\%$. All five of the splitting variables were the same. The first split was forage type, splitting the same forage types as the designated use tree. The combination of forage type class 1 and productivity predicted the large majority (77%) of overutilized sites. Elevation was the splitting variable of productivity greater than or less than 0.101 kg/m^2 (900 lbs/acre), as with designated use boundaries, and predicted 17% of overutilized sites.

The second splitting variable within forage type class 2 was a second split of forage type for the designated use areas. However the second splitting variable for the exterior use area was productivity greater than, or less than 0.193 kg/m^2 (1725 lbs/acre). As with the designated use boundary, these splits predicted overutilization and underutilization. Due to the similarities of the exterior tree with the designated use tree, the boundary was not sensitive to the exterior position of the utilization boundary.

Rational for Additional Analyses

The results of the CART analysis provided information regarding the statistical hypotheses and allowed rejecting or failing to reject the null hypothesis. However, CART raised questions regarding the scientific hypotheses of the research. The intent of the research was to provide information regarding bison habitat selection that would

enable more effective management of the range. The CART results raised three issues regarding further investigation of bison habitat selection:

- 1) The hierarchical nature of CART examined the predictor variables one at a time.

After the predictor had been selected as the splitting variable, potential splitting of predictors was performed only within the previously selected splitting variable.

Variables that were correlated could be under-represented, because CART recognized the variable with the greatest reduction in deviance and did not indicate a variable with a slightly less deviance reduction. This occurrence is called multicollinearity, and could result in neglecting to indicate an ecologically appropriate splitting variable because of correlation with another variable that reduced more residual deviance. This result was suspected with the predictor variable mineralogy after visual investigation showed that the largest proportion of bison overutilization occurred on the only large area of montmorillonitic soil. ✓

- 2) The spatial modeling output of the CART resulted in a map of the most statistically significant predictors of bison utilization. Mapping of the terminal node criteria did not provide information on the similarity regarding bison utilization of various terminal nodes. To allow further investigation of the geographic and habitat similarities and differences on the FDR, further analyses were required. ✓

- 3) Nutritional variable differences dominated the results of the CART analysis. After bison have overgrazed the overutilized areas, few of their nutritional requirements can continue to be met, however bison remain on these areas. As a result, ✓

additional analysis was required to assess nutritional, physical environmental, and behavioral variables independently.

Results of Bayesian Analysis

Chi Square Analysis

The chi square tests suggested that forage type, forage productivity, mineralogy, soil pH, soil salinity, elevation, slope, surface soil texture, nearest neighbor distance and viewshed were all significantly associated with bison utilization (Table 4). Maps of these 10 variables are provided in Appendix D.

Conditional Probabilities

Conditional probabilities determined the probability of bison presence and bison absence for each of the biophysical variable values (i.e., specific forage types). Conditional probabilities were calculated for all biophysical variables found significant from the results of the chi square test. The presence and absence probability values and the of presence and absence ratios are important. For example, if bison presence values observations are discussed, as these tests might result from ecologically important information.

Nutritional Variables. Bison overutilization presence was highest for valid tests on forage types: wet meadow grass, dry meadow grass, improved pasture, and shallow upland bench grass (Table 5). Bison overutilization absence was highest for valid

Table 4. Biophysical variables and results of the chi square test that allowed to reject or fail to reject the H_0 . Yes = ✓, No = X

Biophysical variable	Chi Square Value	Degrees of Freedom	Critical Value	significant at 99%
<u>Nutritional Variables</u>				
Forage type	Infinity	12	N/a	✓
Forage productivity	Infinity	14	N/a	✓
Mineralogy	1904.204	4	13.28	✓
Soil pH	25.192	4	13.28	✓
Soil Salinity	42.205	2	9.21	✓
<u>Physical Environmental Variables</u>				
Distance from Water	13.406	6	16.81	X
Elevation	23.442	6	16.81	✓
Slope	143.819	3	11.34	✓
Surface Soil Texture	128.878	3	11.34	✓
<u>Behavioral Variables</u>				
Nearest Neighbor	40.741	7	18.48	✓
Distance				
Patch area	9.355	8	20.09	X
Patch shape	6.636	8	20.09	X
Proximity	16.466	8	20.09	X
Viewshed	88.009	8	20.09	✓

tests on moist foothills grass, basin timothy, and dry foothills grass.

Bison overutilization presence was highest for valid tests on forage productivity of 0.0545 kg/m² (600 lbs/acre) and 0.252 kg/m² (2500 lbs/acre) (Table 6). Bison overutilization absence was highest for valid tests on forage productivity 0.0682 kg/m² (750 lbs/acre), 0.1591 kg/m² (1750 lbs/acre), 0.8181 kg/m² (2000 lbs/acre), and 0.2727 kg/m² (3000 lbs/acre).

Table 5. Conditional probabilities and binomial test results for forage types.

Forage type	presence	absence	Test validity	Significance
Moist foothills grass	9.6	29.6	y	99%
Wet meadow grass	12.4	1.5	y	99%
Dry meadow grass	7.3	3.6	y	99%
Improved pasture	41.6	2.2	y	99%
Basin timothy	3.1	5.7	y	99%
Dry foothills grass	5.9	15.7	y	99%
Shallow upland bench grass	15.1	11.3	y	99%

Table 6. Conditional probabilities and binomial test results for forage productivity.

Productivity (lbs/acre)	presence	absence	Test validity	significance
600	15.0	11.5	y	99%
750	3.6	9.4	y	99%
1750	2.9	9.1	y	99%
2000	7.7	13.5	y	99%
2500	56.5	7.1	y	99%
3000	3.1	9.2	y	99%

Bison overutilization presence was highest for an invalid test on montmorillonitic soils

(Table 7). Bison overutilization absence was highest for valid tests on carbonatic soils.

Table 7. Conditional probabilities and binomial test results for soil mineralogy.

mineralogy	presence	absence	Test validity	significance
carbonatic	51.2	87.3	y	99%
montmorillonitic	31.8	.5	n	Ns

Soil salinity was a significant predictor of bison overutilization from the chi square test. However, none of the soil salinity presence and absence values were significantly different in probabilities from each other from the binomial test of proportions. Bison overutilization presence was highest for valid tests on soils with a pH value of 7.3 (Table 8). Bison overutilization absence was highest for valid tests on soils with a pH value of 7.8.

Table 8. Conditional probabilities and binomial test results for soil pH.

Soil pH	presence	absence	Test validity	significance
7.3	83.2	74.0	y	99%
7.8	10.6	20.9	y	99%

Physical Environmental Variables. Bison overutilization presence was highest at elevation ranges of 1591-1733 m, and 2020-2162 m (Table 9). Bison overutilization absence was highest at elevation ranges of 1448-1590 m, and 1734-1876 m. Bison overutilization was never present on elevation ranges of 1877-2019 m, and 2163-2305 m.

Bison overutilization presence was highest on slope ranges 1-5 degrees (Table 10). Bison overutilization absence was highest on slope ranges 6-10 degrees, and 11-15 degrees. Bison overutilization was absent for invalid tests on slope ranges 16-20 degrees. Bison overutilization presence was highest on surface soil textures of fine soil without fragments (Table 11). Bison overutilization absence was highest on surface soil textures fine with fragments, and coarse without fragments. Bison overutilization was absent for invalid tests on coarse soil with fragments.

Table 9. Conditional probabilities and binomial test results for elevation.

Elevation (meters)	presence	absence	Test validity	significance
1448-1590	4.4	6.8	y	99%
1591-1733	69.8	29.6	y	99%
1734-1876	5.1	12.5	y	99%
2020-2162	20.5	7.1	y	99%
1877-2019	0	13.8	n	Ns
2163-2305	0	6.3	n	Ns

Table 10. Conditional probabilities and binomial test results for slope.

Slope (degrees)	presence	absence	Test validity	significance
1-5	59.4	16.5	y	99%
6-10	31.8	35.8	y	99%
11-15	7.1	27.7	y	99%
16-20	1.1	13.9	n	Ns

Table 11. Conditional probabilities and binomial test results for surface soil texture.

Surface soil texture	presence	absence	Test validity	significance
Fine without fragments	53.9	15.2	y	99%
Fine with fragments	38.4	45.7	y	99%
Coarse without fragment	7.3	9.3	y	95%
Coarse with fragments	.2	29.6	n	Ns

Social/Behavioral Variables. Bison overutilization presence was highest for sites with nearest neighbor distances (NND) of <30 and NND range 58,650-68,430 m (Table 12). Bison overutilization absence was highest for sites with NND value ranges of <30-48,150 m, and 48,180-58,620 m.

Table 12. Conditional probabilities and binomial test results for nearest neighbor distance.

NND (meters)	presence	absence	Test validity	significance
<30	72.4	56.6	y	99%
<30-48,150	6.6	22.9	y	99%
48,180-58,620	2.1	9.6	y	99%
58,650-68,430	18.1	7.2	y	99%

Bison overutilization presence was highest for sites with viewsheds of 24,840-28,920 m², and 28,950-33,030 m² (Table 13). Bison overutilization absence was highest for viewsheds 4290-8370 m², and 8400-12,480 m².

Table 13. Conditional probabilities and binomial test results for viewshed.

Viewshed (meters)	presence	absence	Test validity	significance
4290-8370	6.8	17.6	y	99%
8400-12,480	9.8	16.2	y	95%
24,840-28,920	16.2	7.5	y	99%
28,950-33,030	14.6	3.3	y	99%

Bayesian Models

The results of the Bayes' models are in the form of maps showing the probabilities of bison utilization, as a result of nutritional variables (Figure 12), physical environmental variables (Figure 13), and behavioral variables (Figure 14).

