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Spatial Precipitation Variability, Snowfall, and Historical Bison Occurrence in the Northwest United States

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SPATIAL PRECIPITATION VARIABILITY, SNOWFALL, AND HISTORICAL BISON OCCURRENCE IN THE NORTHWEST UNITED STATES

by

HEATHER ANNA WILLIAMS

Under the Direction of Paul A. Knapp

ABSTRACT

Throughout the Holocene, bison have always been more abundant east of the Rocky Mountains with considerably fewer bison found west of the Rocky Mountains. It is likely that drought frequency and snowfall characteristics have influenced the pattern of historical bison occurrence across the northwest United States. Using monthly average snow and precipitation data from the past several decades, average April snow water equivalent (SWE) and summertime drought frequency were analyzed at sites across the northwest United States. A climatic stress index (CSI) was developed by combining average SWE and drought frequency for sites, as these are the climate factors that will most likely affect bison success. The results of the CSI revealed that locations west of the Divide experience heavier snowfall and a greater frequency of droughts, thus presenting a "double whammy" of climate conditions that bison would have to endure. The locations of highest combined snow and drought frequencies coincide with locations of low bison occurrence.

INDEX WORDS: Bison, northwest United States, snow water equivalent, drought, climatic stress index

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LIST OF ABBREVIATIONS

BP	Before present
CD	Continental Divide
CSI	Climatic Stress Index
ENSO	El Niño/Southern Oscillation
GIS	Geographic Information System
ICBEMP	Interior Columbia Basin Ecosystem Management Project
JA	June through August
KA	Millennium
NCDC	National Climatic Data Center
NOAA	National Oceanic and Atmospheric Administration
NPP	Net Primary Productivity
NRCS	National Resources Conservation Service
NWCC	National Water and Climate Center
NWS	National Weather Service
PCA	Principal Components Analysis
PDSI	Palmer Drought Severity Index
PDO	Pacific Decadal Oscillation
PNV	Potential Natural Vegetation
SNOTEL	Snowpack Telemetry
SST	Sea surface temperature
SWE	Snow Water Equivalent
USGS	United States Geologic Survey

CHAPTER 1: INTRODUCTION

The distribution of animal populations is principally limited by the availability of food, shelter, and competitive interactions with other animal species. Other factors, however, also influence populations, including the role of climate. While the influence of climate has often been mentioned, it has never been fully explored as a possible cause for the lack of bison west of the Continental Divide (CD) in the northwest United States (Moore 2002), despite what appears to be suitable grazing habitats (Grayson 1982, Burkhardt 1996). Understanding the reasons for the distribution of bison is ecologically critical as it is the largest mammal in North America and has exerted a significant impact on the landscape (Lott 2002). Thus, many have attempted to investigate the puzzling distribution pattern of bison abundance (Mack and Thompson 1982, Daubenmire 1985, Van Vuren 1987, Flores 1991, Garret 2001, Martin and Szuter 1999 and 2002, Lyman and Wolverton 2002, Moore 2002). One area that has received less attention, but may be of exceptional importance, is the role of climatic variability. This analysis will show that drought frequency and snowfall have likely influenced the pattern of historical bison distribution across the northwest United States.

Historical documents from early explorers and traders provide a significant resource of knowledge on the natural landscape of the Northwest before European settlement. During the 1804-1806 Corps of Discovery Expedition leaders Meriweather Lewis and William Clark meticulously recorded daily observations and experiences on the trail. In addition to botanical, geological, and meteorological documentation, the journals chronicle hunting conditions along the trail as detailed as the exact number and species of game killed per day: "*Every copse of timber appears to have elk or deer. D. killed 3 deer, I killed a buffalo, York 2, R. Fields one. Captain Clark, 9 September 1804*" (Moulton 1983). Bison appear to have been the preferred game when it was abundant because one bison could supply as much meat for the

expedition as 5-6 deer in a single day (Martin and Szuter 1999). It is clear from their journal entries that bison game became scarce as soon as they crossed westward over the Continental Divide, without an apparent significant change in plant communities, but why? What caused bison to become absent from the headwaters of the Missouri River westward?

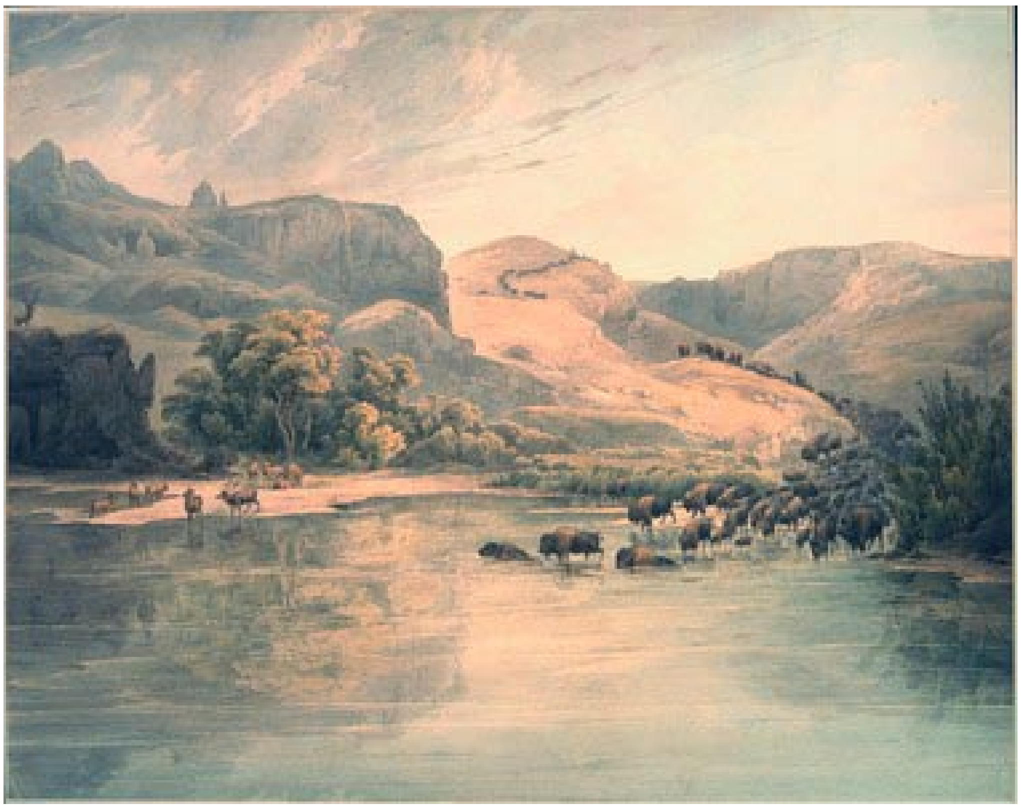

Figure 1. Bison along the Missouri River. Painting by Karl Bodmer/Historical Picture Archive/Corbis ("Lewis and Clark", 2004 www.nationalgeographic.com)

Figure 2. Missouri Headwaters State Park, Montana. This is the approximate location where Lewis and Clark began to observe a decline in bison numbers. This area also represents grass communities suitable for bison.

Using Lewis and Clark's journals, Martin and Szuter (1999) mapped the abundance of game recorded along the Lewis and Clark Trail. Game was plentiful along the Yellowstone and Missouri Rivers in Montana but scarce west of the CD - observations that are consistent with archaeological evidence of relative bison and elk scarcity in this region during the late Holocene ~450-2000 years B.P (Van Vuren 1987). Why such a difference in population sizes has been a topic of great interest that has been principally examined from an ecological perspective. Few (e.g., Daubenmire 1985) have explored how climate may affect the suitability of rangeland for bison west of the Continental Divide. Moreover, most studies regarding bison and climate have been conducted at localized scales to understand the dynamics of current bison populations (e.g., Yellowstone National Park) (Van Camp 1975, Meagher 1976, Turner 1994, Farnes 1996) Thus,

an opportunity exists to address, at a regional scale and from a climatological perspective, the question: Have climatic conditions west of the Continental Divide precluded historical bison occurrence?

The purpose of this study is to explore the relationship between climatic conditions, suitable grazing habitat, and bison occurrence in the Northwest United States (NW U.S.). This will be accomplished by examining general climatology patterns across the NW U.S. region, and more specifically, by comparing inter- and intra-annual meteorological drought frequency and snowfall variables between known locations of suitable bison habitat east and west of the Continental Divide. In addition to providing a geographic/climatalogical perspective into the problem of bison distribution, the results of this investigation should contribute additional insight on current climate variability regions; supplementing previous work on climate regionalization in the Northwest United States (Mitchell 1976). This research should also be useful because of increased interest in bison production in the areas within the NW U.S. (Urness 1989, Moore 2002).

In this study, I explore three areas that will provide insights on the historical patterns of bison occurrence across the NW U.S. Specifically, I address three questions:

1. Do significant differences in the spatial patterns of variability of inter-annual, intra-annual, and sustained drought frequency exist across the Northwest United States?
2. Are there significant differences in snowfall amounts and snow water equivalents (SWE) between locations east and west of the Continental Divide?
3. Given suitable opportunities for grazing and reproductive activities, what is the threshold of climate variability that bison populations could endure in this region?

Review of Literature

The question of Holocene bison abundance west of the Continental Divide has been an active topic of debate among researchers for decades (Moore 2002). The topic is especially contentious because the precise distribution and abundance of bison in the NW U.S. throughout

the Holocene has not been completely resolved (Lott 2002), and because there has not been a recent comprehensive survey of archeological bison evidence for the Northwest United States (Van Vuren and Bray 1985). Bison remains continue to be unearthed, and bison populations west of the Rockies were exterminated over 100 years ago, leaving researchers few present day analogues for a complete understanding of distribution patterns (Van Vuren 1987). However, it can be concluded from archeological data and the writings and descriptions of early explorers and Indians that bison occurred throughout the NW U.S., but were only abundant east of the Rocky Mountains (Mack and Thompson 1982, Daubenmire 1985, Van Vuren and Bray 1985, Van Vuren 1987, Flores 1991, Garret 2001, Martin and Szuter 1999 and 2002, Lyman and Wolverton 2002, Moore 2002).

What factors have controlled bison distribution in the Northwest United States? Four main arguments exist on the cause of low bison abundance west of the CD: 1) Human predation (Martin and Szuter 1999, 2002), 2) Poor forage (Mack and Thompson 1982), 3) A combination of human predation, forage quality, and migration obstacles (Van Vuren 1987, Lyman and Wolverton 2002), and 4) Climatic factors including winter severity (Daubenmire 1985, Bjornlie and Garret 2001) and drought (Flores 1991).

General Bison Ecology

Until the late 1800s, the Plains bison, (*Bison bison*) were one of the most abundant mammals in North America (Lott 2002). Bison ranged from Great Slave Lake in Canada south into Mexico, and from eastern Oregon to the Atlantic Ocean. Their abundance was highest, however, in the Great Plains (Lott 2002), and because of the advancement of European-descent settlers associated with the westward expansion of the United States, bison numbers were reduced to near extinction by over hunting (Van Vuren 1987). Currently, bison populations are limited to isolated herds on ranches, reserves and parks, including free-ranging herds in Yellowstone National Park in Wyoming and the National Bison Range in Montana.

Throughout much of the Holocene, bison, in addition to elk (*Cervus elaphus*), pronghorn

(*Antilocarpa americana*), white-tailed (*Odocoileus virginianus*) and mule deer (*Odocoileus nemonius*) were the dominant grazers of the Great Plains grassland communities. Bison are considered to have been an important species because of their beneficial role in the nitrogen cycling process and promotion of species richness through grazing patterns (Knapp *et al*. 1999). Bison diets will vary based on the habitat, but in general, bison are grazers of primarily grasses and sedges (Reynolds and Peden 1987), but will forage for herbs and occasionally browse woody plants (Meagher 1976). They are generally considered "bulk feeders", selecting forage based primarily on quantity of forage, rather than quality, compared to elk (Wallace *et al*. 1995). Notwithstanding, grazing patterns can to some degree be predicted based on patterns of precipitation or fire (Risser 1990). For example, bison tend to prefer recently burned areas, favoring new-growth grass, which is believed to be an important mechanism for maintaining grassland species diversity (Shaw and Carter 1990, Knapp *et al*. 1999).

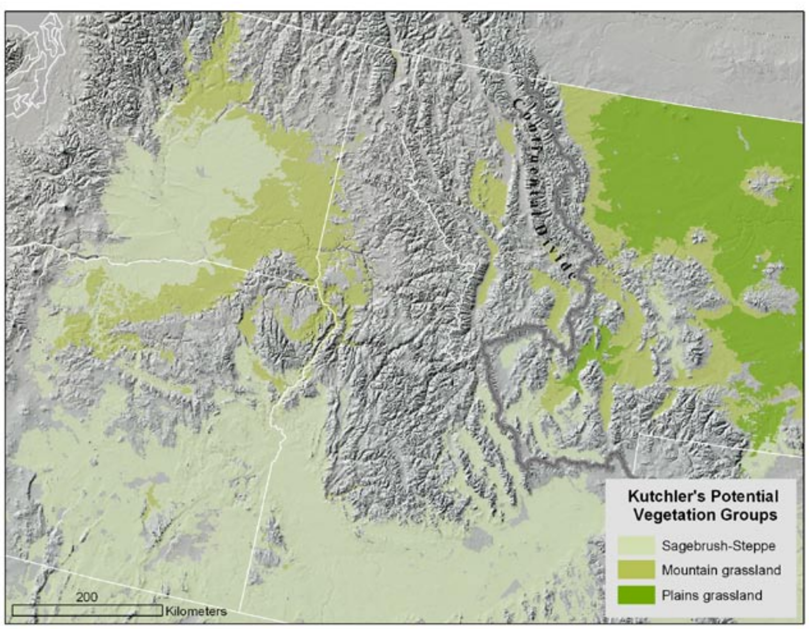

Figure 3. Map of major grassland-steppe communities based on Kutchler's Potential Vegetation (1964).

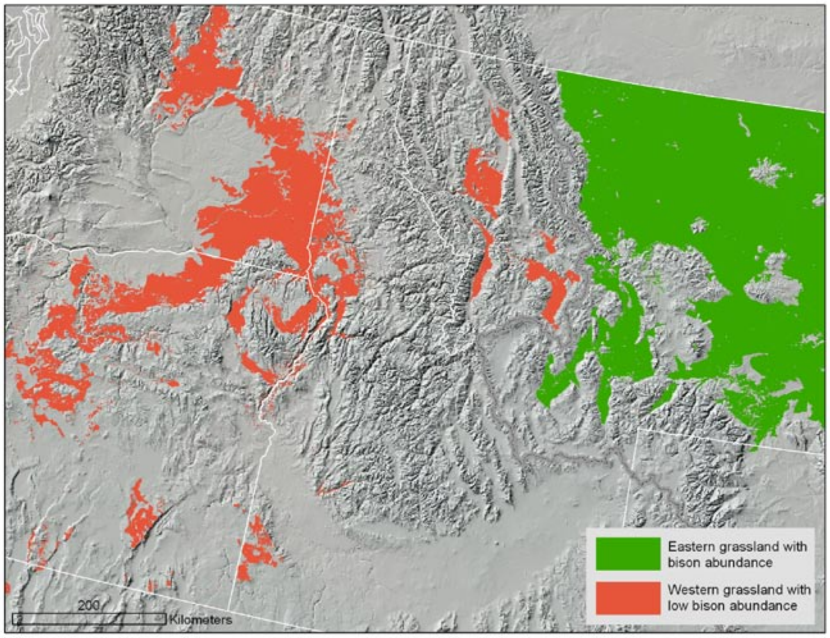

Figure 4. The distribution of suitable grassland habitat for bison across the Northwest United States. Areas highlighted in red represent zones of comparatively low bison abundance, while green areas represent high bison abundance.