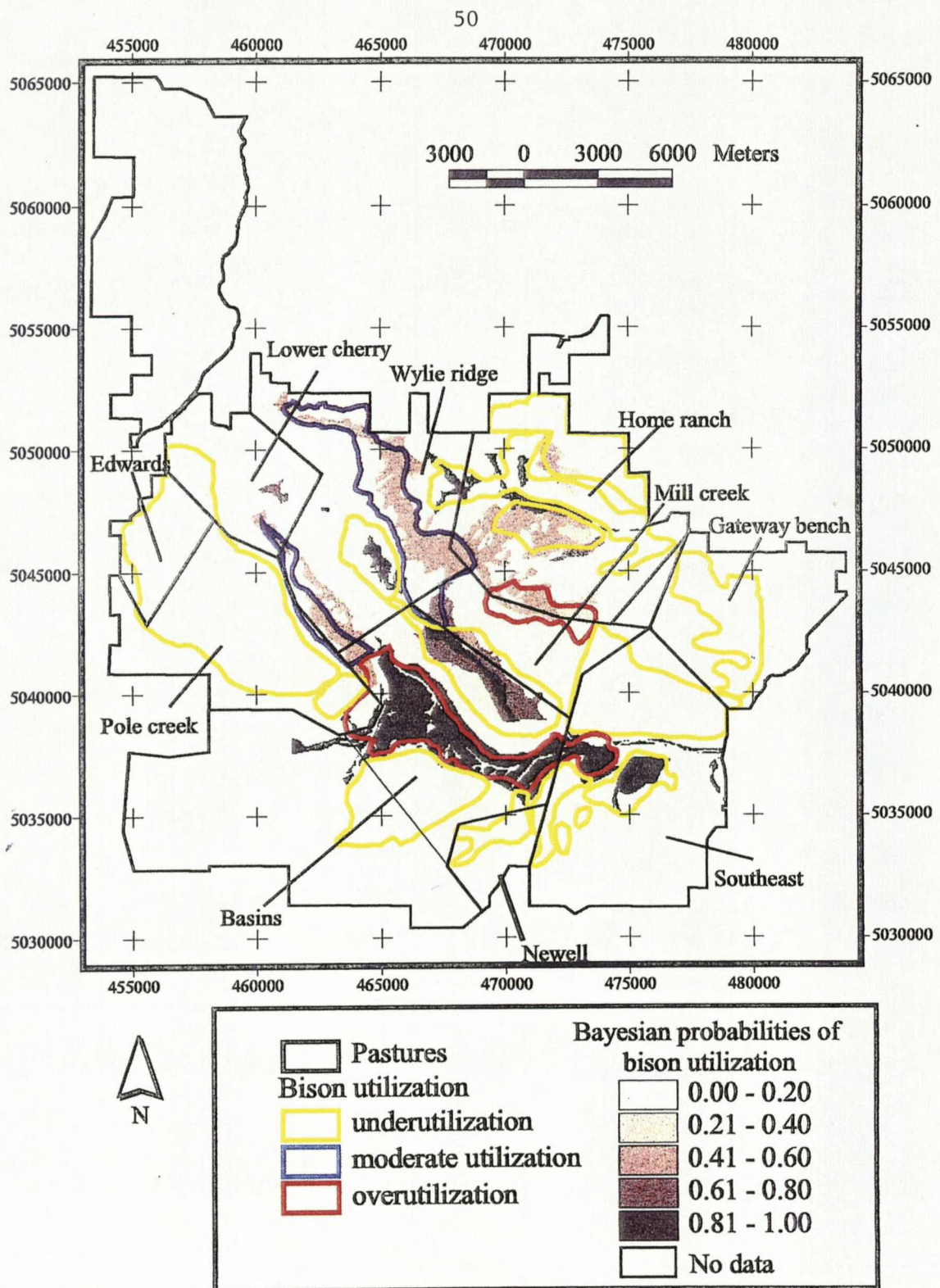


Figure 12. Probabilities of bison utilization, compared to known utilization from the nutritional bayesian model incorporating forage type, forage productivity, soil mineralogy, soil pH, and soil salinity.

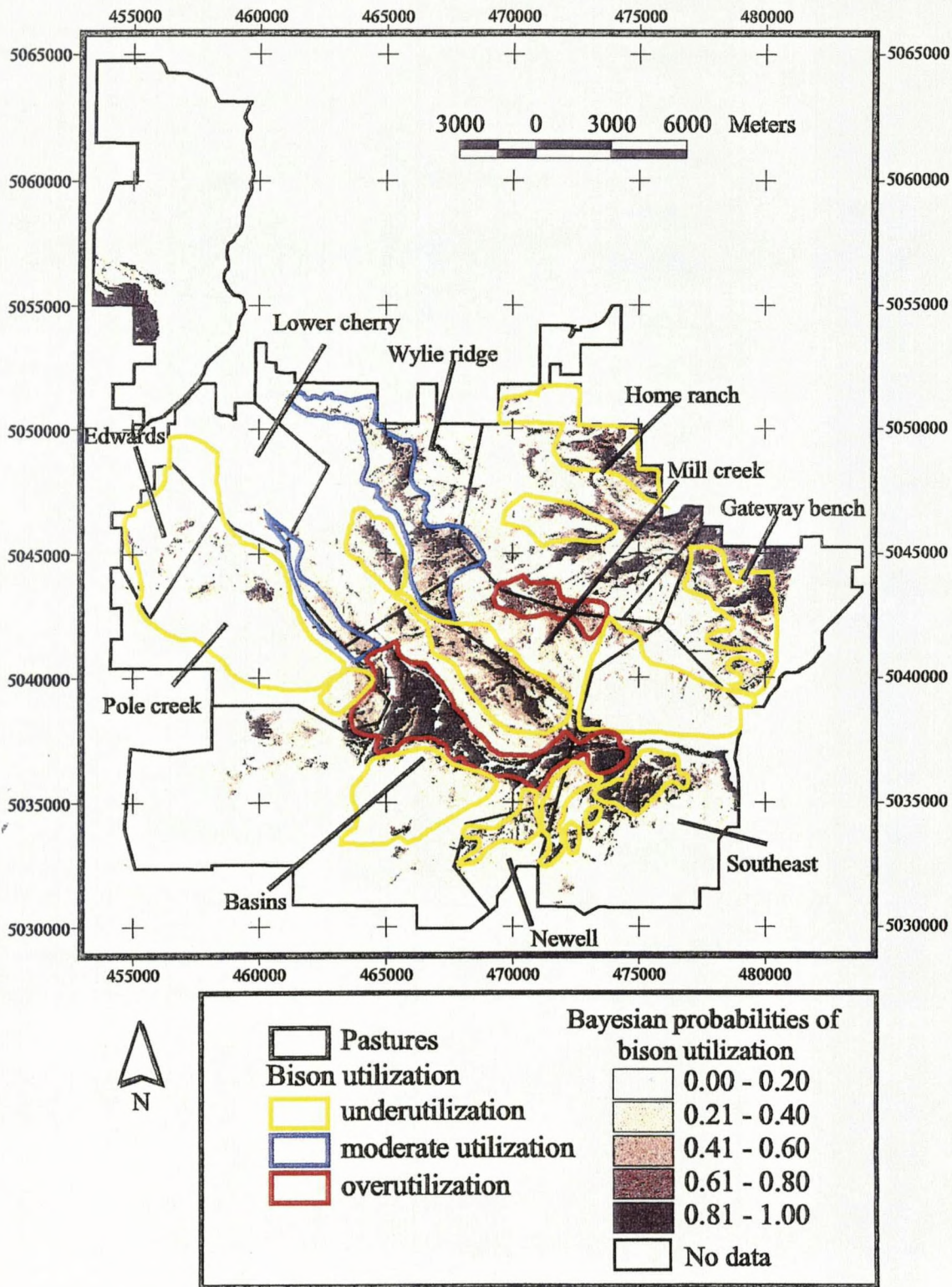


Figure 13. Probabilities of bison utilization compared to known utilization from the physical environmental bayesian model incorporating elevation, slope, and surface soil texture.

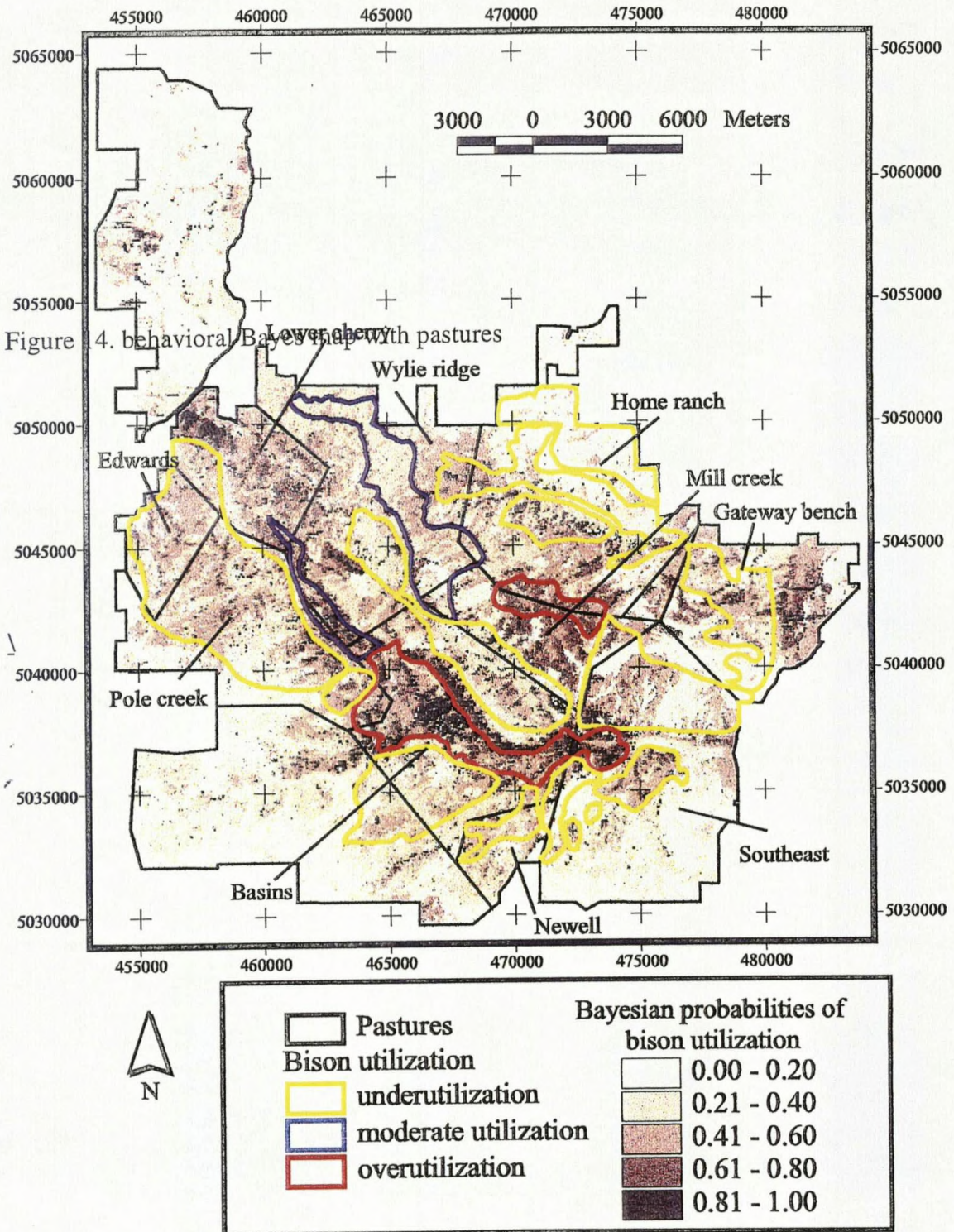


Figure 14.