Bison and Snow

Previous research has attempted to quantify the point at which snow becomes a limiting factor for bison success during winter (Wallace *et al*. 1995, Turner *et al.* 1994, Meagher 1976). Most of these studies have used snow depth (distance from surface to ground) property rather than snow water equivalent (volume of water from melting snow), because snow depth values are easier to obtain when doing local-scale studies of bison behavior. Reynolds and Peden (1987) determined that bison in Yellowstone were able to forage in depths up to 114 cm, but moved to areas of less snow cover when depths were greater than 127 cm. Daubenmire (1985) offered that increased snow depth in the valleys of western Montana is a likely hindrance to foraging, and cites several historical accounts of bison demise during severe winters in Idaho and Utah. His hypothesis focused on snow *depth* rather than forage quantity/quality, because the steppe species east and west of the Divide in Montana, while of different species composition, are both suitable

for grazing. In addition, he notes that bison herds were historically abundant in the steppe habitat of western Montana, and the current herds in the National Bison Range (west of the CD) have done well for decades. According to his research, bison can move up to ~75 cm of snow with their heads, but cannot forage in either deeper or crusted over snow (Figure 5). He postulated that attempts to cross over the Continental Divide through mountain passes were thwarted by deeper snows encountered on the western slopes. Daubenmire's conclusions of low bison abundance due to increased snow depth are based on historical accounts, and do not include climate data.

Others have found that snow density also influences foraging behavior, and may be more important to consider (Turner *et al.*1994). In addition to snow depth, snow density and hardness will influence foraging ability (Turner *et al.* 1994, Farnes 1999). In general, the density of fresh snow is inversely related to temperature; therefore, it could be expected that snow densities will be greater at lower elevations, if all other factors are equal. But after the snow falls, density is influenced by other factors such as wind abrasion, and melting and refreezing (http://www.or.nrcs.usda.gov/snow/about/swe.html). An additional consideration that has been noted is that deep or high-density snow associated with severe winters presents an especially difficult challenge for bison calves, which is a concern if snow falls late in the season during the onset of calving season (late April-May) (Reynolds and Peden 1987). It has been observed that snow depths greater than 50 – 60 cm can prevent calves from foraging (Van Camp 1975).

A review on the studies of winter grazing habits of bison in snow in the Slave River basin of Canada and Yellowstone National Park (Wallace *et al*. 1995, Turner *et al.* 1994, Meagher 1976) indicate the point at which snow becomes a limiting factor is complex and unclear. It is known, however, that bison cannot cope well with snow that is deep, heavy, or crusted over, because these conditions restrict forage availability, and increase the energy costs of foraging and mobility (Meagher 1976, Telfer and Kelsall 1984, Daubenmire 1985, Fancy and White 1987, Turner *et al.* 1994, Farnes 1999, Bjornlie and Garret 2001). Telfer and Kelsall (1984) used chest height, foot loading and behavior to calculate indices of snow coping ability for several North American ungulates, those with higher indices occurred in snowier regions. Of the species studied, pronghorn, short-grass plains

specialists, had the lowest indices. Elk, white-tailed deer and bison tolerate the shallow soft snow of the southern boreal forest. In order of decreasing adaptation to deep snow foraging across regions in Canada south into Montana and Wyoming, bison ranked second to last (Pronghorn antelope) following caribou, moose, wapiti, deer, and bighorn sheep (Telfer and Kelsall 1984).

Figure 5. Bison foraging in snow. Bison use their broad heads as plows to remove snow to access the vegetation below. Snow that is dense or compacted requires greater effort than powdery snow. National Park Service photo by Tom McHugh.

The deleterious effects of heavy snowfall associated with severe winters on bison is made particularly evident by a study reporting that herd populations decreased up to 50 percent in some cases, after the heavy snowfalls during the severe winters of 1956-57 and 1970-71 (Meagher, 1976). This study lends weight to the assertion made by Turner *et al.* (1994) that "winter range conditions are the primary determinant of ungulate survival and reproduction in Yellowstone."[1] So, while it is unquestionable that bison in general are adapted for cold, snowy climates, considering their thick coats of fur and broad heads used to plow through snow, too much (particularly heavy) snow is likely

1. The following excerpt was taken from The National Park Service "Morning Report", on June 15th 1995: *The intensity and duration of the past winter has taken its toll on bison living in the interior of the park. Winter in the Lake area continued well into spring. As of May 5th, Lake ranger station recorded 40 inches of snow, with more still falling. The severity of the winter causes large-scale movements and mortality among the small bison population that winters in the Lake area. A number of bison made their way over Sylvan Pass out the East Entrance and to the North Fork of the Shoshone River. Since April, bison mortality has increased …As of May 5th, a total of 23 carcasses had been found in these areas… The mortality toll will likely continue until there is significant green-up in the Yellowstone Lake area*. (Daniel Reinhart, in "The Buffalo Chip", Resource Management newsletter).

the main limiting factor for winter survival (Meagher 1976, Daubenmire 1985, Turner *et al.* 1994, Bjornlie and Garret 2001). Thus, the question arises: are snowfall characteristics between the west and east sides of the continental divide significant enough to contribute to the geographical differences in bison populations?

Bison and Drought

In addition to snowfall, drought is also important to consider as a climatic variable that affects bison distribution and abundance. A paleoclimatic study based on tree-ring reconstructions of drought along the Colorado Front Range has provided evidence that a severe and persistent drought of the mid- 19th century in the western plains likely increased the vulnerability of bison herds to the decimation by humans (Woodhouse *et al*. 2002). In Yellowstone National Park, Frank and McNaughton (1992) reported that a severe drought in the late 1980's, followed by a winter of heavy snowfall was responsible for a reduction in the local bison population by ~50%. While bison are adapted to the cycles of drought intrinsic to the short grass/steppe prairies, the frequency and duration of drought spatially varies across the western U.S., therefore it is possible that the threshold of this tolerance is exceeded in some locations, and has historically restricted bison populations (Woodhouse *et al*. 2002). For example, Knapp *et al.* (2004) identified a core region of persistent drought within the interior Pacific Northwest. This area within central Oregon was identified as within an air mass transition zone identified by Mitchell (1976), where persistent droughts are more frequent than any other location in the continental United States (Cook *et al*., Knapp *et al*. 2004).

These studies provide supporting evidence that the frequency of droughts combined with high snowfall in the interior NW U.S. may explain the lack of bison occurrence in regions that appear to have sufficient food resources to support bison herds. Locations with a greater frequency of droughts and heavy snowfall could be considered a climatological "double whammy", thus presenting greater challenges to foraging and reproductive activities, and possibly either restricting or excluding bison populations. The results of this hypothesis may

have implications resolving the debate of bison distributions and current bison reintroduction plans to the NW U.S.

Human Predation

The human predation model is similar to Martin's (1984) "Pleistocene Overkill" hypothesis of the extinction of North American megafauna because of the arrival of humans. This model explains that Indian hunting activities reduced the abundance of game. From the journal entries of Lewis and Clark, Martin and Szuter (1999) discovered a spatial pattern of bison abundance in Montana east of the Rockies related to "war zones", or regions of dispute between groups such as the Sioux, Crow, and Pawnee nations. These areas would be avoided by hunting parties; therefore game abundance would be greater. Martin and Szuter (1999, 2002) contend that bison would be abundant in "game sink" areas, such as southeastern Washington, in the absence of human predation.

Lyman and Wolverton (2002) have disputed the validity of the human predation explanation stating that bison abundance throughout the entire Holocene was never as great in southeastern Washington as it was in Montana during the time of the Lewis and Clark expedition (Figure 6). They support an "environmental alternative" explanation first proposed by Van Vuren (1987) that explains low bison abundance in these areas "resulted from low carrying capacity and from periodic local extinctions followed by slow rates of colonization" (Van Vuren 1987). This explanation is based on the "mosaic of habitats" characteristic of the Pacific Northwest, because of the physiographic diversity compared to the relative homogeneity of the grasslands east of the Rockies (Van Vuren 1987). Immigration rates would be slower in the west of the CD after local extirpations caused by severe winters or human hunting, because bison populations were disjunct, thwarted by a landscape of physiographic features such as mountains, canyons, and deserts (Van Vuren 1987).

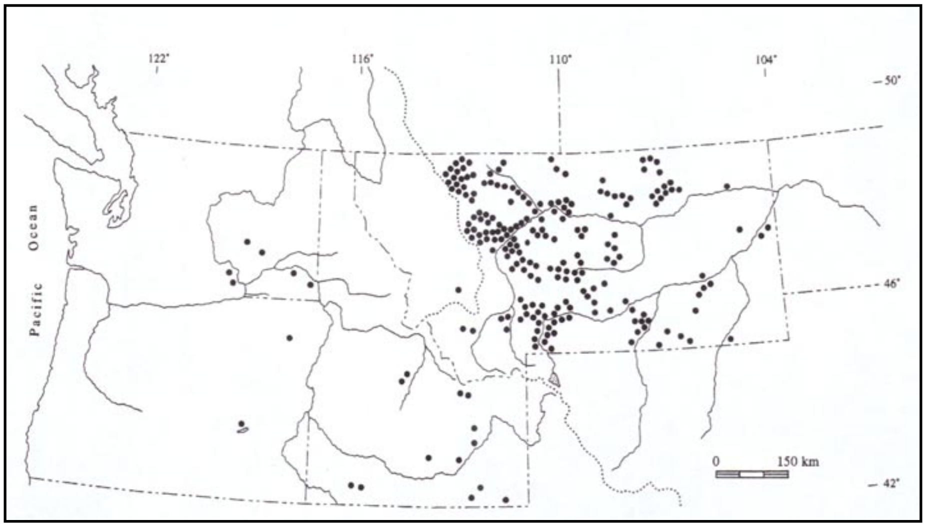

Figure 6. Bison kill sites (archeological evidence of a bison kill) for past 10,000 years (Lyman and Wolverton 2002).

Forage Quality and Quantity

Proponents of the “low forage” hypothesis assert that the protein content of forage in the Palouse prairies of the Pacific Northwest is inadequate to support large herds of bison (Johnson 1951, Mack and Thompson 1982). This hypothesis is not supported by the Pleistocene fossil record of the Intermountain region, which indicates that bison and other species of the Pleistocene megafauna thrived in this region until the extinction event (Grayson 1982, Burkhardt 1996). Bison survived the extinction and evidence indicates that they continued to thrive in the region until the 19th century (Van Vuren and Bray 1985, Urness 1989, Burkhardt 1996). In addition, currently existing bison herds have thrived for decades on the National Bison Range in Montana, which is of similar bunchgrass species composition as grasslands further west in Washington, Oregon, and Idaho. There is no compelling evidence that forage quantity is higher on the shortgrass prairies on the eastern slopes of the Rocky Mountains than the grasslands further west. In fact, while the distribution of forage quality and quantity across the region has been debated, very little empirical data have been presented to describe the regional patterns of forage productivity.

Holocene Bison Distribution and Abundance in the NW U.S.

Based on fossil evidence, it is generally accepted that bison were distributed throughout the NW U.S., but only abundant in southeastern Idaho, and east of the Continental Divide (Osborne 1953, Van Vuren and Bray 1985, Lyman 2004). In eastern Washington, there are more than 50 archaeological sites that have produced bison, but with the exception of a few, these sites have produced remains of only a few individuals (Lyman, 2004). Interpretation of fossil evidence in the Great Plains suggest that bison abundance was highest between 6,000-9,000 years B.P., decreased drastically in the mid-Holocene between 6,000-4,000 B.P., and increased again ~3,000 years ago (Alford 1973). These fluctuations in abundance have been linked to a change in climate from moister, cooler conditions in the early Holocene to a drier, warmer climate in the mid-Holocene (Lyman 1992). The “Altithermal” period, from ~8,000-4,500 B.P. should be the period of lowest mammalian richness in the Columbia Basin during the Holocene based on palynological data (Lyman 1992).Lyman (1992) tested this hypothesis by compiling archeological site data in the Columbia Basin, and found that the mammalian fauna data indicate a steady increase over the last 10,000 years, refuting the hypothesis based on climate alone. He cautions the interpretation of mammalian abundance based on the data due to the confounding effect on human prey selection behaviors. The perceived decrease in large mammalian fauna, rather than an indication of decreased abundance due to climate conditions, may be due to a shift in cultural prey selection habits (Lyman 1992).

To understand bison abundance as a function of climate variability, it is important to establish the range of conditions tolerated. The main assumption held in this project is that while temperature and moisture conditions have oscillated, the spatial pattern of variation has remained fairly consistent for the past millennia relative to the last 10,000 years. Since the relationship between moisture variability and bison occurence for this region will be evaluated using climate data for the current century, it is further assumed- based on sufficient evidence- that comparative bison abundance has not regionally shifted significantly in the northwest since the late Holocene. Additionally, based on paleoclimatic evidence, it is likely that drought severity and frequency

of the current century are moderate compared to the range of drought variability of the past millennia (Woodhouse and Overpeck 2000, Knapp *et al.* 2002).

Summary of Past Research

It is clear from the literature that bison were more abundant on the grasslands east of the Rocky Mountains than on the grasslands of the Pacific Northwest (Mack and Thompson 1982, Daubenmire 1985, Van Vuren and Bray 1985, Van Vuren 1987, Flores 1991, Garret 2001, Martin and Szuter 1999 and 2002, Lyman and Wolverton 2002, Moore 2002). What has not been fully resolved, as indicated by the ongoing debates, is the causal factor/s of this historical pattern. The explanations have implicated forage quality and quantity (Johnson 1951, Mack and Thompson 1982), human predation at the regional scale of the NW U.S. (Martin and Szuter 1999), snowfall depth (Meagher 1976, Daubenmire 1985), and drought (Flores 1991) at more localized scales. The most compelling are explanations that account for the inter-relationship of all of these factors (Van Vuren 1987, Lyman and Wolverton 2002). These studies have greatly improved the understanding of bison ecology; however, continued research is necessary to augment certain gaps within the body of research. Most notable is that a better understanding of the influence of regional climate patterns using empirical data has not been attempted. And while it has been documented that heavy snowfall and low rainfall can adversely affect bison at localized scales, what has not been examined is whether bison occurrence is influenced by regional patterns of *recorded* snow and rainfall. This study will contribute to the research on bison in the NW U.S. by addressing this particular angle from a data driven, geographical approach.

CHAPTER 2: METHODS

Study Area Characteristics

The Columbia River Basin province within the Northwest United States extends from Washington and Oregon east of the Cascades, into western Montana and Wyoming (49°N/109°W to 42°N/121°W) (Figure 7). The climate of the Interior Columbia Basin is highly diverse due to complex physiography. The Cascades and Rocky Mountains are the most dominant landform features that control the influences of three air mass types: cool, moist air from the Pacific; continental air from the east and south which is cold and dry in the winter and hot in the summer; and dry/cold arctic air (Ferguson 1999).

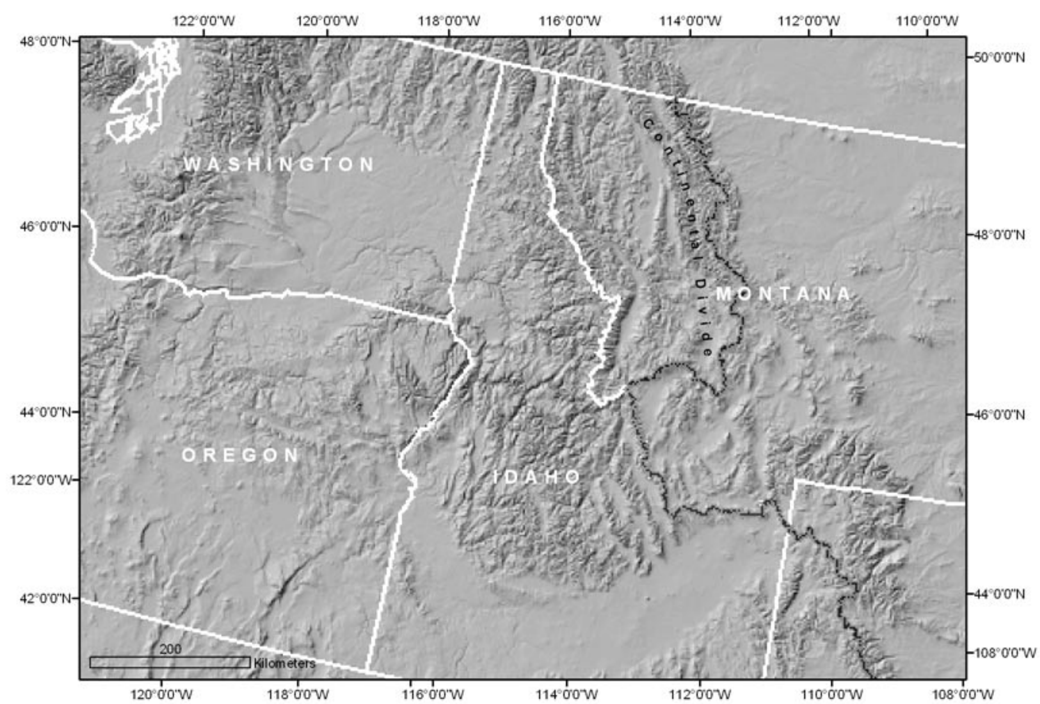

Figure 7. Physiographic characteristics of the study area.

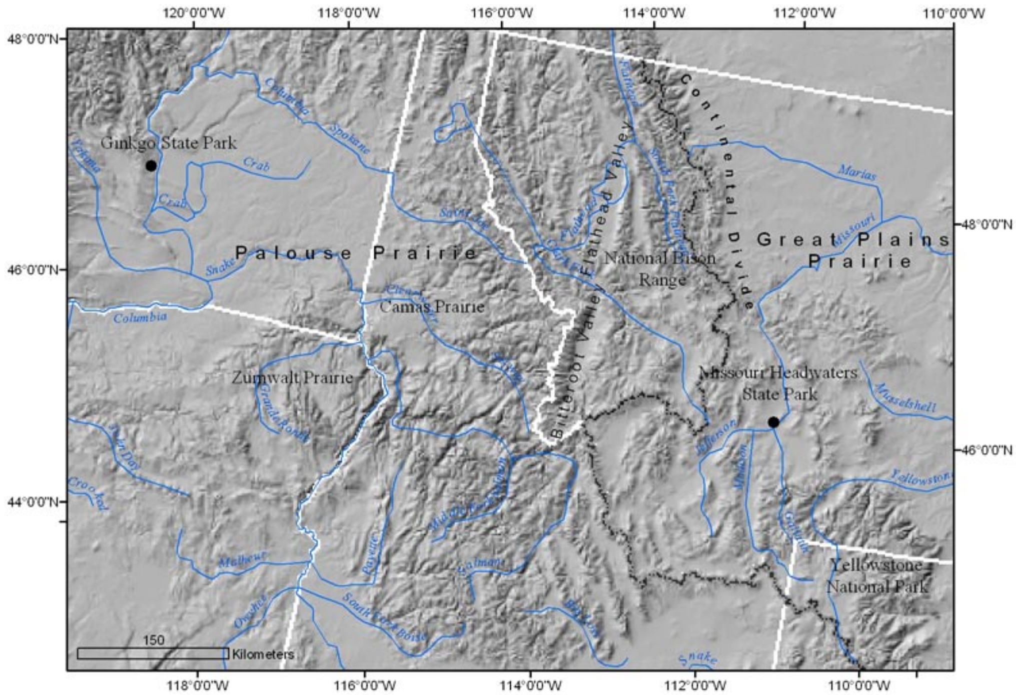

Figure 8. Map of places mentioned throughout the text.

There are three general climate regions identified within the Basin: the temperate desert division (central Oregon and Washington), temperate steppe division (Palouse prairie across southwest Washington into Idaho), and the temperate desert mountain division, which includes the intermountain semidesert province (northeast Oregon, northern Idaho, and western Montana) (Figure 9). Seasonal precipitation is the primary factor that distinguishes these provinces. Figure 10 illustrates the differences in seasonal precipitation averages across the NW U.S. Approximately half of the annual precipitation in Montana east of the CD falls in the summer months, whereas summer precipitation in central Washington and Oregon is approximately 10 percent of the annual precipitation total. In Figure 11, climographs for four climate divisions across the NW U.S. further demonstrate the major difference in seasonal precipitation patterns. These four divisions, southeast Washington, north central Oregon, central Montana, and

southeast Idaho, represent suitable grassland habitat for bison. Central Montana and southeast Idaho are areas of higher reported historical bison occurrence, and the areas within southeast Washington and north central Oregon have lower reported historical bison occurrence (Osborne 1953, Van Vuren and Bray 1985, Lyman 2004).

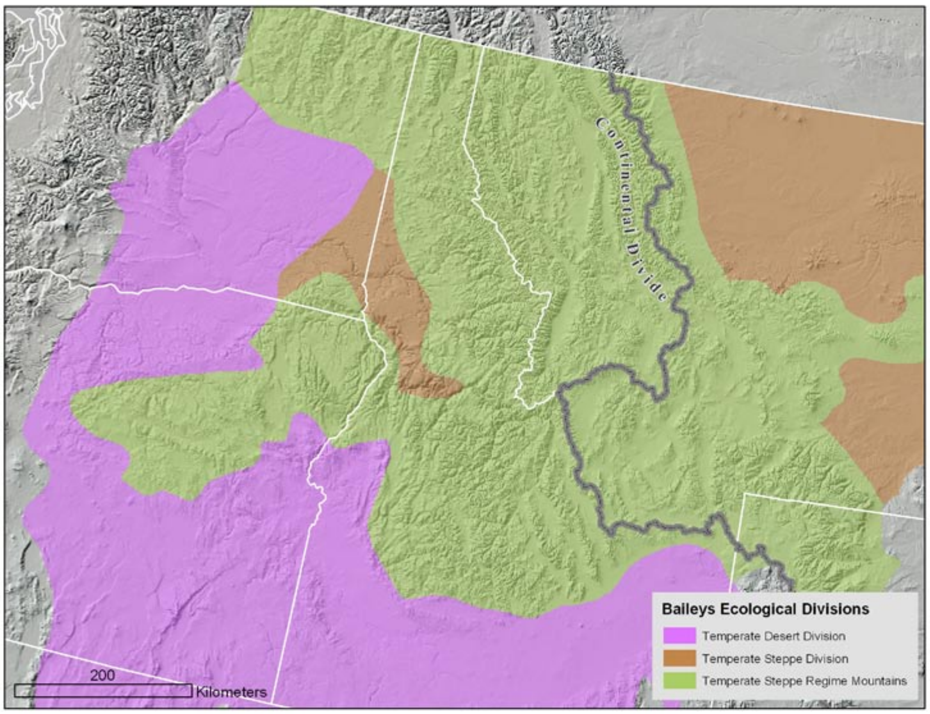

Figure 9. Bailey’s major ecological divisions.

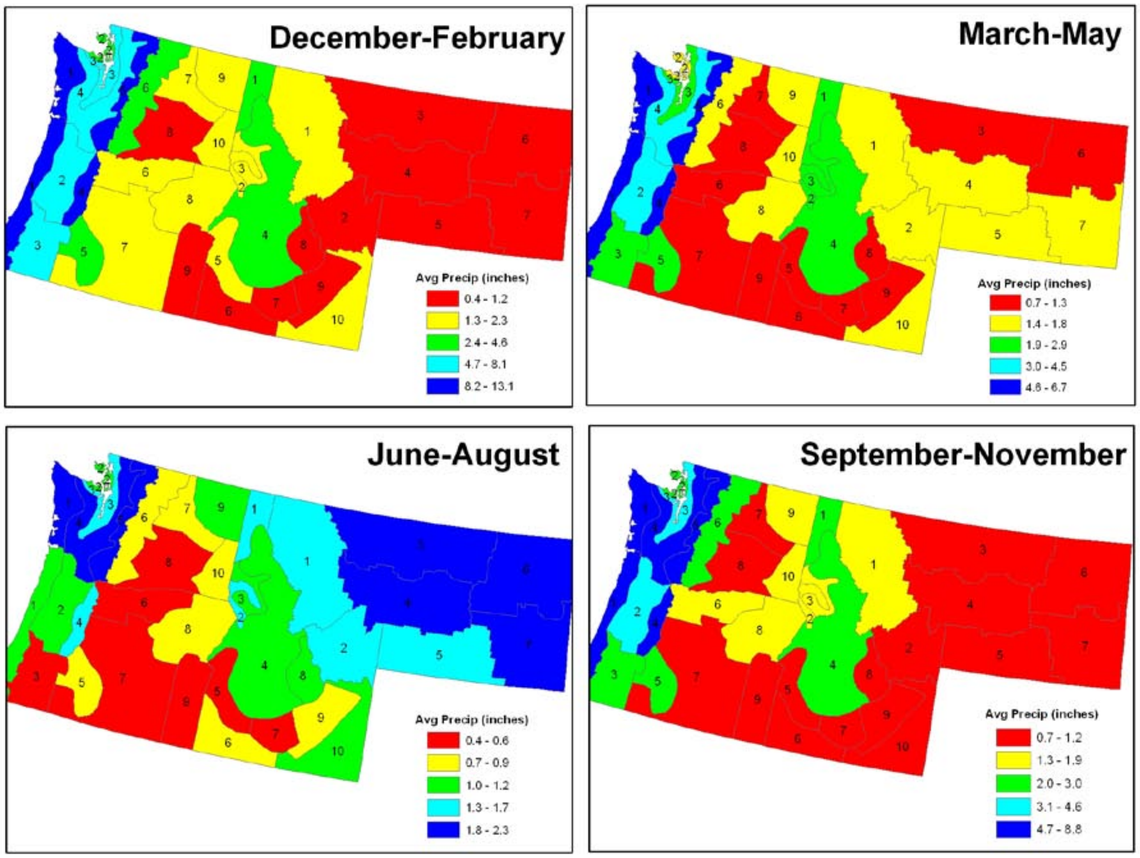

Figure 10. Average seasonal precipitation by climate division. Monthly data (1895-2004) from the National Climatic Data Center (<http://www.ncdc.noaa.gov/oa/ncdc.html>, 2005).

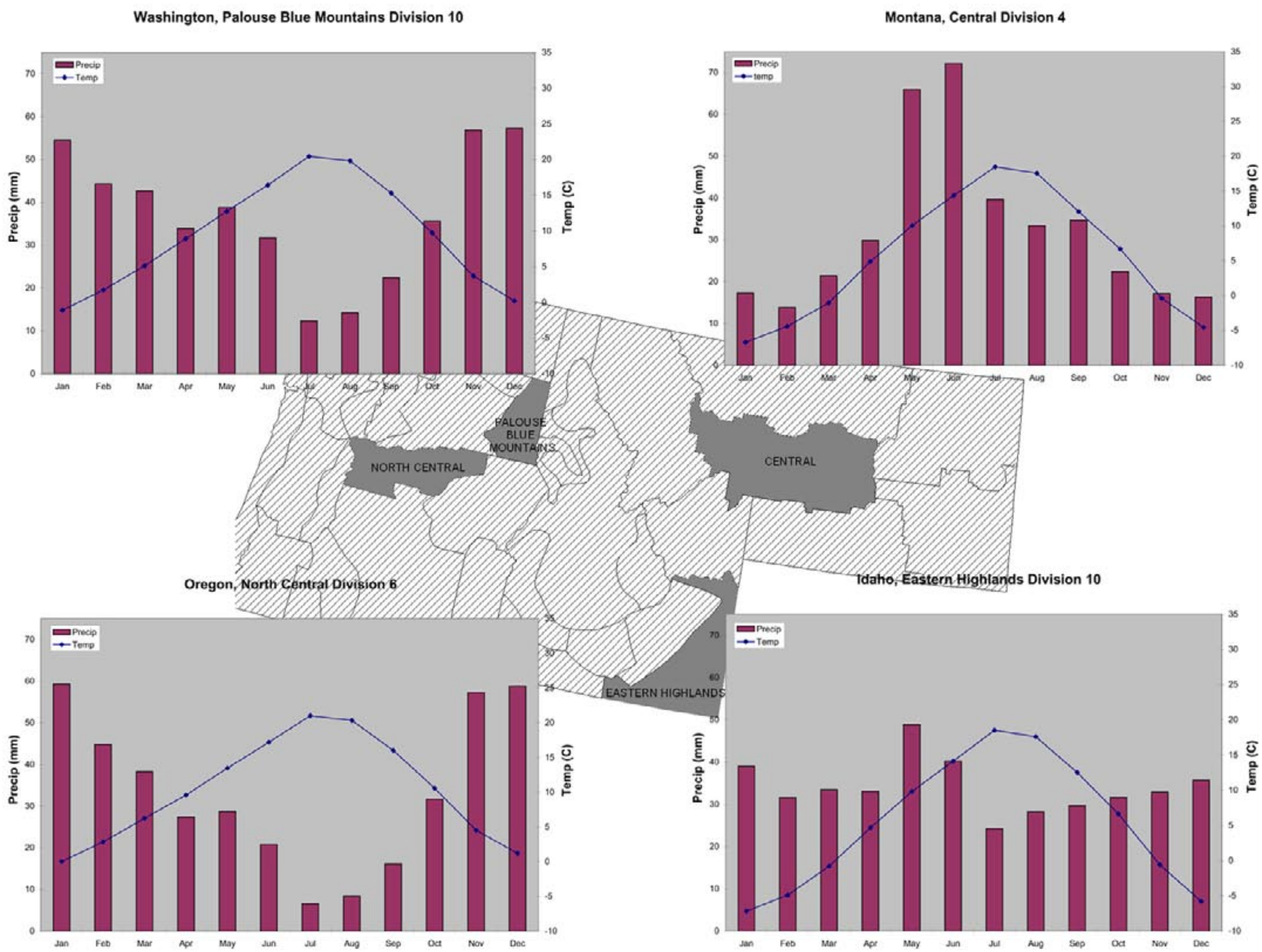

Figure 11. Climographs of selected climate divisions in the study area. These divisions were selected as most representative of suitable bison habitat areas.