Probabilities of bison utilization compared to known utilization from the social/behavioral bayesian model incorporating nearest neighbor distance and viewshed.

Chapter 5

DISCUSSION

The purpose of this research was to determine biophysical differences that existed between areas of bison underutilization, moderate utilization, and overutilization. Biophysical differences were found between all three levels of bison utilization. The CART analysis indicated that differences between the three areas were a result of predominantly nutritional variables. The Bayesian analysis was performed to assess the predictive values of nutritional variables, physical environment, and behavioral variables independently. The Bayesian analysis indicated significant differences as a result of nutritional, physical environmental, and behavioral variables.

After determining the differences that existed for the three levels of bison utilization, the probabilities of bison utilization were modeled throughout the ranch. This was intended to determine areas that have similar biophysical characteristics as areas that are overutilized, thus, highlighting areas of potential bison utilization that are currently underutilized. There were some areas of the ranch that are currently underutilized, yet have high probabilities of bison utilization. These areas might be the best areas best to focus future bison utilization efforts. Additionally, the two areas that are currently overutilized, contain high probabilities of bison utilization for

nutritional, physical environmental, and behavioral variables. This might indicate that the areas that meet bison habitat selection requirements are limited, and bison are overutilizing the best bison habitat on the ranch.

This research suggests that many biophysical variables are related to bison overutilization. The specific biophysical values are: improved pasture and shallow upland bench grass forage types; forage productivity of 0.0545 kg/m² (600lbs/acre) and 0.2272 kg/m² (2500 lbs/acre); montmorillonitic soil mineralogy; soil pH of 7.3; elevations below 2162 m; slopes less than 10 degrees; surface soil textures without rock fragments; NNDs of less than 30 m; and large viewsheds of greater than 24,000m.

CART Discussion

The CART analysis provided useful information as an exploratory technique and focussed the additional Bayesian analysis. The y-probability results of the CART analysis indicated that overutilized areas were more easily distinguished than either underutilized or moderately utilized areas. The probabilities of predicting moderate utilization and underutilization were very similar for many terminal nodes. The probabilities of predicting overutilization were very high for all terminal nodes predicting overutilization. This could be a result of the way utilization was classified by the ranch manager. Data describing utilization were collected subjectively by noting the historic pattern of bison use of the ranch. Overutilization and underutilization might have been more discernible by ground observations than

moderate utilization. If these similarities were not a result of response variable data collection, then the biophysical characteristics of moderately utilized and underutilized areas was more similar than either was to overutilized areas.

The CART analysis indicated that nutritional variables were the best predictors of bison utilization. Forage type and forage productivity were the best predictors of bison utilization. However, the hierarchical nature of traditional CART methodologies could fail to highlight some ecologically important bison habitat variable predictors. Additionally, since the quality of nutritional variables (i.e., forage type and forage productivity) diminishes in late summer months, modeling bison physical environmental variables and behavioral variables independent of nutrition was performed. This analysis allowed nutrition, physical environment, and behavioral variables to be considered independently of one another. This modeling was performed with the Bayesian analysis.

Bayesian Probability Discussion

The Bayesian analysis indicated that 10 of the 14 biophysical variables were significantly different with respect to bison overutilization and underutilization of the range. Additionally, the Bayesian analysis provided maps that indicated the probability of utilization for areas outside the areas of known utility.

Forage type and forage productivity were found significantly different for the two levels of bison utilization. The probability of bison utilization on improved pasture was highest. Improved pastures are areas that have been historically cultivated, but

since 1989 have been uncultivated (pers comm Brian Sindelar). Improved pastures had high forage productivity 0.2272 kg m^{-2} (2500 lbs/acre) and were located in flat, open portions of the ranch. It was not known whether bison utilized these areas for the same reasons that they were initially farmed (i.e., flat, highly productive, deep soils) or if bison prefer them as a result of the historic cultivation (i.e., species composition).

Wet meadow grass was also a forage type with a high probability of bison utilization. Wet meadow grass was also highly productive 0.2272 kg/m^2 (2500 lbs/acre) and found in flat, lower elevation areas. Bison are not selective feeders, as they are the least selective feeders of 4 ungulates on the shortgrass prairies (Pedan *et al.* 1974, Schwartz and Ellis 1981). The FDR research supports previous studies (Houston 1982) that indicate that bison prefer highly productive meadows where a high quantity of forage is available for little energy cost and do not prefer moist foothills grass and dry foothills grass, where they are required to forage more selectively. However, the highest productivity forage 0.2727 kg/m^2 (3000 lbs/acre) had very low probabilities of bison utilization. This is likely a result of the plant composition of the forage. Timothy grass is a coarse forage that bison do not prefer unless it has been cut early in the growing season (Sindelar and Ayers 1998). Therefore this forage could be managed to increase bison utilization.

The FDR bison's low utilization of browse forage supports previous studies. The probabilities of bison utilization of moist mountain browse and dry mountain browse are low. Previous studies indicate that bison are grazers of grasses during all seasons

(Pedan *et al.* 1974, VanVuren 1984) and consumption of browse and forbs has been almost negligible in nearly all diet studies (Shaw and Meagher 1999).

Most of the ranch soils consist of carbonatic soils, except in the flat Spanish Creek basin area where soils are montmorillonitic. The influence of soil mineralogy appeared to be more important than the CART analysis indicated. The largest overutilized area on the ranch was the only large area on the ranch composed of montmorillonitic soils. The variable forage type predicted overutilization better than mineralogy, and after this split in the CART analysis, all montmorillonitic soils were already classified by forage type. The Bayesian analysis indicated that the probability of bison utilization of montmorillonitic mineral soils was a better predictor of bison utilization than carbonatic soils, however, this might be a result of the correlation of montmorillonitic soil and other nutritional variables. Because three variables, forage type, forage productivity and soil mineralogy were correlated, it was not possible to determine which were affecting bison utilization.

Montmorillonitic soils are clayey soils with a large surface area enabling a large water holding capacity. The selection of these soils by bison could be a result of the environmental conditions in which these soils are found. Montmorillonitic soils are found in highly drained areas where accumulation of sediment occurs.

Distance from water was not found to be significant from the CART analysis or the Bayesian analysis regarding bison utilization. This supported other studies regarding the potential influence on foraging behavior from horizontal distance from water (VanVuren 1983). All foraging areas on the ranch might be an adequate

traveling distance for bison drinking requirements, therefore not influencing bison utilization. J

Elevation was found to have statistical significance ($p \leq 0.01$) influencing bison utilization. This supports previous studies that indicate that elevation is an important biophysical variable in bison habitat selection. Specific elevations, however, were different in this research than were found in other studies. The bison herd in the Henry Mountains, Utah, summered at 2500-3500 m and wintered at 1700-2100 m. The Utah study area elevation ranged from 1500-3540 m, and the FDR ranges from 1305-2305 m which are comparable in altitudinal distributions. Bison overutilization never occurred at elevations above 2163 on the ranch, and the highest probability of presence occurred at 1591-1733 m, and 2020-2162 m. This might suggest that the FDR bison herd utilize winter range all year, and, because of the fenced exterior ranch boundary, are not able to migrate to lower elevations during winter months. The elimination of potential seasonal migration might influence bison selection of seasonal foraging sites on the ranch. The Henry Mountains bison herd was studied at approximately 6 degrees lower latitudinal location. Equivalent habitats at higher latitudes are found generally at lower elevations due to decreasing energy availability at higher latitudes. A large part of the Mill Creek pasture overutilized area is located in the elevation range of 1591 – 1733 m. The western section of the Basins pasture overutilized area is located in the elevation range of 2020 – 2162 m.

Slope was not found to have an important association with FDR bison habitat selection from the results of the CART analysis, however the chi square analysis

indicated otherwise. The probability of bison presence was highest on the least slopes and absence values increased as slopes increased. Previous studies have indicated that bison graze 1/3 of the time on slopes of 25 degrees and higher (Van Vuren 1981). The probability of the FDR bison herd utilizing slopes greater than 15 degrees was low, and use was most frequent on 1-5 degree slopes.

Surface soil texture does appear to be an important predictor of moderate utilization and underutilization from the CART analysis. The split of soil textures does not make biological/ecological sense regarding bison behavior. The CART analysis groups soils with rock fragments and soils without rock fragments together, yet surface soil texture was included in this research because of its potential influence on bison's creation of wallows. If surface soil texture was a determining factor in creation of wallows, it was theorized that soil textures with no rock fragments would predict bison moderate utilization or overutilization and soil texture with rock fragments would predict bison underutilization. The Bayesian analysis indicated a high probability of bison presence on soils without rock fragments and low probabilities of bison utilization of soils with fragments. This supports the ecological importance for the ability of bison to create wallows and supports the potential predilection of bison to utilize soils that do not consist of rock fragments for wallowing.

Patch area was not found to have significant association with bison utilization on the FDR. Female bison have larger home ranges than males, and are associated with larger groups than males (Larter 1988). It has been suggested (Coppock and Detling 1986) that females might require larger food patches than males, however the results

of this study of the FDR bison herd, regardless of sex, does not support this association. Patch shape was also not found to have a significant association with bison utilization on the FDR. Patch area and patch shape were not good predictors of bison habitat. This might be because the patch areas and patch shapes of the foraging areas throughout the FDR are not different with respect to bison utilization.

Proximity and NND were used to represent the connectivity of foraging areas, as bison utilization of forest is minimal (Meagher 1973) and bison travel routes are usually along well defined travel routes in mountainous regions (Meagher 1973). Proximity was not found to have a significant association with bison utilization from the CART analysis or the chi square analysis. However NND was found to have a significant association with bison utilization from the results of the chi square analysis. The NND was the sum of the distance to the nearest neighboring patch of the same type, based on nearest edge-to-edge distance for each patch. Spatial pattern analysis has not been conducted previously with respect to bison. The probability of bison utilization was highest for patches closest together and farthest apart. The Spanish Creek basin is composed primarily of NND values of less than 30 m. The second overutilized polygon was composed largely of NND values less than 30 m and between 30 – 48,150 m. This indicated that these two areas were well connected to similar patches. The areas with high NND values might be areas of dry grassland and wet grassland scattered throughout the foraging area. The pattern analysis would not indicate the similarity of the two patches, so dry grassland and wet grassland would be considered the same as wet grassland and forest. The distribution of the two grassland

types could be the reason for the high probability values for areas of large NND values.

Viewshed was not found to have a significant ($p \leq 0.01$) association with bison utilization from the results of the CART analysis, however it was found to have a significant association from the results of the chi square analysis. The CART analysis might not have indicated viewshed as an important predictor of bison utilization, because areas of large viewsheds were previously predicted by a nutritional variable. Probabilities of bison utilization were consistently high in areas of higher visibility, and were consistently lower in areas of lower visibility. Previous research found a positive correlation between bison utilization and size of forest opening (Van Vuren 1983). Additionally, bison are known to communicate visually and can distinguish large objects at about 1 km (McHugh 1958). Bison commonly vocalize with grunts at short distances and bellows at longer distances (McHugh 1958). Therefore, bison utilization of areas of larger viewshed is supported by previous bison behavior studies.