The temperate desert division region is the driest of the divisions, with increasing summertime aridity west towards the rainshadow of the Cascades. With the exception of occasional convective rainfall events, summer in this province is the dry season. During the long and cold winters, this area can receive between 40-80 cm. of snowfall, because of maritime air mass incursions, which supply most of the year-round moisture for this province (Ferguson 1999). Temperature ranges of the temperate desert are high between winter and summer (Bailey, 1995). The vegetation in this region is dominated by shrub-steppe species, including *Artemisia tridentata* (big sagebrush), *Purshia tridentata* (bitterbrush), and bunch grasses (Hessburg *et al*, 2000).

Figure 12. Sagebrush-Steppe community in Gingko State Park, central Washington (photo from Washington State University, 2004. <http://www.wsu.edu/~wsherb/>).

The semiarid temperate steppe division (includes the Palouse and Great Plains prairies), which includes southeastern Washington and extends into western Idaho and east of the Rocky Mountains in Montata, receives higher annual precipitation than the temperate desert division, most of which occurs in the winter, and temperatures tend to be cooler. The steppe vegetation, also known as shortgrass prairie, has a greater diversity of grass species, with *Buchloe dactyloides* (buffalo grass) as the most typical of these regions (Bailey 1995).

Figure 13. Camas Prairie in western Idaho
(Stock image, 2004 <http://www.stckxchng.com>).

Figure 14. Zumwalt Prairie in northeastern Oregon (Nature Conservancy 2004 “Zumwalt Prairie” <http://www.nature.org/wherewework/northamerica/states/oregon/>).

The temperate steppe mountain division which crosses from eastern Oregon across northern Idaho into western Montana is the most complex division, but overall is the coldest region of the basin, with milder summer temperatures, and higher annual moisture (Hessburg *et al.* 2000). Snowfall densities tend to be lower than the snowfall on the western edge of the Cascades steppe division due to colder winter temperatures (Ferguson 1999). Summertime convective storms are concentrated east of the Divide in western Montana, with incursions of moisture from the Gulf of Mexico (Burkhardt 1996). The intermountain semidesert ecological regime, located within this zone is dominated by sagebrush steppe vegetation.

Figure 15. Flathead Valley of northwestern Montana.
(Stock image, 2004 <http://www.stckxchng.com>).

The landscape features of the NW U.S. control the influence of the dominant air mass types, the maritime polar and continental arctic and polar air masses. Movement of these air masses determines the timing of the seasonal precipitation maximum- the significant distinguishing factor between the climate east and west of the Divide in the basin. From the eastern Cascades region the season of maximum precipitation grades from November/December to January/Febuary at higher elevations to the easternmost edge of the Northern Rockies region (western Montana), the season of maximum precipitation grades from November - December to May – June (Mock 1996).

Data

Three variables of climate that would most likely affect bison success were examined: snow water equivalent, snow depth, and precipitation. These data were collected within the study area based on the longest continuous records. Data stations with more than 20% missing data values were eliminated, and missing data of the remaining stations were calculated using regression methods (snow course) or listwise deletion (precipitation) to minimize bias. Snow data were examined for a single month (April), so a regression method was used to estimate these missing snow values; whereas precipitation was analyzed by season, therefore listwise deletion would not affect the dataset to the same degree as this method applied to the snow data. Stations with records that extends back at least to the early 1950s to the year 2000 were selected in order to normalize for both warm and cool phases of the Pacific Decadal Oscillation, which is the dominant mode of inter-decadal variability for climate in the NW U.S. (Cayan 1996). The PDO is a 20-30 year oscillation of warm and cool Pacific sea surface temperatures (SST) that interact with the El Niño/Southern Oscillation (ENSO) (Gershenov and Cayan 1999). The positive (warm) phase of the PDO is characterized by cooler than average SSTs near the Aleutian Islands and warmer than average SSTs near the California coast; conditions that favor the influence of El Niño. The negative (cool) phase of the PDO enhances La Niña teleconnections (i.e., winter wetness in the Pacific Northwest) (Latif and Barnett 1994). The PDO was in the cold phase from 1946-1976, and has been in the warm phase since 1976 (Zhang and Battisti 1997). El Niño winters in the NW U.S. tend to be warmer and drier during the warm phase, and cooler and wetter than average during La Niña winters (Cayan 1995).

Digital Spatial Data

For the maps and spatial analysis, a 7.5 minute (30 meter resolution) digital elevation model (DEM) was downloaded from the United State Geological Survey (<http://edc.usgs.gov/geodata>). Bailey's (1995) Ecoregions digitized coverage, and major river network layers were downloaded from the National Biological Information Infrastructure (NBII) website (http://www.

nbii.gov/index.html). Kuchler's Potential Vegetation dataset (5 km resolution) was obtained from the National Oceanic and Atmospheric Administration's Geophysical Data Center (http://www.ngdc.noaa.gov). This spatial dataset (GIS coverage) was digitized by the US Environmental Protection Agency from the 1979 *Physiographic Regions Map* produced by the Bureau of Land Management, which added an additional 10 vegetation classes to Kuchler's USGS *Potential Natural Vegetation* map.

Potential Natural Vegetation (PNV) is the "climax" vegetation that would normally occur on a given site without disturbance or climatic change (Kuchler 1964). This dataset is used as a proxy of what general habitat types would have been present before widespread human activities transformed the landscape. It is used in this analysis as a reference for information regarding the most likely bison habitat. In addition, suitable grazing opportunities are evaluated by comparing the historical annual Net Primary Productivity (NPP) of grassland areas east and west of the Continental Divide as modeled by the Interior Columbia Basin Ecosystem Management Project for a "normal" climate year (ICBEMP 2005). Net Primary Productivity is the total amount of biomass produced (including leaves, stems, coarse roots and fine roots) minus the annual total respiration (ICBEMP 2005). The dataset is a grid of one kilometer resolution that estimates grams of carbon per square meter, and was produced by running a Biogeochemical Simulation Model (BGC) for Historical (circa 1900) conditions for each weather year of 1982 (cool and wet), 1988 (warm and dry), and 1989 (normal conditions) (Thorton 1998). Because the data only extends to the boundaries of the Columbia River basin, NPP for grasslands outside of the boundary cannot be estimated (Figure 16). However, the eastern section of the coverage does overlap areas of historic bison abundance, so it was determined that this dataset would be sufficient for comparison of relative NPP between areas of disparate bison abundance. For this analysis, the dataset modeled on 1982 was used, because this year represents average climatic conditions across the region (Thorton 1998). Only grid cells that intersect selected grassland habitat determined suitable for grazing (based on Kutchler's Potential Vegetation) will be calculated for estimated annual historical NPP.

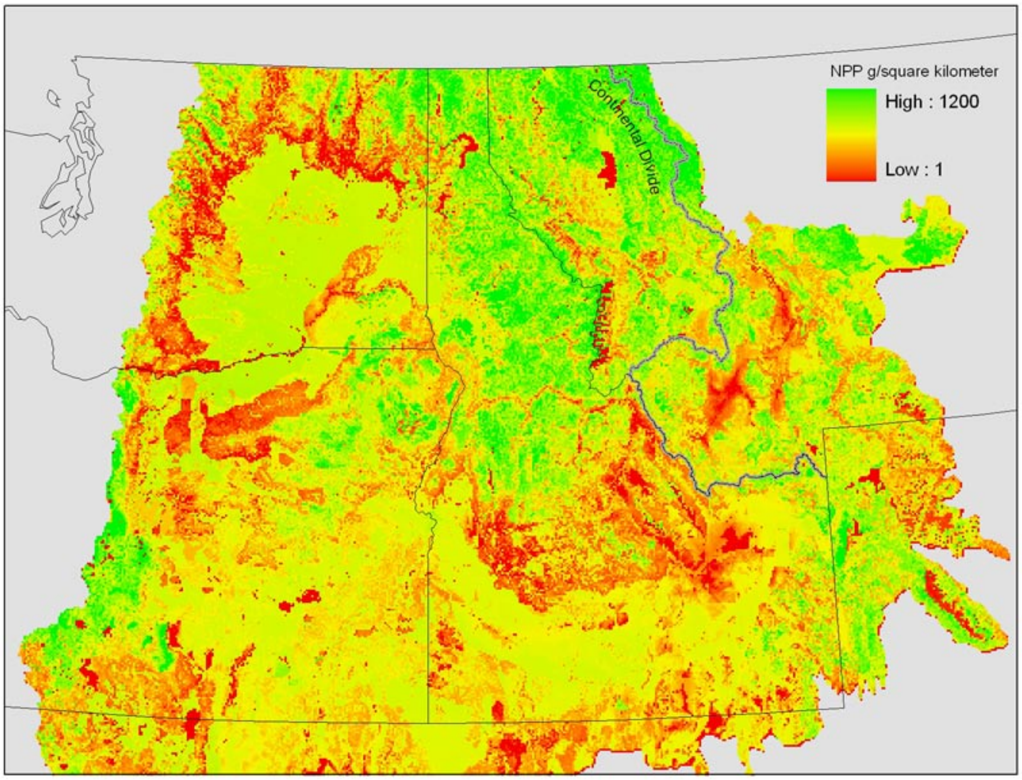

Figure 16. Annual Net Primary Production of the Columbia River Basin.

Bison Data

Locations of archaeological sites that have contained Bison remains were obtained from FAUNMAP, an experimental electronic database that has been documenting, in a GIS format (ArcInfo), the late Quaternary distribution of mammal species in the United States (http://www.museum.state.il.us/research/faunmap). The data available on FAUNMAP were collected based on published reports, including peer-reviewed literature, contract reports, and selected theses (Figure 17). The assembled information includes mammal species, taxonomic attributes, site names and numbers, lat/long coordinate positions (at least at the county level), relative and absolute chronologies, cultural associations, and depositional environments (see Appendix IV). For the past four years, data have been captured from paleontological and archaeological sites that contain mammalian remains back to 40 ka. The database is set up so that a user may query a species of interest, and time frame of interest (e.g., Holocene), and an on-the-fly map is produced

with a table of the site characteristics. Bison sites from the Holocene period were queried from the database and using the site records produced (in html format) the data was converted to a point shapefile, so that the records could be mapped. The creators of FAUNMAP caution that because the database is an experimental, dynamic project, results produced from the queries may not be entirely representative of the entire database. For the purposes of this investigation, the data queried were used only as a reference of locations of likely bison *occurrence,* rather than abundance or non-occurrence, in comparison with literature reports of abundance patterns, as there is likely a sampling bias inherent in the archeological record (Daubenmire 1985, Lyman and Wolverton 2002 and 2004).

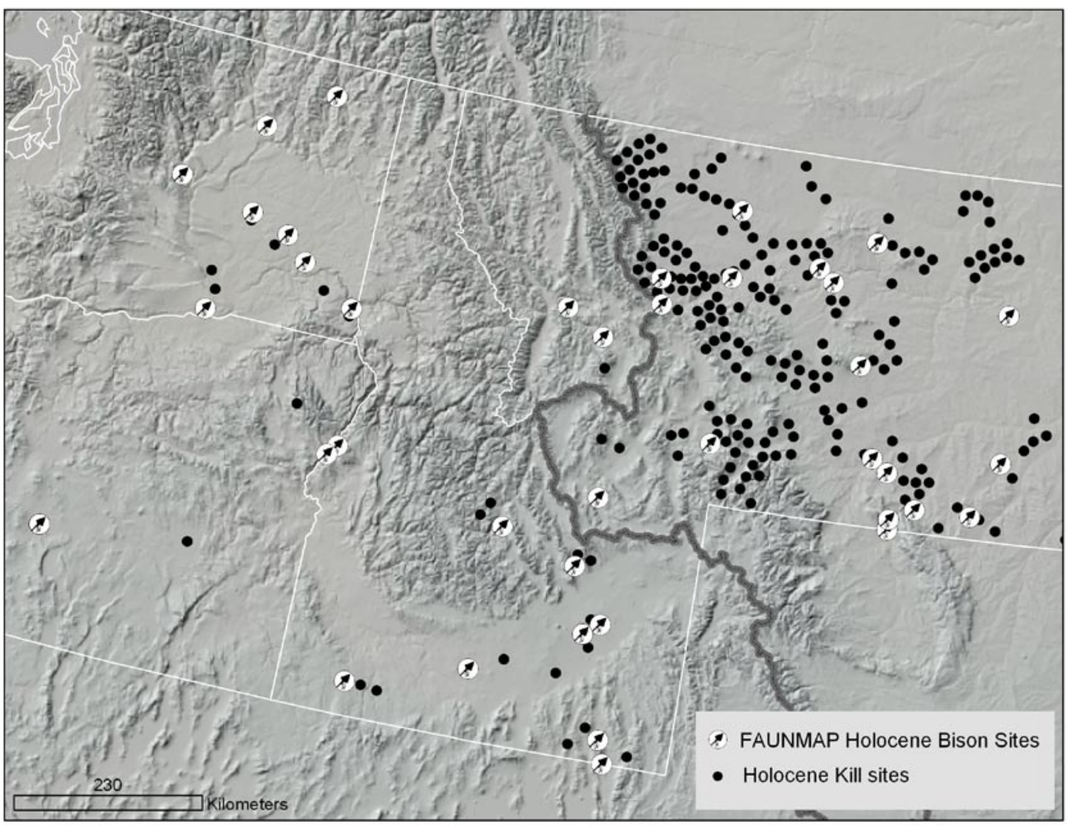

Figure 17. Archaeological sites from the FAUNMAP database with Holocene Bison remains and locations of Holocene Bison kill sites from Lyman and Wolverton (2002).