Utilization Probabilities by Pasture

After the probabilities were modeled throughout bison range, the potential for increasing the probability of bison utilization could be considered for future management. Within individual pastures, the probabilities for bison utilization varied, however general probabilities for bison utilization were considered.

The general probabilities for bison utilization for the nutritional Bayesian model, physical environmental Bayesian model, and behavioral Bayesian model (Figures 12-

14) are provided (Table 5). The probabilities for bison utilization by pasture can be considered independently for each column. For example, in the pastures that contain high probabilities of bison utilization resulting from physical environmental qualities, nutritional and behavioral variables could be altered to increase bison utilization. In pastures containing low probabilities of bison utilization resulting from physical environmental variables (since elevation, slope, and distance from water cannot be altered), altering the nutritional and behavioral qualities of the area likely would not increase bison utilization.

Nutritional aspects of bison utilization could be altered by rangeland practices. Changing the forage quality by altering species composition and/or increasing productivity by burning or cutting might increase bison utilization of these low probability areas resulting from nutritional variables. It is unlikely that viewshed or NND could be altered, as the ranch is currently managed subject to a conservation easement, held by The Nature Conservancy (The Nature Conservancy 1989). Therefore, management efforts could focus on areas with high probabilities of bison utilization regarding the physical environmental model, and moderately high probabilities regarding the social behavioral model if nutritional probabilities are low.

For example, management strategies might be most efficient, if applied to Edwards, Gateway bench and Newell pastures. The limiting factors for these three pastures are the nutritional variables as revealed in the probabilities. Therefore if the nutritional characteristics of the areas could be increased through management practices, then the overall utilization of these pastures might also increase.

Table 14. The general probabilities of bison utilization by pasture.

Pasture and general utilization level	Nutritional Model Probabilities (forage type, productivity, mineralogy, soil pH and soil salinity)	Physical Environmental Probabilities (elevation, slope, and surface soil texture)	Social/Behavioral Probabilities (nearest neighbor distance, and viewshed)
The Basins- overutilized	high	high	high
Edwards- underutilized	low	moderate/low	moderate/high
Gateway bench- underutilized	low	moderate/high	moderate/low
Home ranch- underutilized	moderate	moderate	moderate/low
Lower Cherry-na (lack of forage data)	not sufficient data	not sufficient data	high
Mill Creek- overutilized	mostly low	moderate	high
Newell Creek- underutilized	low	moderate	moderate
Pole Creek- underutilized	low	low	moderate
Southeast- underutilized	low and high	moderate/high	moderate/low
Wylie Ridge- moderately utilized	low and high	low and high	moderate

Chapter 6

CONCLUSION

This research was intended to provide ranch managers with information regarding the biophysical environment of areas receiving different utilization by bison.

Knowledge of the differences in the biophysical characteristics of areas of bison utilization might be important regarding management of the FDR.

The distribution of the bison utilization on the FDR was represented by 3 levels of utilization. A database of biophysical variables that had potential to influence bison habitat selection was developed, and analysis of these variables was performed using classification and regression trees (CART) and the Bayesian method in GIS. CART analysis provided information on the similarity of underutilized areas and moderately utilized areas. CART indicated that forage type, forage productivity, elevation, soil mineralogy, and surface soil texture were important predictors of bison utilization. The Bayesian analysis indicated that forage type, forage productivity, soil mineralogy, soil pH, soil salinity, elevation, surface soil texture, NND, and viewshed had significant associations with bison utilization. Calculation of conditional probabilities with the Bayesian method allowed modeling of the likelihood of bison utilization throughout the FDR as a result of these variables.

Management Implications

Of the nine biophysical variables that were found to be significantly ($p \leq 0.01$) associated with bison utilization, four of these variables could potentially be altered to improve bison utilization. These variables are forage type, forage productivity, NND, and viewshed. The Grazing Plan and Resource Base document provided by Rangehands, Inc. (Sindelar and Ayers 1999) addressed options for more widespread distribution of bison utilization on the ranch by manipulation of nutritional characteristics. Probabilities for bison utilization regarding nutritional characteristics are mapped (Figure 12) and can be incorporated into current management strategies regarding bison foraging.

Two behavioral variables, NND and viewshed, have significant ($p \leq 0.01$) associations with bison utilization and could be manipulated by managers. Viewshed could conceivably be increased by decreasing forest cover, however forest removal is likely not a feasible management strategy. NND could be decreased by creating corridors between foraging patches. Manipulation of these two variables could improve bison utilization in selected areas.

NNDs were lowest in areas of bison overutilization. This indicated that bison appear to prefer foraging areas that were well connected to adjacent areas. When the connectivity of the area increases, the NND value decreases. Viewshed values were highest in areas of bison overutilization. This indicated that bison had larger visible areas in these foraging areas.

The probabilities for bison utilization for each of the three models, nutritional, physical environmental, and social/behavioral, allow ranch managers to increase bison distribution

by addressing the reasons for the higher and lower utilization probabilities. It was not known if the reasons for the low probabilities justify the low bison utility on the ground, as the bison utilization was modeled for known bison foraging locations, not rules or criteria for bison habitat requirements. For example, bison in other geographic locations might utilize the low probability areas more efficiently. However, for the FDR bison herd, manipulation of the two behavioral variables, NND and viewshed, might result in more widespread utilization of the range.

Future Research

Future research regarding bison habitat requirements should include soil mineralogy, as the largest area of bison utilization consists largely of montmorillonitic soils. This research was not conclusive whether bison selected habitat as a result of soil mineralogy because other biophysical variable differences were also present. Bison utilization of certain soil mineralogy might be of interest to ranch managers for information regarding future ranch acquisitions.

Surface soil texture was found to be a significant predictor of bison habitat selection, however little research has been done of this relationship. Future research regarding the relationships of bison habitat and surface soil textures could indicate if this pattern is found for bison populations found in other geographic regions.

Additionally, bison appeared to prefer highly productive grasses in flat areas. However, after overgrazing of these grasses has occurred, nutritional demands of bison might be better met by foraging in less desirable foraging types, such as the bunch grasses

in the foothills regions. Many of these areas indicated high probabilities of bison utilization regarding physical environmental variables and behavioral variables. This could indicate that bison selected habitat because an innate quality or variable not included in this research.

$$I_{o\beta\gamma} = I_{sc} E_o [(\sin\theta\cos\beta - \cos\theta\sin\beta\cos\gamma)\sin\delta + (\cos\theta\cos(\beta + \sin\theta\sin\beta\cos\gamma)\cos\delta\cos\omega_i + (\cos\delta\sin\beta\sin\gamma\sin\omega_i))]$$

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APPENDICES

Appendix A
Details of Biophysical Data

The **FDR boundary** was obtained by the Natural Resources Information System (NRIS). NRIS is a clearinghouse for GIS databases in Montana. The data for the boundary came from a 1:62,500 scale map in the Flying D Ranch Conservation Easement Documentation Report, 12/19/89, that was produced by The Nature Conservancy. This boundary was transferred to 1:24,000 scale maps by the State Historic Preservation Office and digitized at the State Library. The exterior FDR boundary has been verified by Bud Griffith, ranch manager, however analysis will only include areas of known utility designated by him as the ranch manager.

Forage Type and Forage Productivity information was collected in spring 1997 by Rangehands, Inc. Forage types were identified based on physiography, types of vegetation, and forage production capability. Thirteen forage types were identified. This information was initially delineated on 7.5 minute topographic quadrangles and digitized. Forage productivity was generalized to represent the potential yield of each forage type and is measured by pounds per acre.

Soils - The FDR is located in Madison and Gallatin Counties, and the southernmost edge lies in the Gallatin National Forest. All soil parameters were gathered for all three of the entities, however only the county coverages were joined as all areas of known bison utility were located in Madison and Gallatin counties. All three of the soil coverages were mapped at 1:24,000 scale and were collected using the national standards used to construct the soil maps in the Soil Survey Geographic (SSURGO) data base, and are

therefore SSURGO certified. SSURGO is the most detailed level of soil mapping done by the Natural Resources Conservation Service (NRCS).

The four soil parameters included are soil mineralogy, soil pH, soil salinity, and surface soil texture. The mineralogy classes found on the FDR are carbonatic, montmorillonitic, and very small quantities of mixed soil mineralogy. Soil pH ranges from 6.0 to 8.4. Soil salinity indicates the electrical conductivity of the soil in a saturated paste. Values are expressed in mmhos/cm and range from 0 to 16.

There are 37 surface soil textures found on the Ranch. The 37 categorical variables have been grouped into 4 classes (pers comm Dr. Cliff Montagne) representing 1) fine soil without rock fragments, 2) fine soil with rock fragments, 3) coarse soil with rock fragments, and 4) coarse soil without rock fragments.

Elevation - The elevation data for the ranch was gathered from the US Geological Survey website (www.usgs.gov) as a digital elevation model (DEM). This data is represented as a grid and has 30 meter grid cells. The DEM is required to derive the datasets slope, and viewshed. All derived datasets are either level I-good or level II-fair quality.

Slope - The slope for the ranch has been derived from the digital elevation model, therefore having the same scale and grid cell size. This derivation is performed by identifying the rate of maximum change in the z (elevation) value from each cell. Then cells are reclassified and represented as a grid showing pixels as degrees of slope. The

Flying D ranch has a minimum degree of slope of 0 degrees and a maximum degree of slope of 46 degrees based on the dem.

Distance from Water - Rivers and streams were digitized from 7.5 minutes topographic quadrangles. Distance from streams was calculated by creating a grid using 30 meter grid cells. This grid represented the number of cells away from a water source. For example, the distance from 0 to 30 meters away from Spanish creek was represented with a value of 1. Distances from 31 to 60 meters away from Spanish creek were represented with a value of 2.

Spatial Pattern Metrics - FRAGSTATS was used to perform this spatial pattern analysis. After input of the land cover dataset, a search was performed for contiguous patches of habitat and calculated a set of landscape metrics (values) based on individual patch (forage types), each class type, and the landscape as a whole. Metrics included patch size, patch shape, nearest neighbor distance, and proximity. The pattern analysis was completed using five land cover classes resulting from a classification of a Thematic Mapper (TM) satellite image. These classes are non-vegetation, forest, riparian, wet grassland, and dry grassland.

The land cover data was a product of Landsat Thematic Mapper satellite imagery. This dataset was used rather than the forage type dataset because the forage type dataset contained information only in the pasture lands, which was not sufficient for landscape pattern analysis. The TM data consisted of pixels that represented the average reflectance

of 900m² on the ground, each pixel representing 30x30 m on the ground. An unsupervised classification was performed from three bands of a tasse-cap transformation. The labeling of individual clusters was completed using expert opinion of FDR manager Bud Griffith, Nature Conservancy Vegetation maps, expert knowledge of vegetation characteristics relating to their geographical position, and three days of field work using a Global Positioning System (GPS) and empirical observations.

Wet and dry grassland were determined by using bands 1, 2, and 3 from a tassled cap transformation which highlighted wetness in vegetation, and additionally considered slope, aspect, and numerous observations on the ground.

Patches were defined as areas of similar land cover. **Patch Size** was the area of each patch in hectares. **Patch Shape**, which indicated the regularity of a patch, was calculated by dividing patch perimeter by the square root of patch area. Metrics that indicated the connectivity of patches included **Nearest Neighbor Distance** and **Proximity**. Nearest neighbor distance calculated the distance in meters of the nearest neighboring patch of the same type, based on shortest edge to edge distance. The proximity index calculated the number of neighbors of the same patch type within a search radius, weighting patches differently according to the size and distance away from the patch considered. Both of these metrics indicated the heterogeneity of the landscape, or the connectivity of patches within the landscape. All metric values were taken to log base 10, and multiplied by 1000 to obtain feasible values for analyses.

Viewshed - A viewshed analysis was completed for the FDR. Viewshed was calculated using a digital elevation model (DEM) for relief and incorporating the forest class from the classified TM image. Areas of the ranch consisting of forest were given an additional height value of 30 meters, the average height of lodgepole pine and Douglas-fir. This forest cover was added to the ranch DEM and a visibility analysis performed on this dataset. The viewshed analysis determined the number of observed points that could be seen from each cell, therefore indicating the amount of visibility from each cell. An offset of 2 meters was provided to simulate the height of a bison view height, which was the average hump height in male and female bison found in bison literature. A 2000 meter vertical distance maximum was assigned to limit the farthest distance a bison could view. The 2000 meter horizontal distance was used to limit the viewing area for computational purposes and provided a point to stop calculation of viewshed so that the viewing area didn't potentially go on forever. No research could be located regarding the distance that bison can see or a nearer distance would have been considered. Because of the computational intensity of the viewshed calculation, a 90 m cell size was required to facilitate the completion of this dataset.

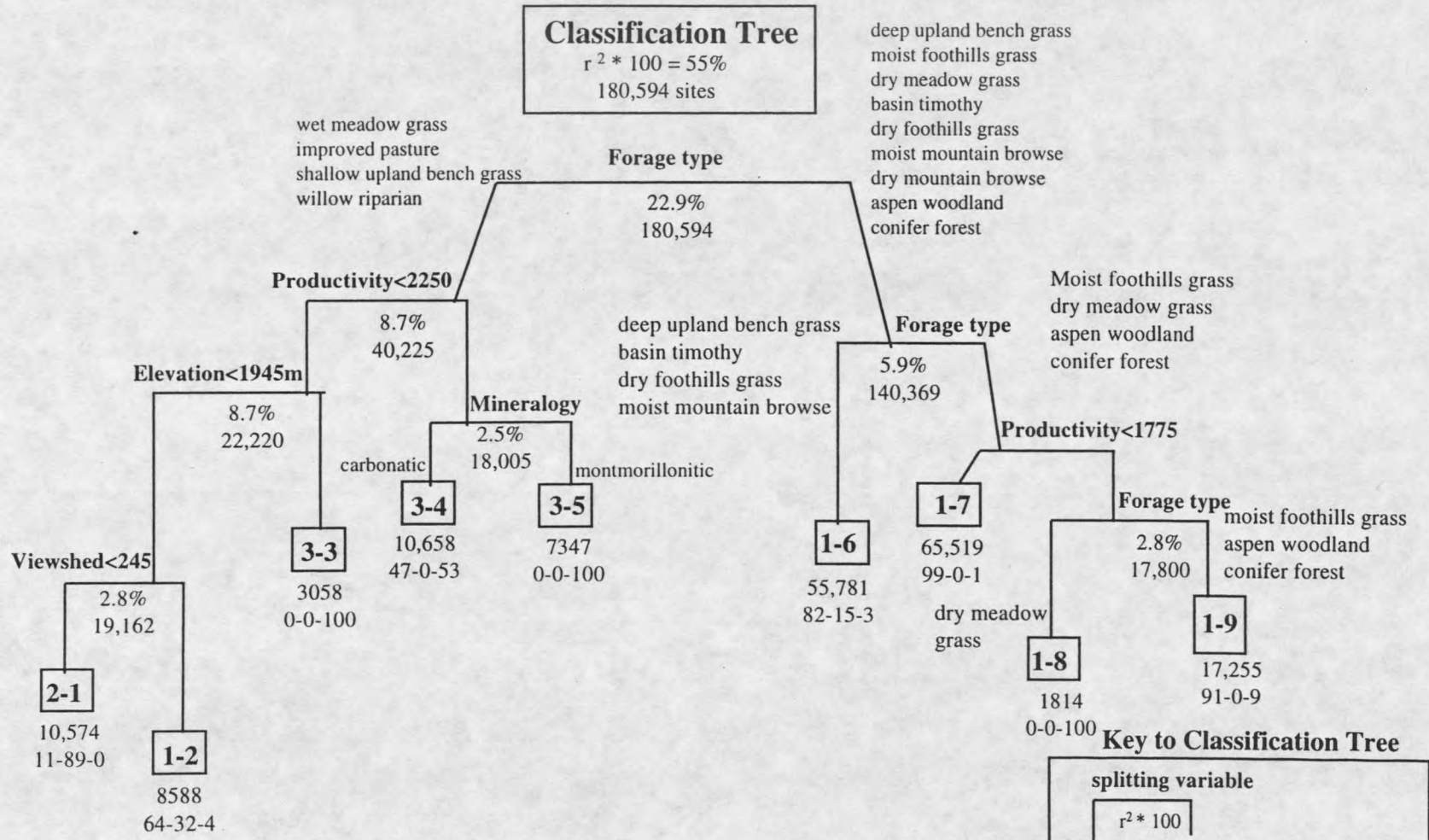
Utilization - Utilization information was provided by Bud Griffith and portrayed as polygons on 7.5 minute topographic quadrangles. These data were digitized and labeled according to the level of utility. Bison utility indicated represented the historical level of utility since bison inhabitation. Bison receive supplemental food during winter months, therefore utilization represents only the months of April through September.

Appendix B

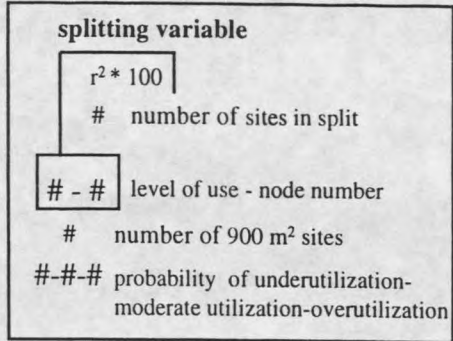
Interior boundary Classification Tree

Classification Tree

$r^2 * 100 = 55\%$
180,594 sites



Key to Classification Tree



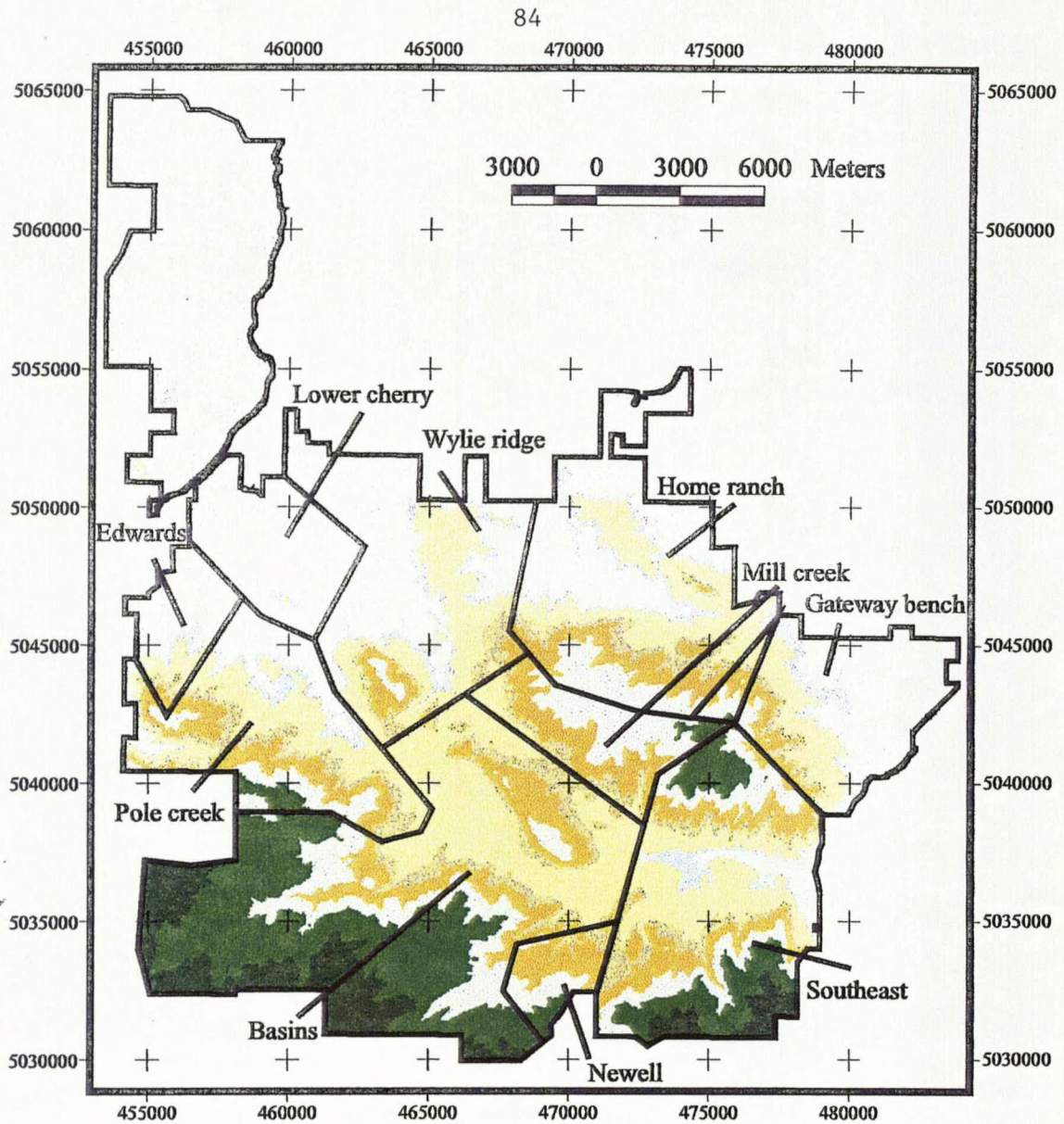
Appendix B. Classification tree of interior use areas pruned to 9 terminal nodes with $r^2 = 55\%$. Splitting criteria is true to the left of the split.