Snow Water Equivalent

Because SWE integrates the properties of depth and density, I selected it as the primary snow variable used in this analysis, although I also consider snow depth. Snow water equivalent describes how much water is obtained by melting a volume of solid snow. The volume of water produced by solid snow of a known depth varies based on the density, or compactness of the snow. The relationship between the three properties of snow can be expressed as:

$$SWE = depth \times density$$

Snow course and SNOTEL data were used in the analysis of patterns of snow water equivalent. Snow data have been collected across the United States for the past 90 years in some locations, along what are referred to as “snow courses”, and more recently by automated SNOTEL (Snowpack Telemetry) stations, operated by the U.S. Department of Agriculture Natural Resources Conservation Service (NRCS). A snow course is a transect of 5 to 50 sample points, along which snow water, density, and depth are measured manually, at some locations once a month January through May, but most frequently measurements have been taken the beginning of April. In the late 1970s, many of these snow courses were enhanced or replaced by SNOTEL stations, due to a demand for an automated system that would provide more frequent snow measurements in inaccessible locations. The typical SNOTEL sensor includes snow pillows, a storage precipitation gauge, and a temperature sensor (Figure 18) (NRCS, “Snow Surveys and Water Supply Forecasting” 2004. <http://www.wcc.nrcs.usda.gov/factpub/sect_4b.html>). Snow pillows are panels of stainless steel or synthetic rubber, about 4x5 feet, filled with an antifreeze solution. The weight of snow as it accumulates on the pillows, forces the fluid to a pressure sensing electronic device that converts the pressure reading to snow water equivalent, which is then transmitted by radio signal via meteor burst to the National Water and Climate Center (NWCC) central computer system in Portland, Oregon (NRCS, “Snow Surveys and Water Supply Forecasting” 2004. <http://www.wcc.nrcs.usda.gov/factpub/ sect_4b.html>).

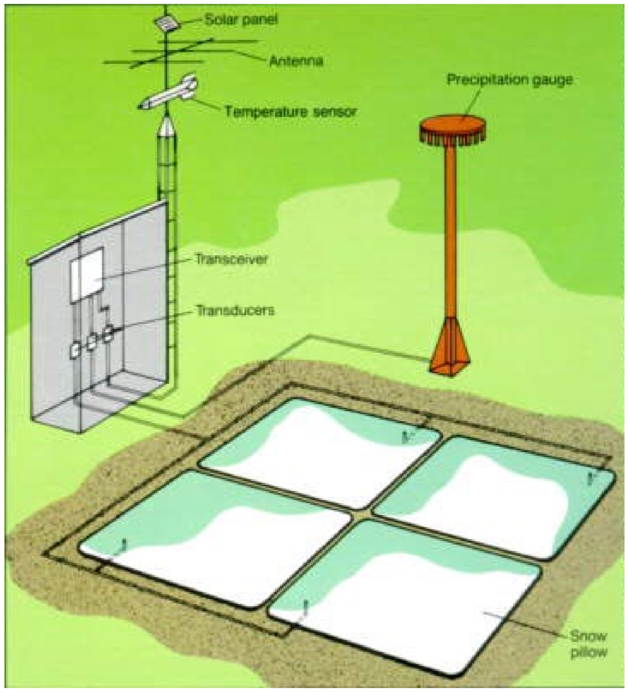

Figure 18. Example of a typical SNOTEL station. From NRCS “Snow Surveys- SNOTEL” 2004. (http://www.wcc.nrcs.usda.gov/factpub/sect_4b.html).

When a manual snow course is discontinued, usually there is a sufficient period (about 10 years) of overlap with SNOTEL to evaluate the consistency of the two measurements; the SNOTEL stations at these sites have integrated real-time and historic data, and in general there is strong agreement between the manual snow course and automated SNOTEL values (Serreze *et al*. 1999).

SWE data were downloaded in text format from the Natural Resource Conservation Service National Water and Climate Center website for all snow course and SNOTEL sites in Oregon, Washington, Montana, and Idaho (NRCS, “National Water and Climate Center” 2004 (<http://www.wcc.nrcs.usda.gov>) (Figure 19). Two hundred and ten stations were selected based on the longest records between 1940 and 2002 with no more than 20% missing data. April SWE was selected from the dataset, because snow course measurements are taken most frequently at the beginning of April, and also because April represents the typical cumulative peak of snowfall in this region (Regonda *et al*. 2003). Most stations used were at or below 2500 meters in elevation- east of Rocky Mountains, stations range from between 1400-2500 meters,

and west of Rocky Mountains, stations range from 600 meters to 2600 meters (see Appendix I for station inventory).

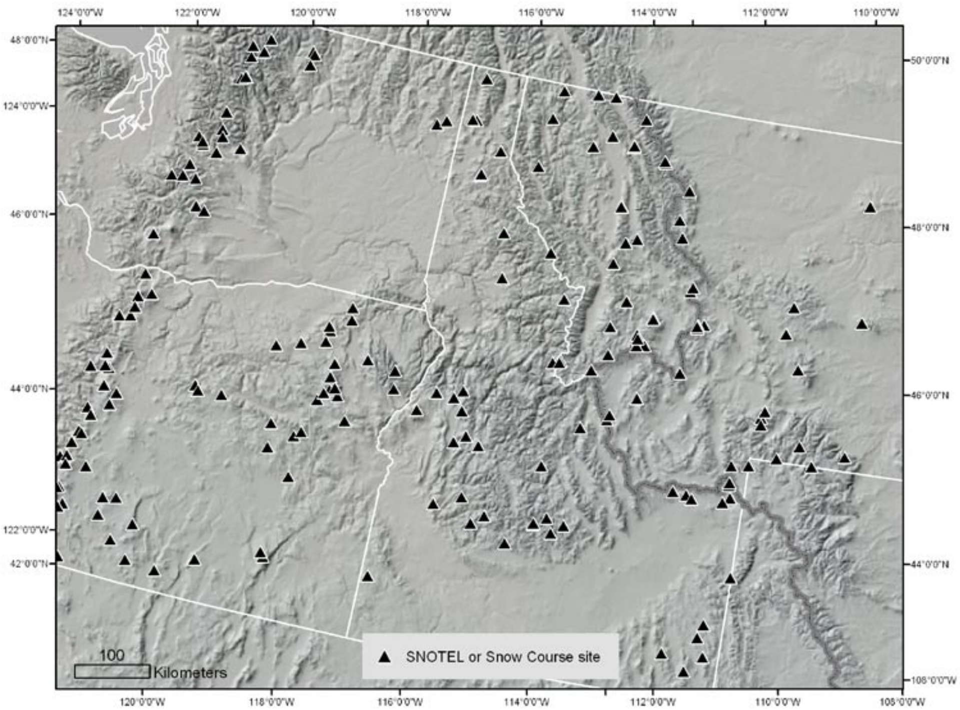

Figure 19. Distribution of SNOTEL or snow course sites.

NCDC NWS and Cooperative Stations Data

Monthly summary total precipitation and snowfall data were obtained from the National Weather Service (NWS) and cooperative U.S. station network (TD3220), which is archived at the National Climatic Data Center (NCDC) (<http://www.ncdc.noaa.gov>). The period of record available is from the late 1930s-1950s to present for most stations. The data are quality checked by both automated and manual methods before distribution. Because of the relatively high spatial density of the NWS network (compared to the SNOTEL network), 254 stations were selected for precipitation data that had the longest records and the least amount of missing data (Figure 20). The highest percent of missing data for a station was 13% (see Appendices II and III), and the months with no data appear randomly. Sixty-two percent of the 254 stations have data that

extend to the late 1930s, thirty-two percent of the stations have data to 1950, and six percent have data that extend to the 1960s (these were retained to provide coverage for remote areas).

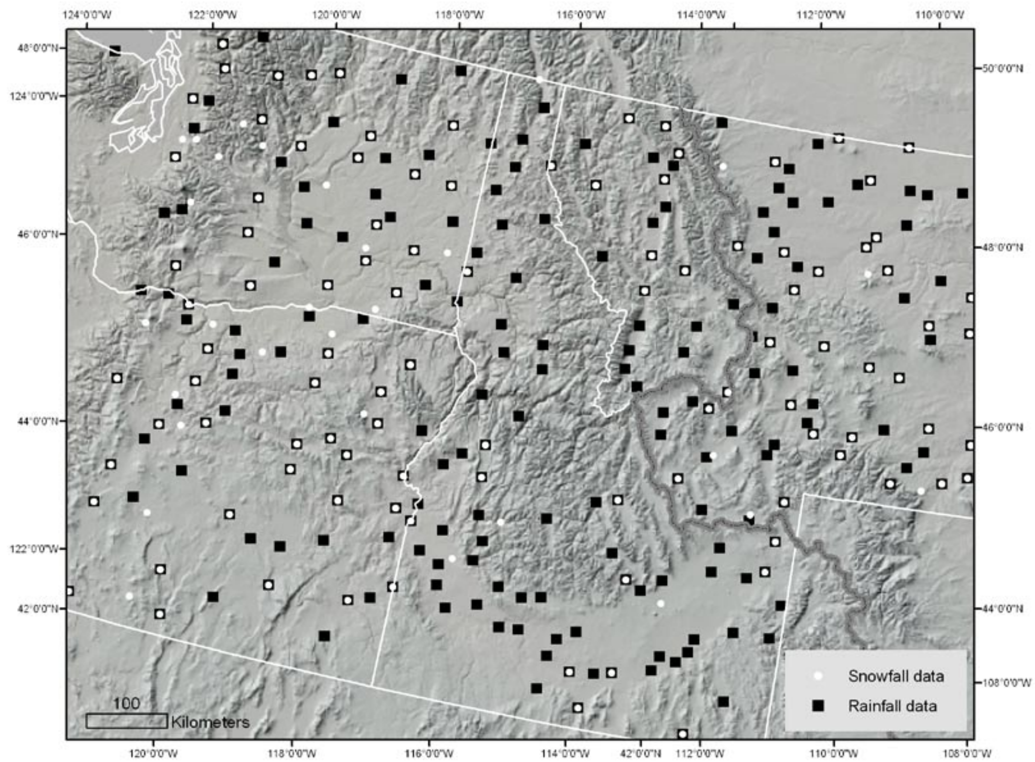

Figure 20. Distribution of NWS/Cooperative stations selected for analysis.

Palmer Drought Severity Index Data

To validate the veracity of calculated drought frequency from the NWS/Cooperative network, data from the "North American Drought Variability PDSI Reconstructions" by Cook *et al.* (2004) were used. The Palmer Drought Severity Index (PDSI) is an imperfect, but commonly used meteorological indicator of wet and dry periods-or departures from normal- based on temperature, precipitation, and soil type (Palmer 1965). PDSI indices are typically expressed on a scale between -6 and +6 (but can extend beyond); negative PDSI values indicate dry conditions and positive values indicate wet conditions. The dataset is a 2.5-degree grid covering the Continental United States based on a network of 835 tree ring reconstructions of annual Palmer

Drought Severity Index (PDSI). The gridded PDSI was constructed with instrumental data for the past 100 years and the tree ring reconstructions as proxy data for the past several centuries and millennia. The temporal coverage of the data set extends 2000 years for some locations. Data from seventeen grid points across the NW U.S. were selected with reconstructed PDSI values from the years 1500-2000 (Figure 21). The number of tree-ring chronologies used to reconstruct the data increases progressively higher in the time period, from no less than 10 trees in the early 1500s to 80 trees in the last century. The time period from 1500- 2000 was selected to maximize the accuracy of the reconstruction, as the calibration between the proxy data and instrumental data typically weaken back in time at each grid point, due to an increasingly smaller sample of chronologies further back in time (i.e., 500 year old trees are rarer than 200 year old trees) (Cook *et al*. 2004).

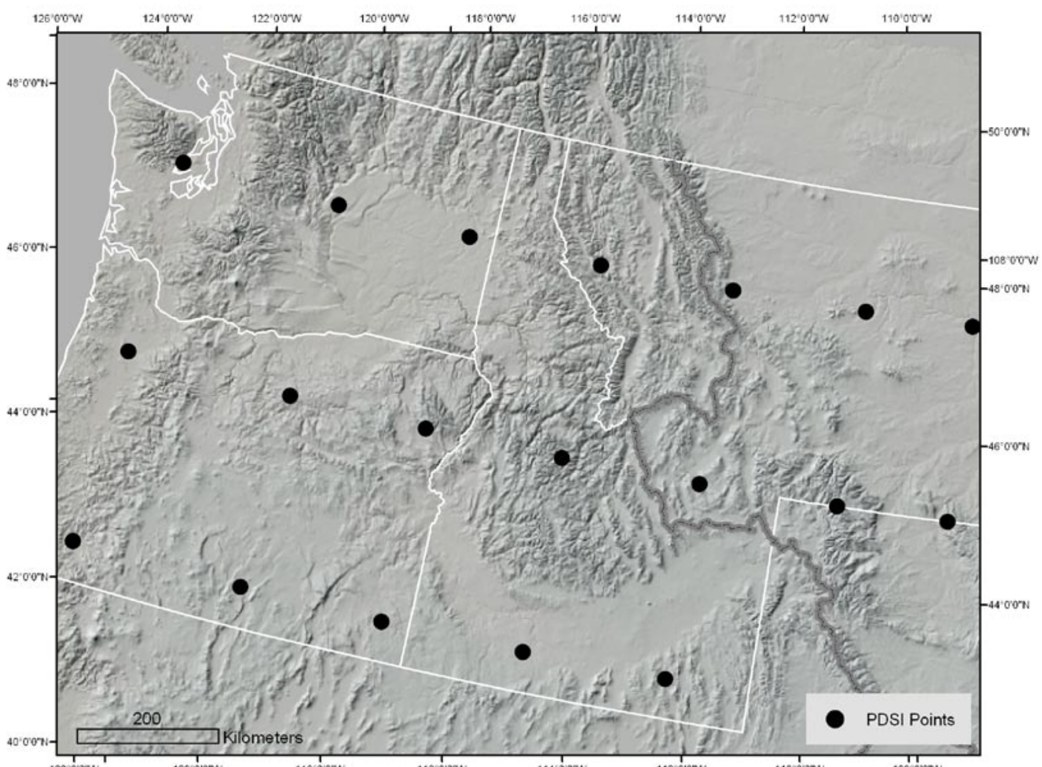

Figure 21. Grid of reconstructed PDSI network based on Cook *et al.* (2004).

Study Methodology

Snow Water Equivalent

Snow water equivalent data from 210 stations (see Appendix I) during the period from 1938 to 2000 were first analyzed by Principal Components Analysis (PCA) to explore and contrast regions of snow water content. Specifically, the objective was to discern any significant differences between mean SWE values. Because the SNOTEL stations are not evenly distributed across the NW U.S., an accurate regionalization of SWE is not possible. Most SNOTEL stations are situated above 1000 meters, because the original purpose of this network was to provide snowpack and climate data for high elevations for predicting spring melt runoff and streamflows. Consequently, unlike the NWS cooperative network, SNOTEL stations do not reflect low elevations basins such as middle Columbia Basin in Washington, and much of the Snake River Basin in southern Idaho. Thus, spatial gaps in the analysis (e.g., central Washington and southern Idaho) exist, but the purpose of this analysis is not to delineate climate regions based on snow, but rather, to explore, compare, and contrast areas within the study area that have similar snow characteristics.