Appendix C

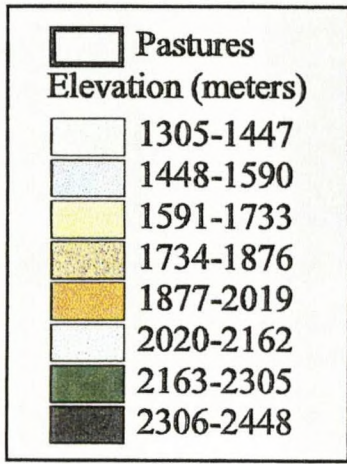
Exterior boundary Classification Tree

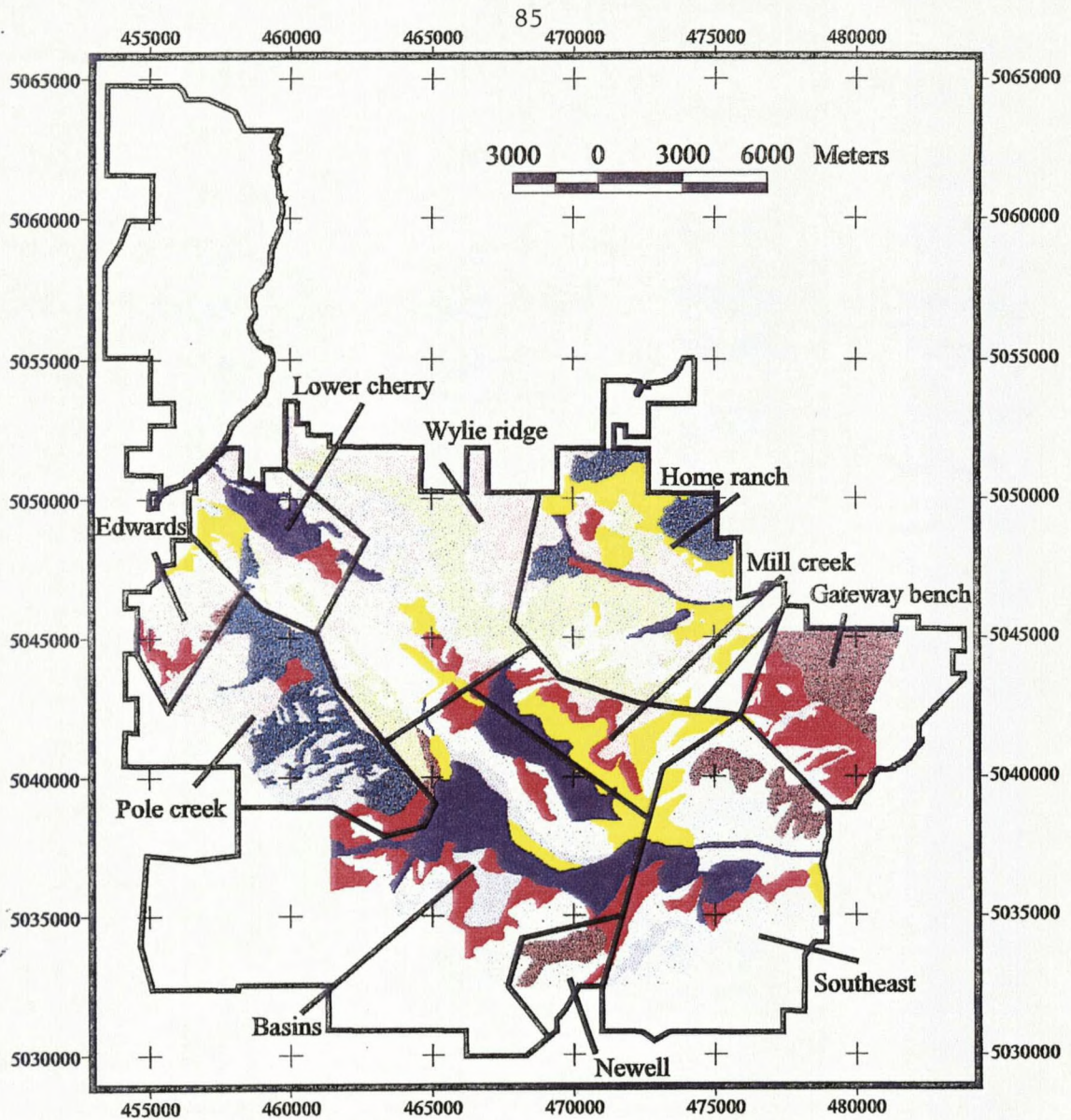
Appendix D

Maps of all significant biophysical variables

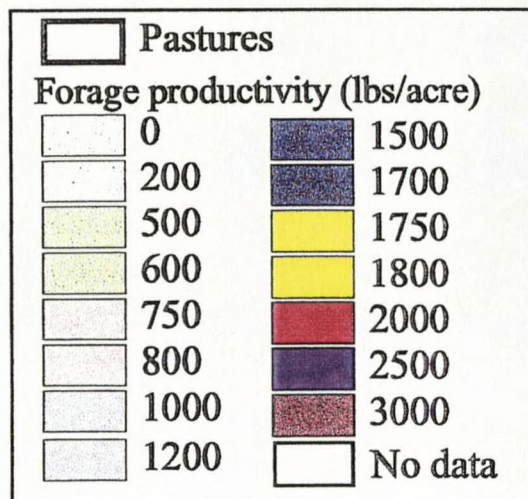


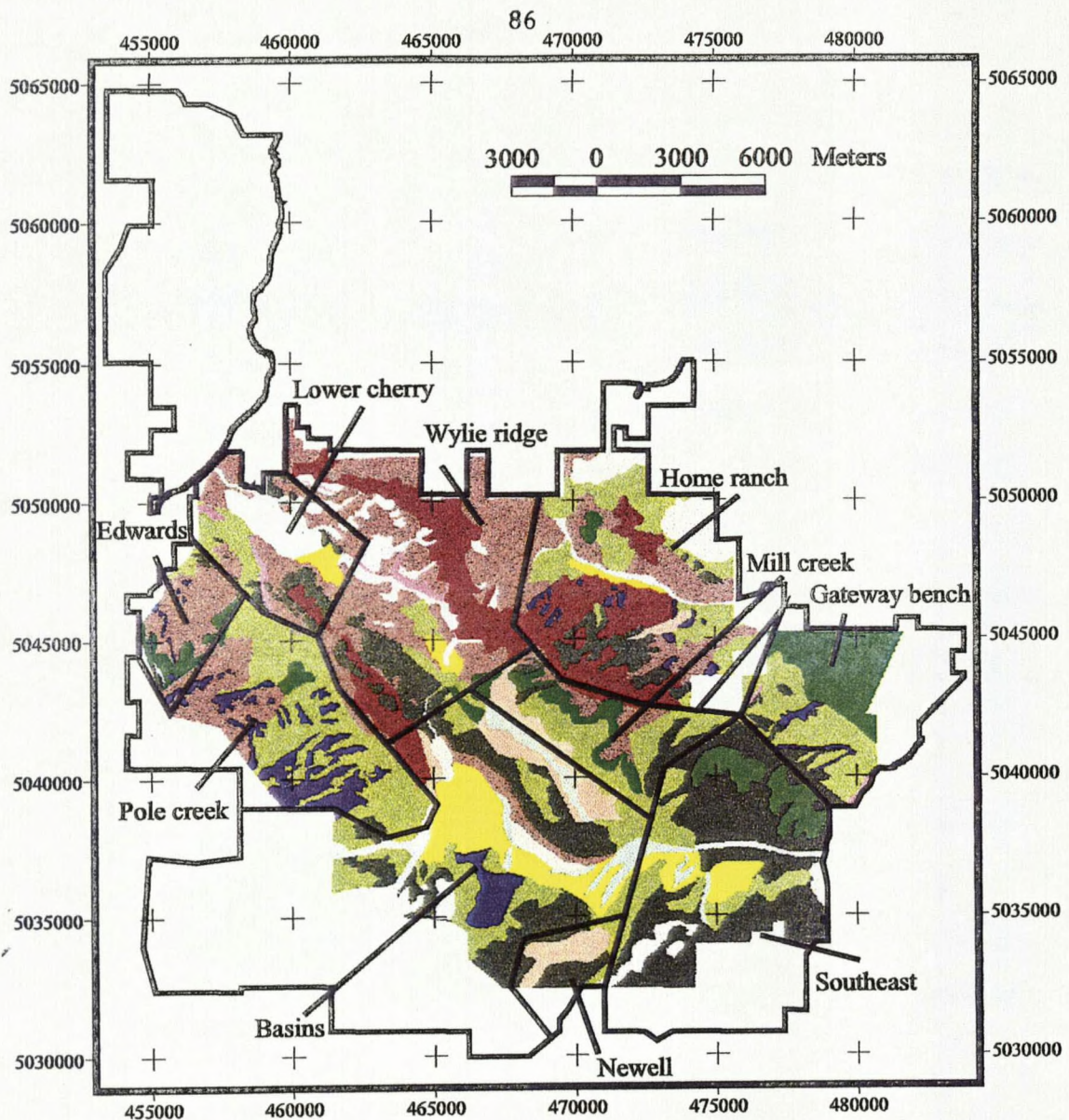
Elevation and pastures


















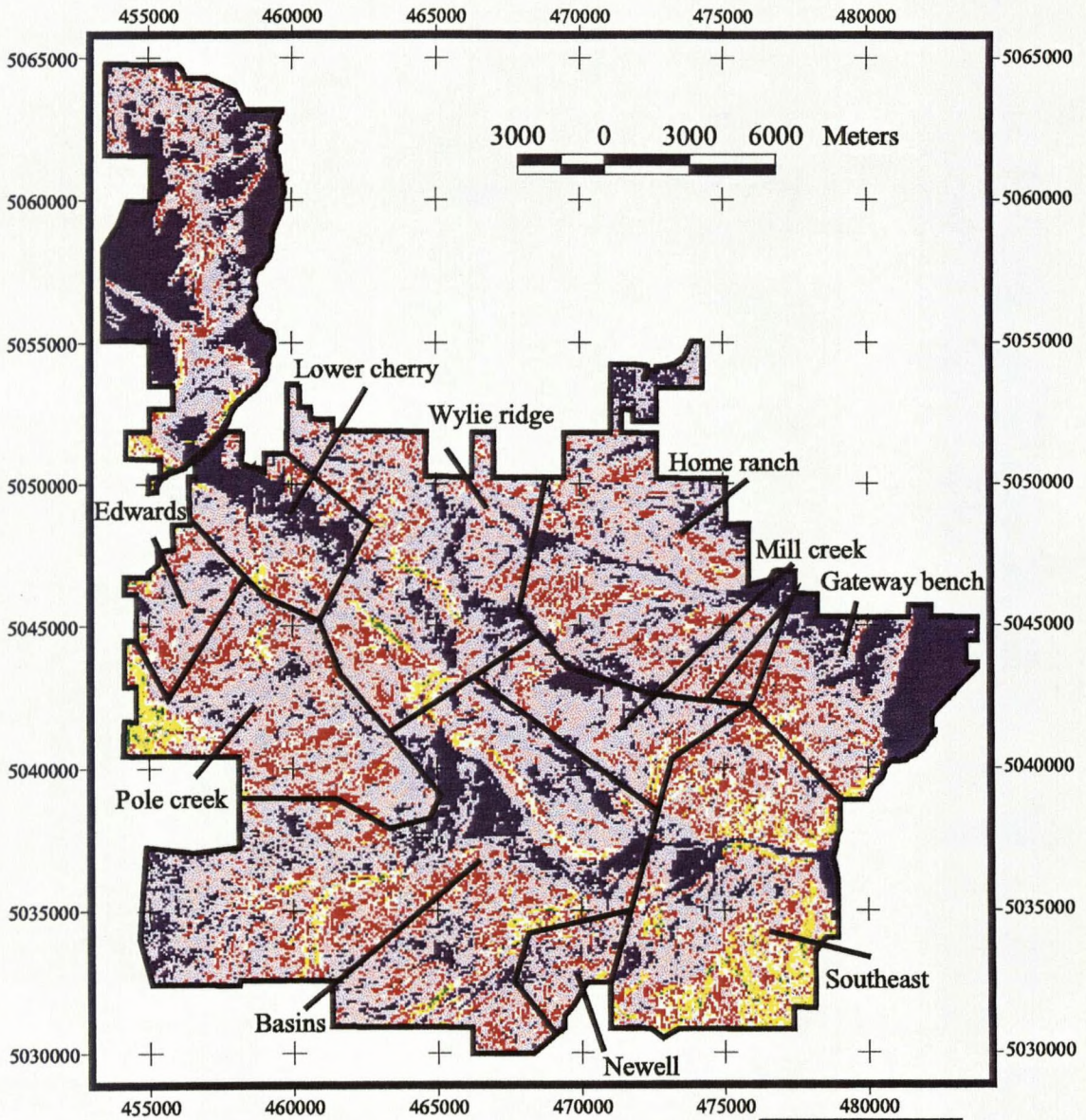
Forage productivity and pastures