PCA is a multivariate analysis process that can reduce multiple variables into a fewer number of uncorrelated variables by axes (line through a cluster of points) rotations. The purpose for this process can be either exploratory or predictive. I used PCA as an exploratory method to reveal patterns through data reduction. The "principal components" are the derivative variables that summarize the original variables by successive multiple regressions through a correlation or covariance matrix. Each component explains a successively smaller amount in variation of the dataset than the previous component, which is quantified by the eigenvalue of the component. To discern where each variable falls on the component axis, the component loadings matrix is used to find the correlation between the components and original variables (Rogerson 2001).

For SWE, a covariance matrix was selected since the units of measurement were the same for all the variables (April SWE). The component matrix was rotated using the Varimax rotation, and orthogonal method used to ensure that the explained variance is more evenly distributed across the components, which makes interpretation of component loadings easier

(Frei and Robinson 1999). To assess whether the components were significantly different, a one-way analysis of variance was used on the SWE values for each assigned component. SWE components were chosen using the criteria of selecting components with eigenvalues greater than one, and after examining the scree plot. To assess whether the components were significantly different, a one-way analysis of variance was used on the April SWE values for each assigned component. A Tukey HSD test was then performed to determine *which* components were significantly different from each other. The station variables were assigned a component based on the rotated loadings matrix. The factor loading correlation coefficients were examined to determine which component each variable loaded most highly on. The variables were assigned the highest loaded component if the correlation coefficient was greater than 0.4. Station variables that did not load higher than 0.4 on any component or that loaded equally on more than one component were not assigned components. To determine whether relative SWE values could be compared across the region and is not entirely dependant on elevation, the relationship between SWE and elevation was tested using a simple regression equation between average April SWE and elevation of all stations (see Appendix I for station elevations).

Drought Frequency

Inter- and intra-annual drought frequency across the study area was assessed using 254 stations from the NWS cooperative network data (see Appendix II). To calculate intra-annual drought frequency (the frequency of monthly departures for each station), the monthly sample average was calculated for each station, and then examined for monthly departures less than eighty percent of this average. The percentage of departures for each month for each station was then calculated as a sum of the number of Junes, for example, with recorded precipitation in the 20^{th} percentile or below, divided by the number of recorded years. The percentage of inter-annual drought (between stations) was calculated as a sum of all months that recorded less than 80% of normal divided by the total number of recorded months. Differences between intra-annual and inter-annual drought frequencies on either side of the CD were evaluated by two-sided studentized t-tests (assuming unequal variances), $\alpha = 0.05$.

Bison populations are likely more vulnerable to periods of sustained summertime drought, which can increase the potential for bison mortality the following winter, because low summer rainfall can reduce forage quality and quantity available to grazers during the subsequent winter (Merrill and Boyce 1991, Frank and McNaughton 1992). Overall, annual grassland productivity in the NW U.S is more dependent on springtime precipitation; however, the variability of grassland productivity in this region is more sensitive to precipitation variability in the summer, when water availability is at its most limited (Xiao and Moody 2004). Summertime precipitation can be used as a relative index of winter forage available to bison on winter ranges (Farnes et al. 1999) Accordingly, in addition to single season drought frequency, sustained summertime (June through August) drought frequency was examined. For this part of the analysis, 164 stations were selected based on proximity to grassland as a representation of potential bison habitat. Stations located within 50 km of potential grassland-steppe habitat, defined by Kuchler's Potential Vegetation dataset, were selected with data back to 1950 (Figure 22).

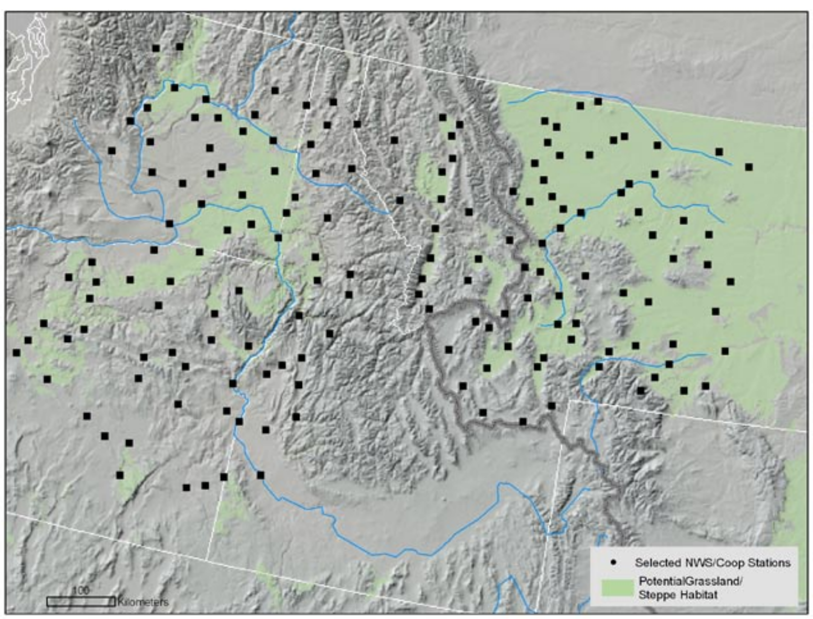

Figure 22. NWS/Cooperative stations selected to analyze sustained drought frequency from 1950-2000.

For each selected station, June through August (JA) precipitation was averaged. Next, the station chronologies were examined for successive JA precipitation values less than 80% of the average, and the frequency of such multiple-year events were summarized by station. For example, if station A experienced less than 80% of average rainfall in years 1951, 1952, 1984, and 1985, then station A has a sustained summer drought frequency of two events. To be parsimonious, and not overestimate the frequency of successive odd numbered summer droughts, a sustained drought for three (five) years was noted as one (two) event/s. In addition, to verify that the last fifty years of recorded data accurately represents the spatial extent of variability for the past several centuries, the frequency of reconstructed annual PDSI values less than -2 (moderate drought) was calculated for the study area back to 1500 B.P.

Climate Severity Index

Development of a standardized index that reflects both snow water equivalent and drought frequency was the final step of the analysis. Sites for the development of the climatic stress index (CSI) were selected that met the criteria in the following order (with decreasing importance): stations with the least amount of missing data, the longest records, and that were within 50 km of grassland-steppe habitat. This excluded much of eastern Washington, and southern Idaho. Historically, bison have occupied more arid areas as far south as Mexico (Lott 2002), but of specific interest were areas of sharp contrast between bison occurrence and lack thereof, such as western Montana east and west of the Continental Divide and northeast Oregon/ west Idaho near the confluence of the Snake and Columbia Rivers.

A 50km grid was created across the study area and the inter-annual June-August drought frequency of stations (both single year and sustained) within each cell was assigned. If more than one station fell inside a cell, then the average frequency was assigned. Next SWE sites that fell within a cell with NWS stations were selected as sites to develop the CSI. The purpose of developing the index on the SWE sites is that there are a higher number of NWS stations than SWE sites. The first step to calculate the CSI index was multiplying 70% of average SWE by

30% of the inter-annual drought frequency value of the cell it fell within. These proportions were selected based on previous recommendations by wildlife managers (Farnes 1999), and also because snow conditions are the most important factor that determine bison survival through the winter (Meagher 1976, Turner *et al*. 1994). The calculated values were then standardized as z-score indices (a measure of the distance in standard deviations from the mean) to compare the composite climate conditions most likely to affect bison between locations of known low and high bison abundance. Differences between z-scores of sites on either side of the CD were evaluated by two-sided studentized t-tests (assuming unequal variances), $\alpha = 0.05$.

CHAPTER 3: RESULTS

Snow Depth

Differences in average April snow depth between locations on either side of the Continental Divide are well expressed within the study area (Figure 23). Snow depths are between two to ten times greater east of the CD than locations west of the CD. This disparity likely reflects the differences between the influences of available moisture and temperatures on the east side of the CD where a colder, drier, continental climate regime dominates, compared to the locations west of the CD, where moister, Pacific air dominates (Ferguson 1999) . Therefore, snow east of the Rocky Mountains tends to be powdery or less dense than snow west of the Rocky Mountains.

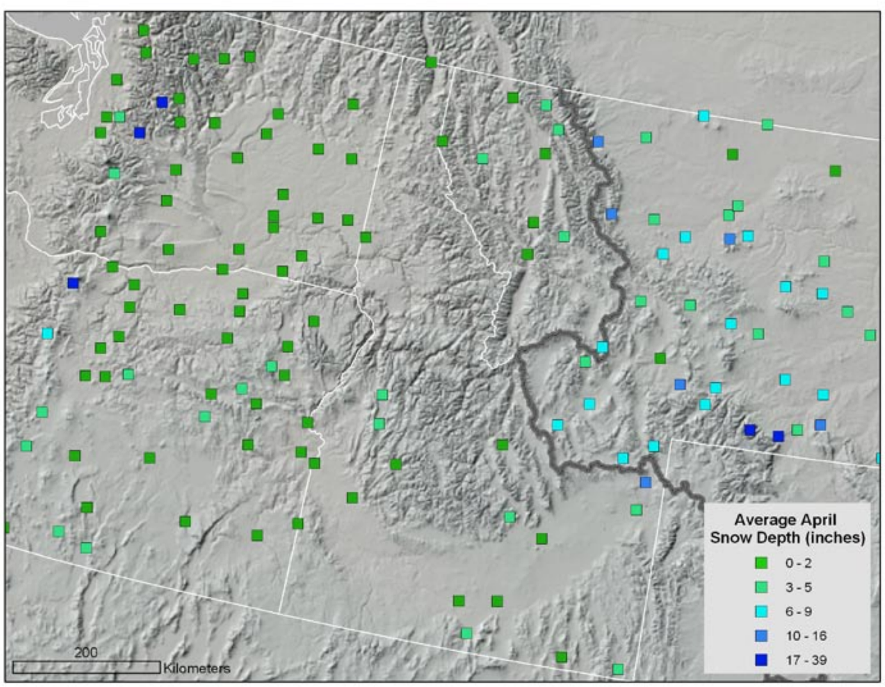

Figure 23. Map of April average snow depth from NWS/Cooperative stations for approximately the past 50 years.

Snow Water Equivalent

Six SWE components were selected that explain 76% of the variance within the dataset (Table 1). The ANOVA test revealed that aggregate difference exist among the group means (significant F ratio, $p < 0.01$). A Tukey HSD test of significance indicated that components 5 and 6 were not significantly different from component 4, so the numbers of components retained were reduced to four (Figure 24).

Table 1. Component eigenvalues and the percent of dataset variance each component explains on both the rotated and unrotated matrices.

	Initial Eigenvalues			Rotation Sums of Squared Loadings		
Component	Total	% of Variance	Cumulative %	Total	% of Variance	Cumulative %
1	110.9	52.3	52.3	50.0	23.6	23.6
2	19.6	9.3	61.6	35.9	16.9	40.5
3	12.9	6.1	67.7	23.7	11.2	51.7
4	8.7	4.1	71.8	21.2	10.0	61.7
5	8.3	3.9	75.7	19.6	9.2	70.9
6	5.3	2.5	78.2	12.1	5.7	76.6

The regression test results between SWE and elevation indicate a low correlation ($r = 0.002$, $p<0.01$) between the two variables (Figure 25). This indicates that the relationship between SWE and elevation is not consistent across the NW U.S. region. The relationship is probably more significant across smaller areas on either side of the CD, but these results indicate that the regional distribution of SWE is controlled by factors other than elevation.

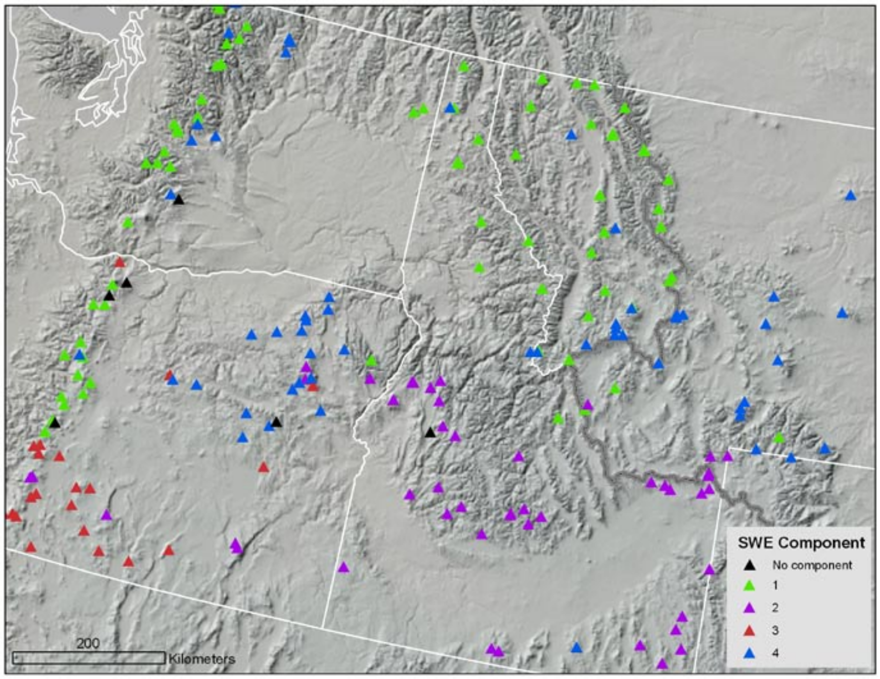

Figure 24. April SWE components.

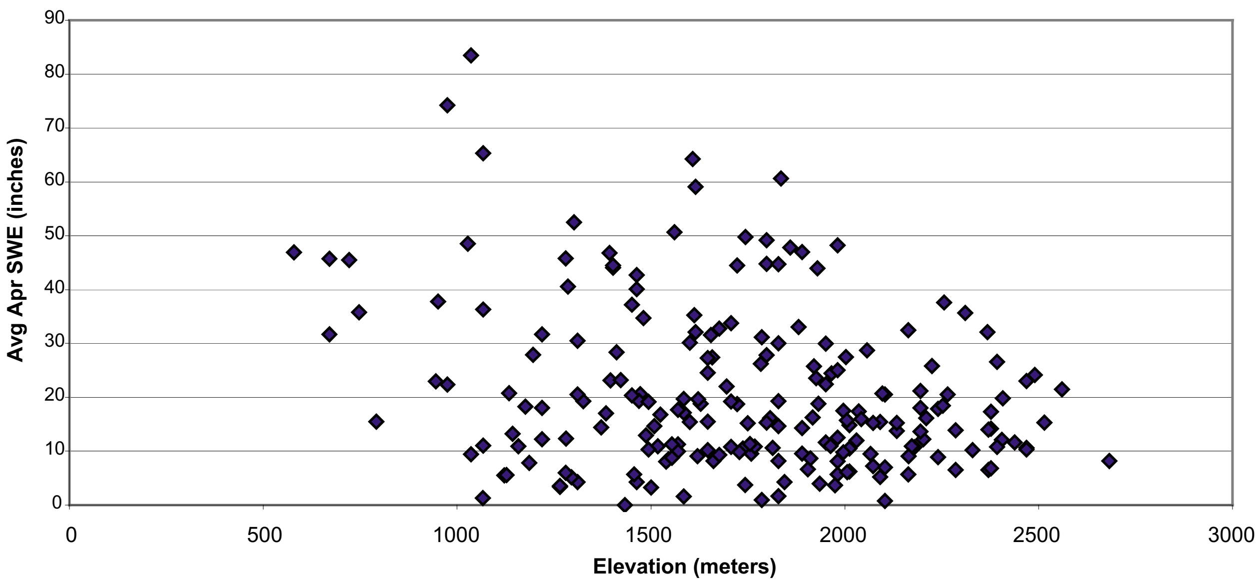

Figure 25. Scatterplot between elevation (meters) and average April SWE.