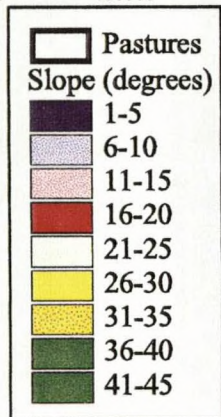


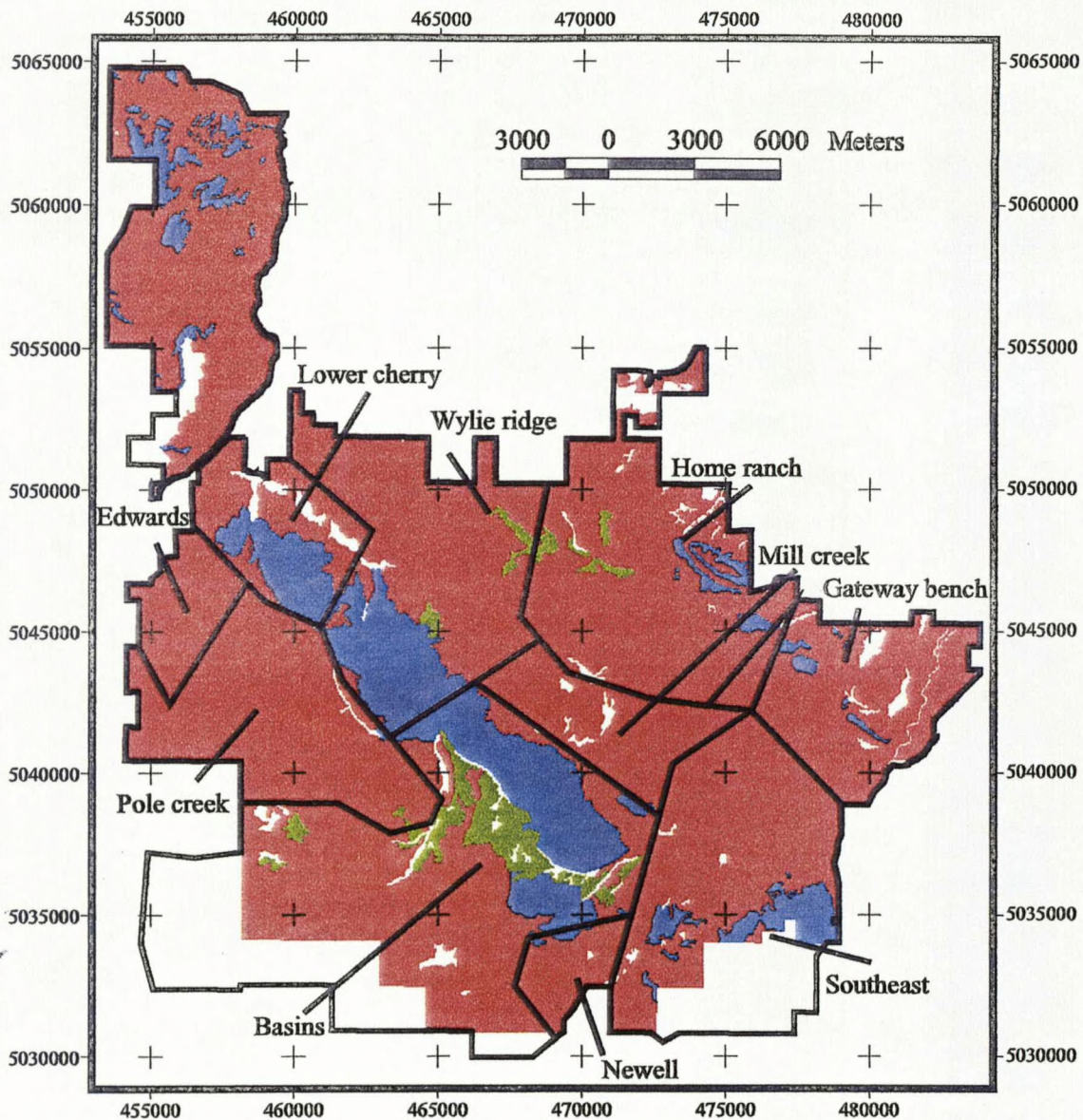
Forage types

- | | |
|--|---|
|  deep upland bench grass |  basin timothy |
|  shallow upland bench grass |  moist mountain browse |
|  moist foothills grass |  dry mountain browse |
|  dry foothills grass |  aspen woodland |
|  wet meadow grass |  willow riparian |
|  improved pasture |  conifer forest |
| |  No data |

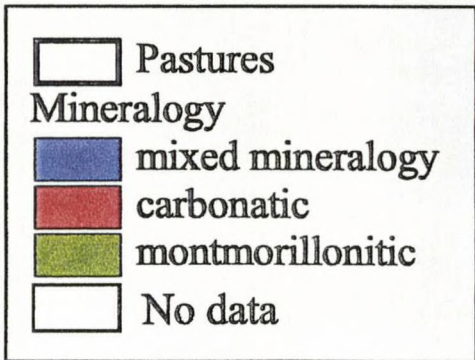


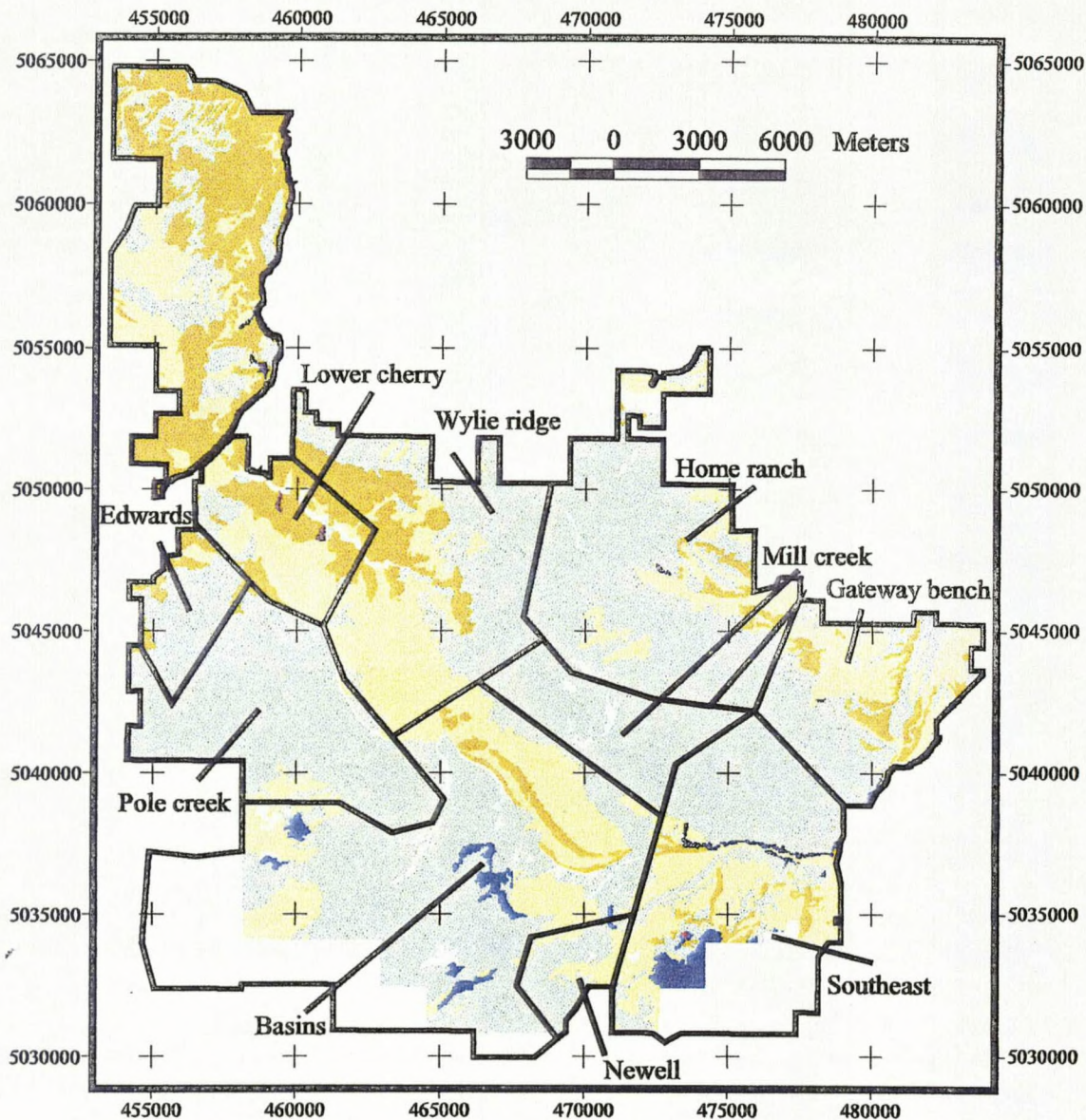
Slope and pastures



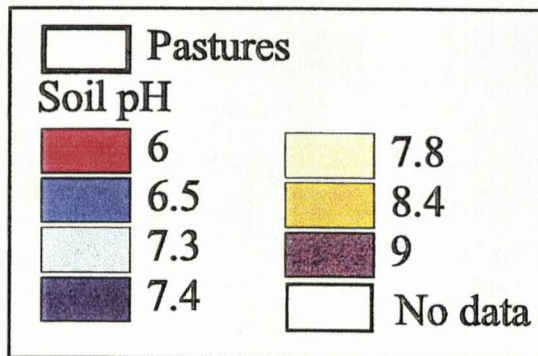


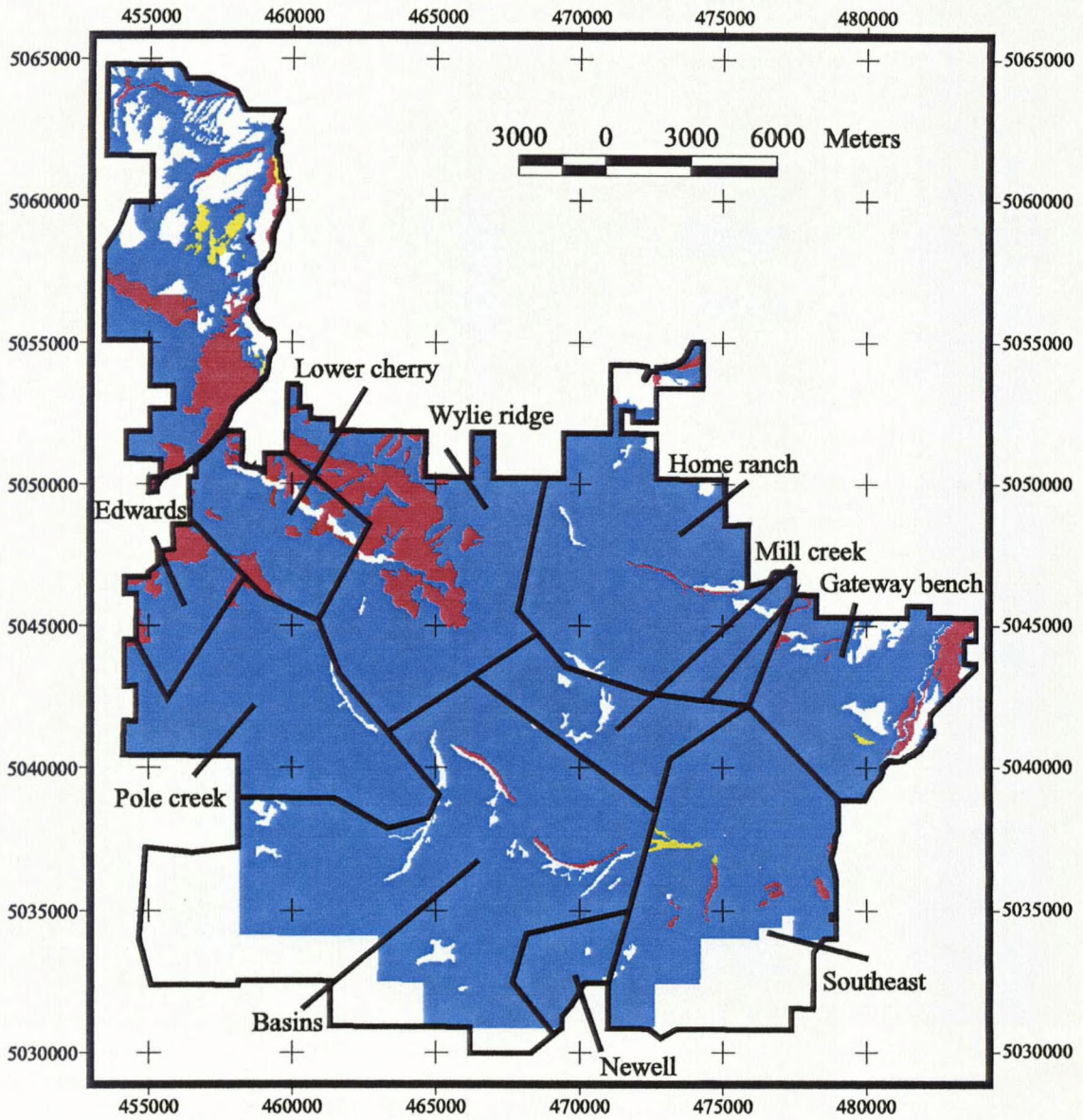
Soil mineralogy and pastures



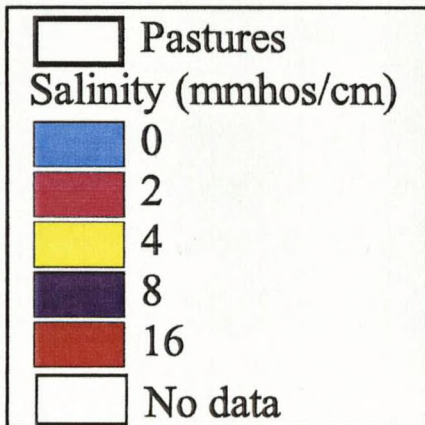


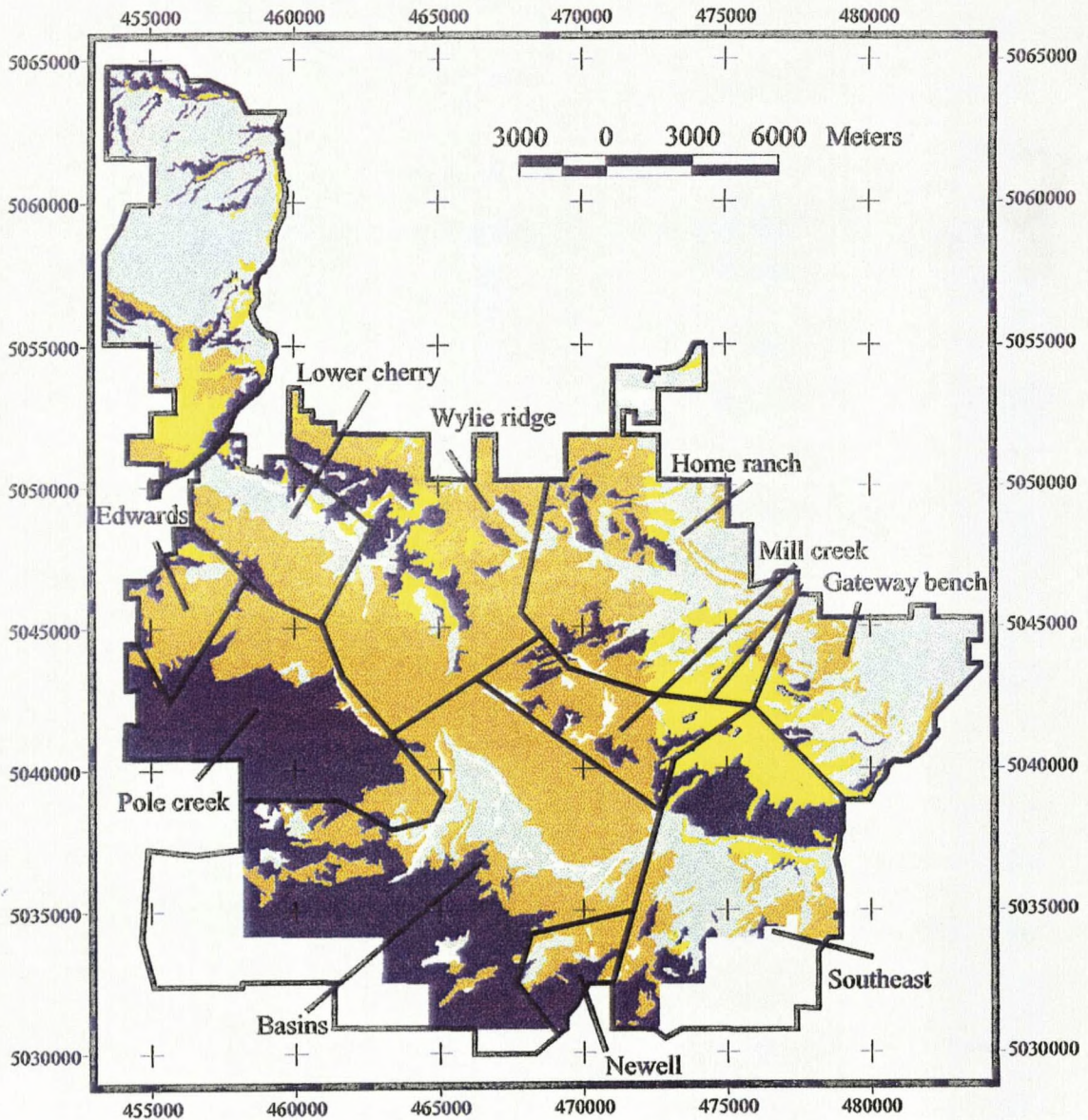
Soil pH
and pastures



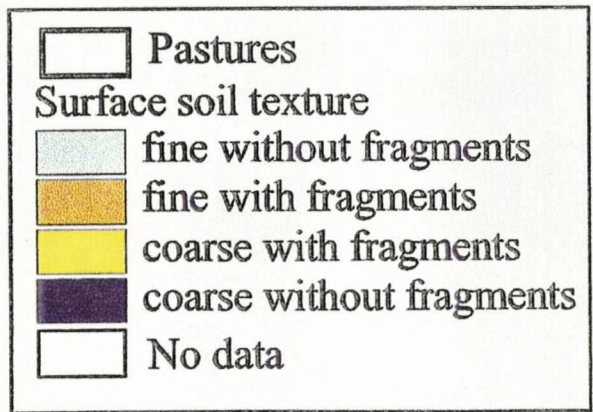


Soil salinity and pastures





Surface soil texture
and pastures



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