The differences of average SWE between the components is displayed in Table 2. Average April SWE values are highest for components CNR and SRM with average April SWE values of 31 (CNR) and 22 (SRM) inches. SWE is lowest for SEO, with an average of 9 inches of April SWE, and slightly higher for NOSM, where April SWE averages are 13 inches. Figure 26 displays the average April SWE for the individual stations and elevation ranges.

Table 2. Average April SWE comparison between components.

Component	Name	Station count	Avg Apr SWE (inches)
1	Cascades/Northern Rockies (CNR)	74	31
2	Salmon River Mountains (SRM)	49	22
3	SE Oregon (SEO)	23	9
4	NE Oregon/SW Montana (NOSM)	19	13
No component		45	*

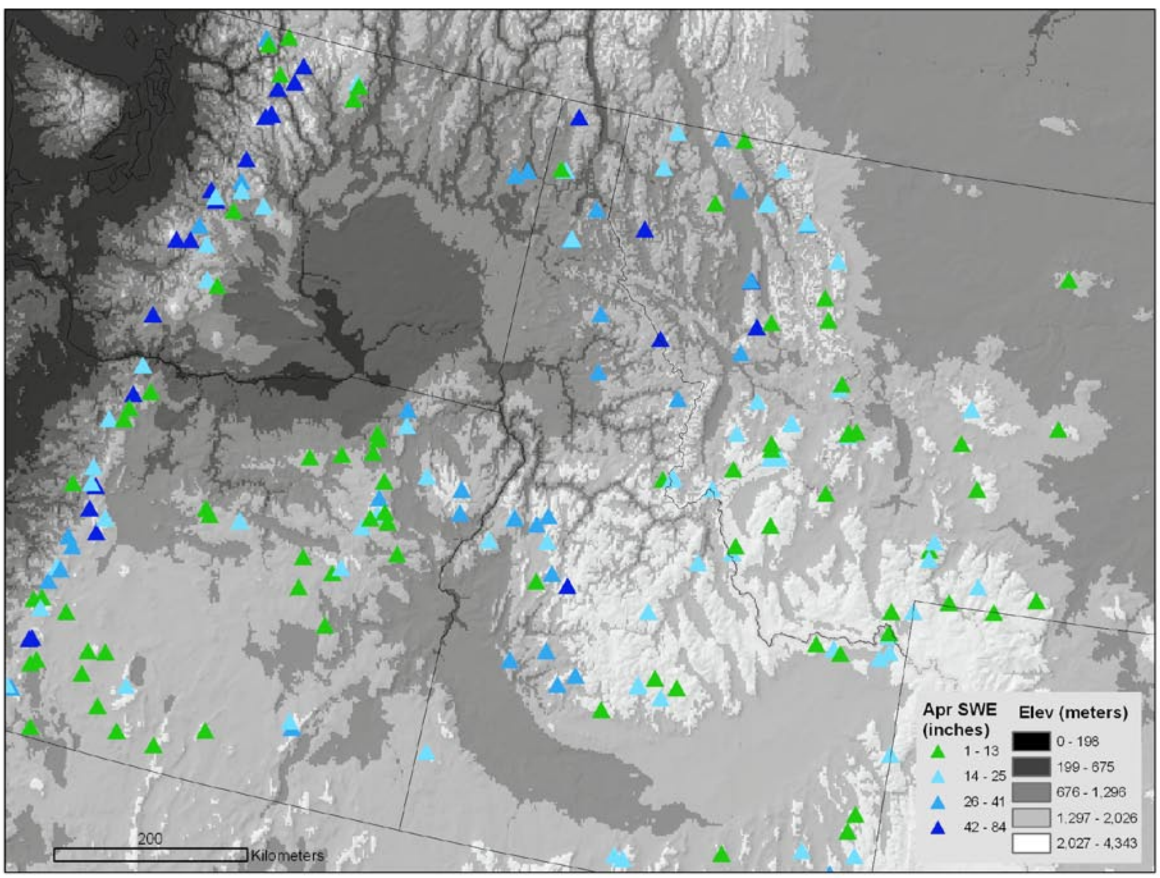

Figure 26. Average April SWE (inches) and elevation (meters).

Intra-Annual Drought Frequency

The results of analysis of intra-annual (seasonal) drought frequency less than 80% of normal of the NW U.S. for the past 50 years indicate that July through September drought frequencies are the highest across central Washington and Oregon, and southwest Idaho (Figure 27). On average, these areas likely experience drought conditions during the summer once every two years. Across the NW U.S., summertime is the season when differences in seasonal drought frequency are most evident. Difference of means testing affirmed that between locations east and west of the Continental Divide, summer droughts were overall significantly more frequent west of the Divide than any other time of year ($p<0.01$).

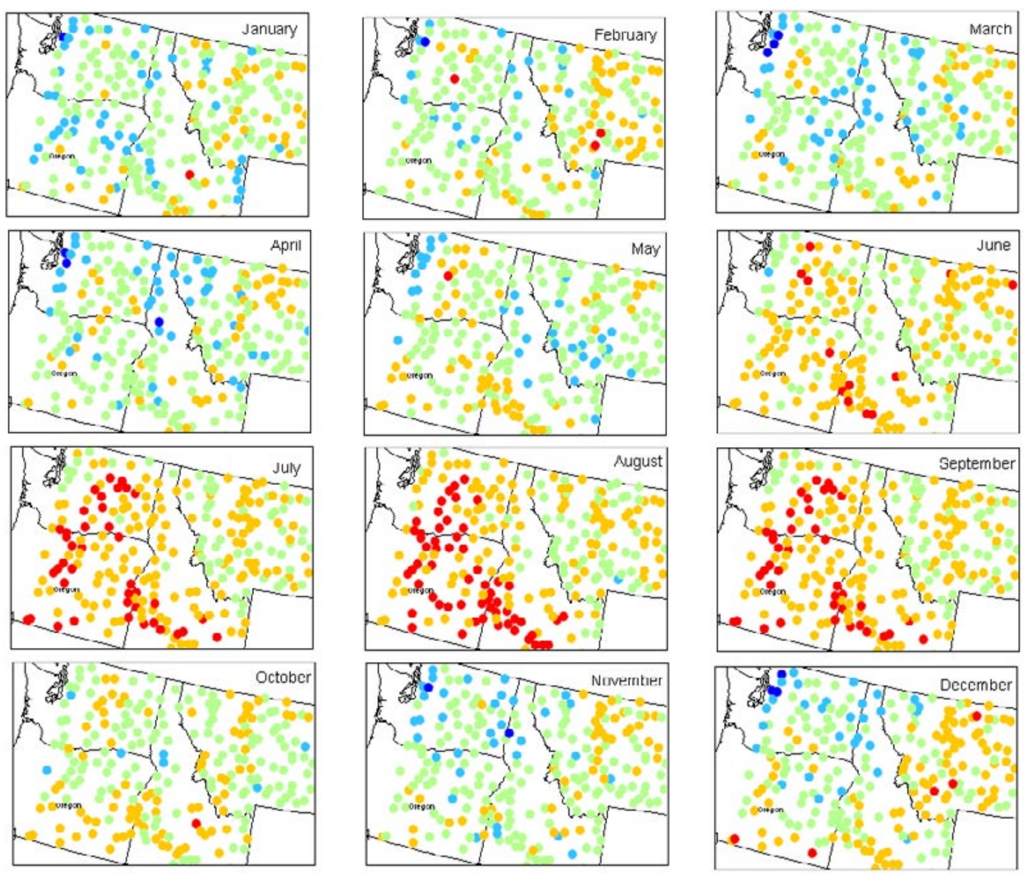

Figure 27. Intra-annual frequency of drought for 254 NWS/Cooperative stations across the NW U.S. for the past ~50 years: Dark blue-Low (7 year or >)*, Light blue-Medium Low (5-7 year), Green-Medium (4-5 year), Orange-Medium high (3-4 year), Red-High (2 year).

* Approximate return interval

Inter-Annual Drought Frequency

Difference of means testing between inter-annual (between years) summer drought frequency of stations east and west of the Divide resulted in significant differences ($p<0.01$). In general, most locations west of the Divide experience summer drought conditions once every two to three years, whereas most locations east of the Divide experience summer drought conditions from three to seven years (Figure 28). Within the region however, there is a similarity of summer single-year drought frequency between locations of bison occurrence: south and north Montana (east of the Rockies) and lack of bison occurrence: northeast Oregon/east central Idaho. Summer drought occurs on average once every three to four years in these areas. However, locations flanking the Columbia River - further south from central Oregon to southern Idaho and in central Washington – the frequency of summer droughts increase to once every two to three years. These locations have the lowest reported bison occurrence across the Northwest United States. Summer drought frequency is lowest (>4 years) east of the Divide and west of the Missouri River where bison occurrence is comparably low in Montana.

A similar pattern emerges when examining the results of sustained summer drought frequencies in areas of grassland/steppe (Figure 29). The number of summer droughts that persist for two years or longer can be up to three times higher (~ once every 6.5 years) for central Oregon and Washington than Montana (~ once every 25 to 50 years). The highest sustained drought frequencies for the last fifty years have occurred in central Washington and Oregon. The lowest frequency of summer drought in Montana occurs in areas of high bison occurrence.

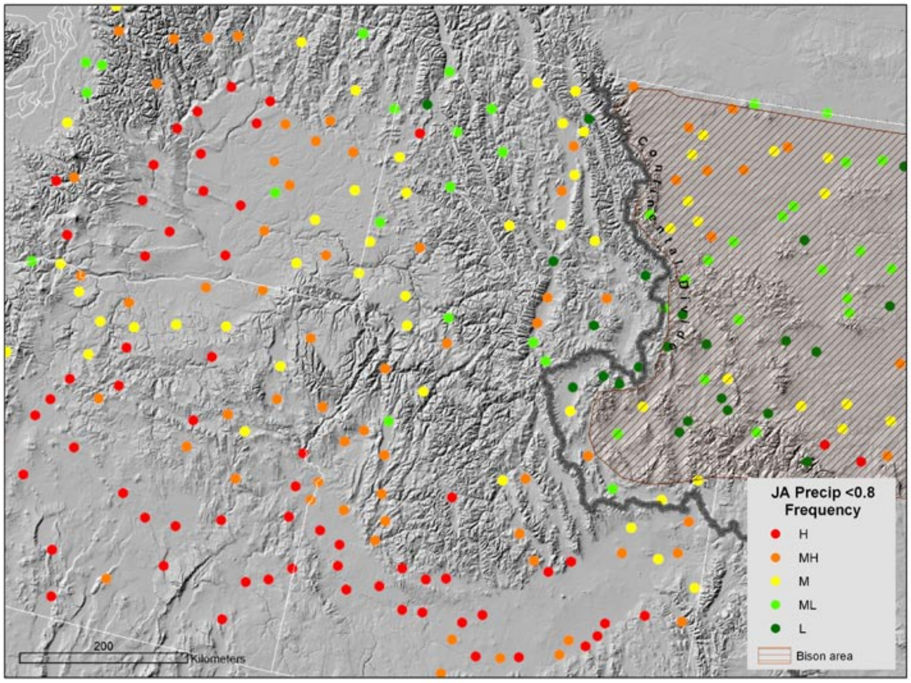

Figure 28. Frequency of June-August precipitation less than 80% of normal of last ~50 years. High- 2 year*, Medium high- 3 year, Medium- 4 year, Medium low-5-6 year, Low- 7 year and greater. *Approximate return interval

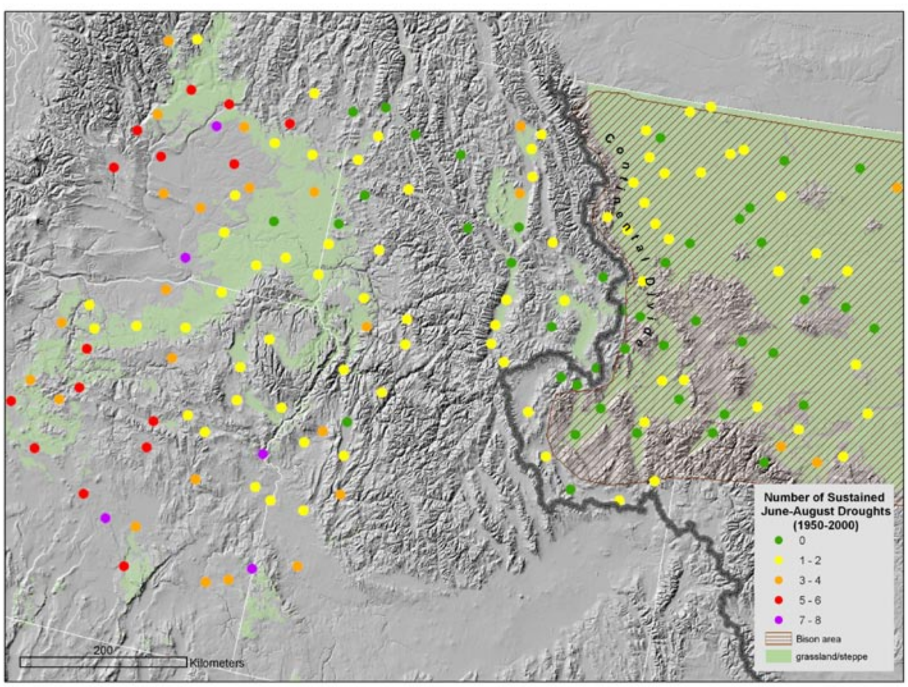

Figure 29. Number of sustained summer drought (>2 years) in grassland/ steppe regions for the past 50 years.

PDSI values reconstructed back to 1500 B.P. for the NW U.S. were examined to see how well the last fifty years represent the spatial extent of variability across the NW U.S. The annual frequency of reconstructed PDSI values less than -2 (moderate drought) is plotted in Figure 30, and supports the finding that drought frequency in general is higher west of the Rocky Mountains.

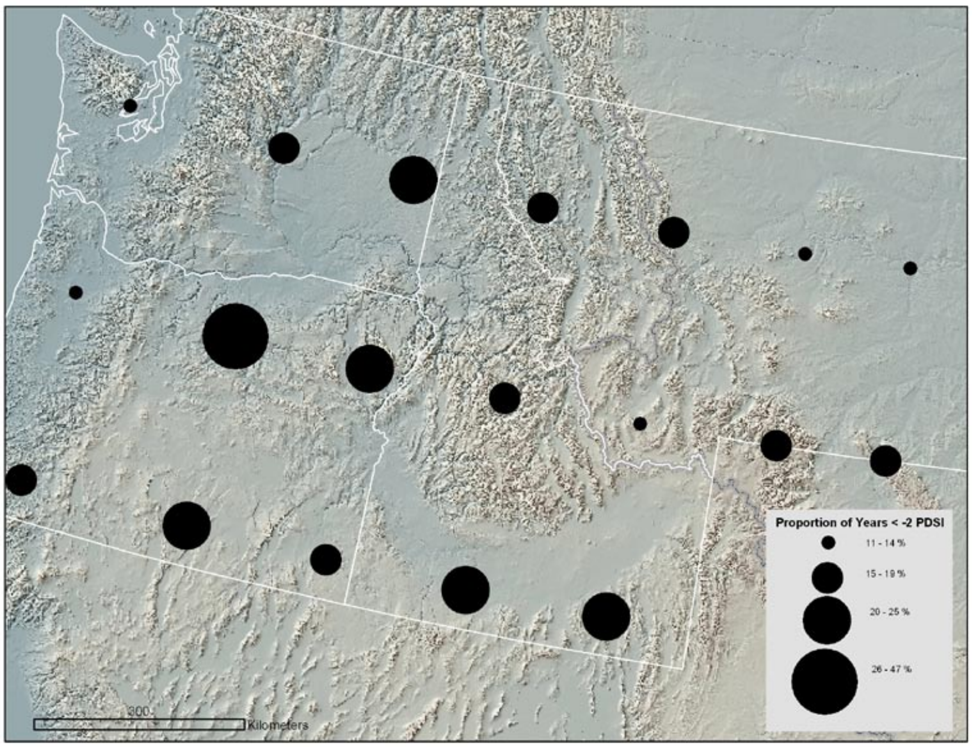

Figure 30. Frequency of annual PDSI less than –2 since 1500.

Net Primary Productivity

According to the modeled NPP dataset, average annual historical NPP for grassland areas west of the CD within the Columbia Basin were calculated as 372 g/km^2, and NPP for grasslands east were calculated to be 376 g/km^2 (Figure 31).

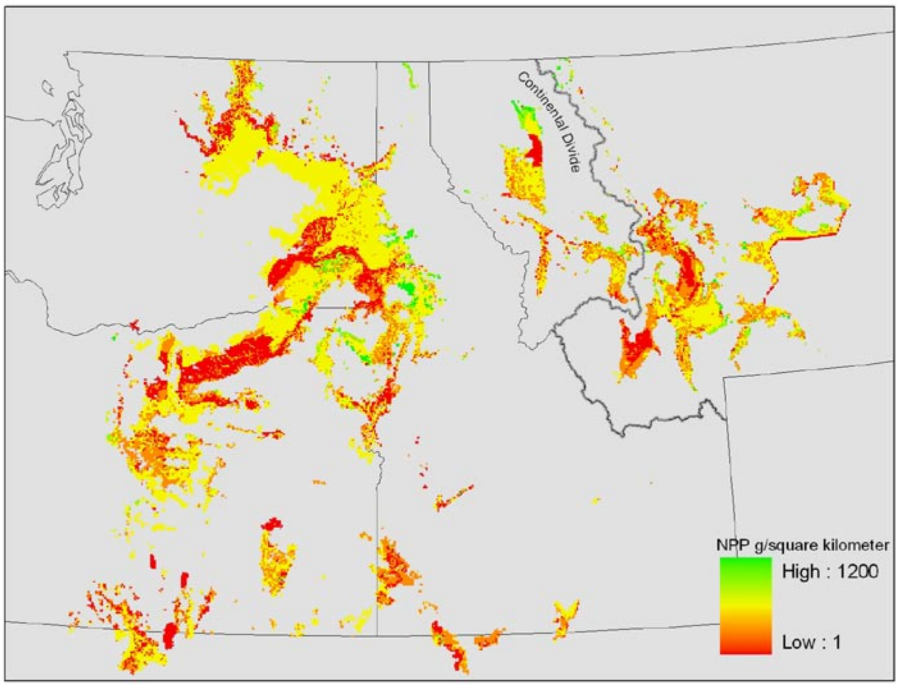

Figure 31. Modeled annual net primary production (NPP) of grassland areas of the Columbia Basin region for 1982, a year of "normal" climate conditions.

Climatic Stress Index

The climatic stress index (CSI) of selected grid sites combining SWE and June-August single-year drought frequency revealed no significant differences ($p>0.01$) across the study area when comparing locations east and west of the CD (Figure 32). CSI indices are slightly higher (worst conditions) in the northern Rocky Mountains region, west of the Divide, and the lower (best conditions) in most locations in Montana east of the Divide (with the exception of southwest Montana- near Yellowstone National Park), and most locations in Oregon, excluding northeast Oregon.

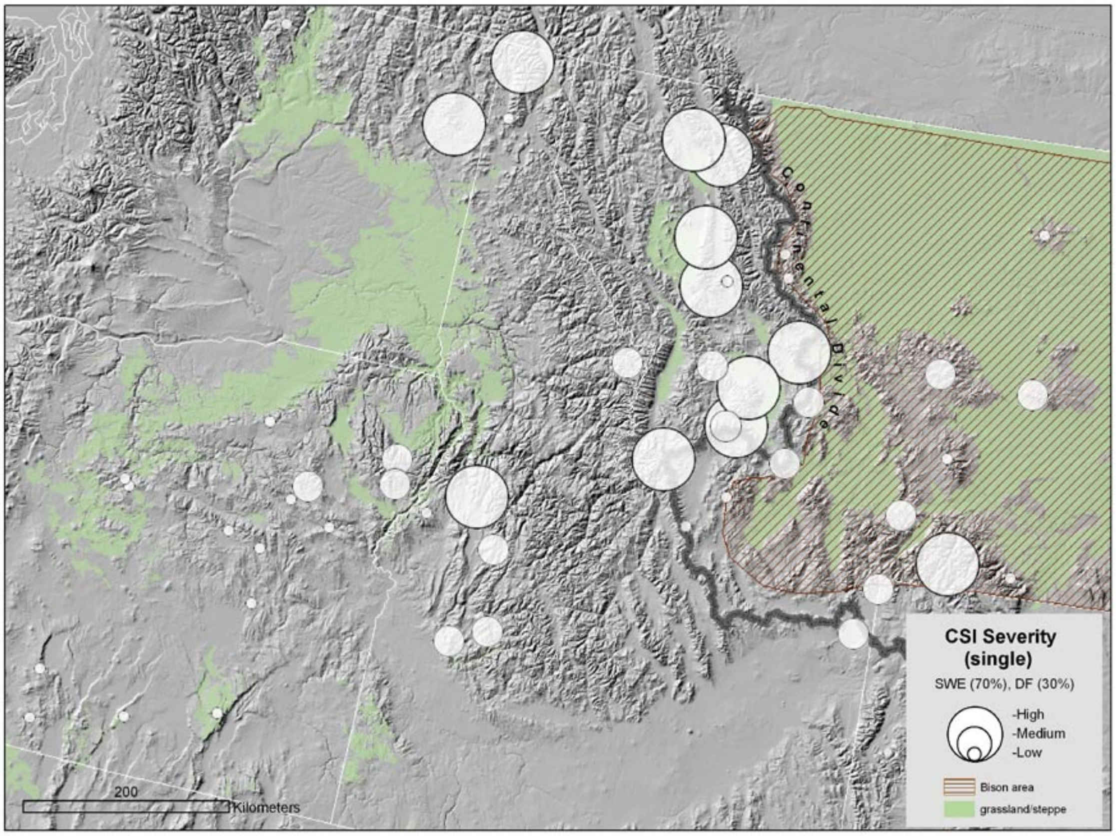

Figure 32. CSI severity for single-year June-August drought frequency and average April SWE 1950-2000. Z-scores: High - 0.68 to 3.33, Medium - -0.32 to 0.067, Low - -1.26 to -0.33.

The calculated CSIs for sustained droughts revealed a dramatic difference in pattern (Figure 33). Most significantly, locations in Oregon with relatively low CSIs calculated using single-drought frequencies, show higher CSIs calculated using sustained drought frequencies (Table 3). The highest indices shift from the northern Rockies to southern Oregon/south eastern Idaho. With the exception of the north westernmost Montana (the Flathead Valley) in the Rocky Mountains, the indices for combined SWE and sustained droughts are lower in western Montana. The disparity between sites across the Divide in Montana is no longer significant, but regionally, the CSI indices calculated for sustained summer droughts are significantly higher for locations west of the CD compared to sites east of the CD ($p<0.01$).

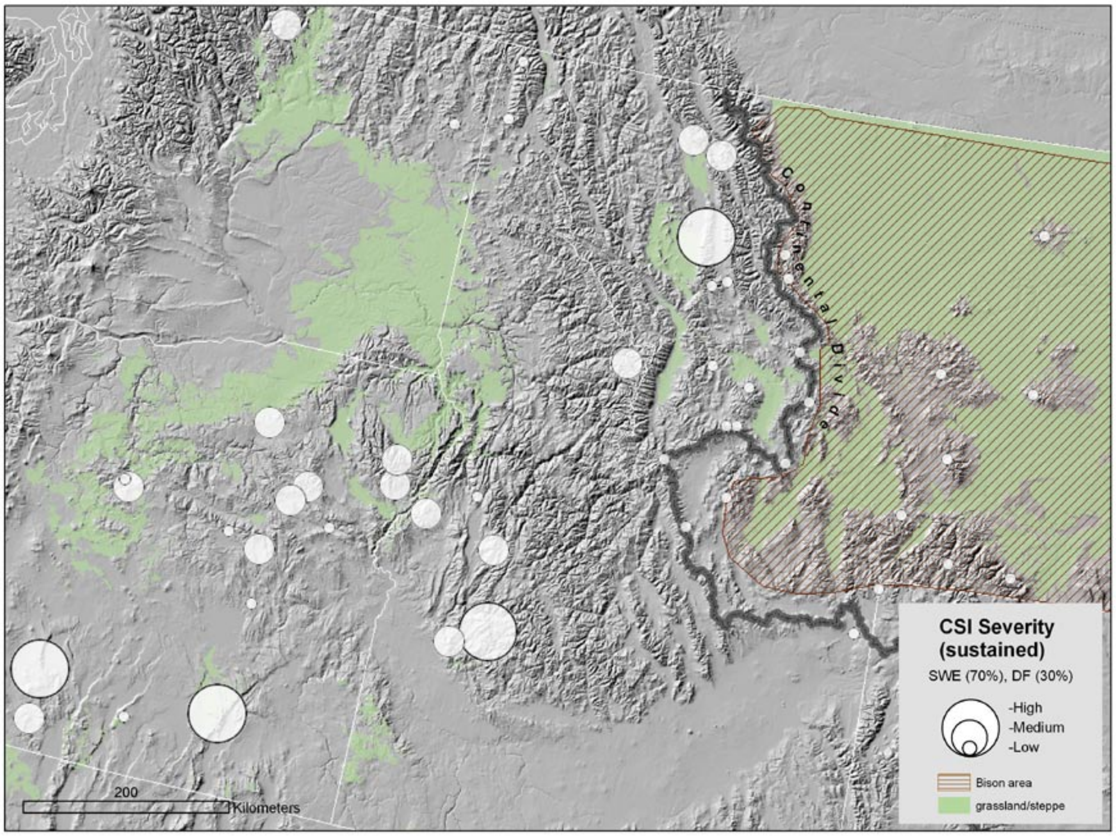

Figure 33. CSI severity for sustained June-August drought frequency and average April SWE 1950-2000 Z-scores: High - 0.91 to 3.32, Medium - -0.17 – 0.90. Low- -0.81 to 0.18.

Table 3. CSI Indices calculated for selected sites on average April SWE and single-year summer (June through August) drought frequency and average April SWE and sustained (>1 year) summer drought frequency.

East or West of Divide	ST	Station Name	Lat	Long	Elev (m)	Frequency of Single Year J-A Drought Events	Frequency of Sust J-A Drought Events	Average April SWE	Sustained CSI	Single Year CSI	Difference
E	MT	CAMP SENIA	45.17	-109.47	2405	0	3	6.53	-0.36	-1.07	0.71
E	MT	CRYSTAL LAKE PILLOW	46.78	-109.50	1844	4	1	12.11	-0.65	-0.22	-0.43
E	MT	ELK HORN SPRINGS	45.47	-113.10	2377	0	2	9.56	-0.29	-0.66	0.37
E	MT	FIVE BULL	47.45	-112.82	1737	0	1	6.20	-0.64	-0.88	0.24
E	MT	GOAT MOUNTAIN	47.65	-112.92	2134	0	2	10.48	-0.38	-0.83	0.45
E	MT	GOLD STONE	45.15	-113.53	2469	0	1	17.30	-0.34	-0.53	0.19
E	MT	INDEPENDENCE	45.22	-110.25	2393	0	0	17.83	-0.81	2.26	-3.07
E	MT	KINGS HILL	46.85	-110.70	2286	13	0	13.78	-0.81	-0.07	-0.74
E	MT	NEVEDA CREEK PILLOW	46.83	-112.52	1975	0	0	13.63	-0.81	1.42	-2.23
E	MT	NEW WORLD	45.57	-110.92	2103	17	0	14.81	-0.81	0.51	-1.32
E	MT	PIPESTONE PASS	45.85	-112.45	2195	1	0	6.09	-0.81	-0.35	-0.46
E	MT	PORCUPINE PILLOW	46.12	-110.47	1981	0	1	7.00	-0.62	-0.44	-0.18
E	MT	ROCKY BOY	48.18	-109.65	1433	0	1	4.25	-0.69	-1.01	0.32
E	MT	TEN MILE UPPER	46.42	-112.28	2438	18	0	14.30	-0.81	0.45	-1.26
E	MT	TWENTY-ONE MILE	44.90	-111.05	2179	0	1	17.41	-0.33	-0.33	0.00
W	OR	ANEROID LAKE #2 SNOTEL	45.22	-117.20	2225	0	1	26.23	-0.09	0.16	-0.25
W	MT	BARKER LAKE PILLOW	46.10	-113.13	2515	22	0	15.47	-0.81	3.33	-4.14
W	WA	BEAVER PASS	48.88	-121.25	1122	12	3	31.69	1.81	0.46	1.35
W	ID	BENTON SPRING	48.35	-116.77	1500	0	1	19.72	-0.54	-0.42	-0.12
W	MT	BIG CREEK	47.68	-113.95	2057	27	3	43.95	2.82	1.14	1.68
W	ID	BIG CREEK SUMMIT S	44.63	-115.80	2006	35	1	34.70	0.14	0.24	-0.10
W	ID	BIG SPRINGS	44.48	-111.27	1951	1	1	20.50	-0.25	-0.16	-0.09
W	ID	BOGUS BASIN	43.77	-116.10	1932	9	2	25.03	0.57	-0.18	0.75
W	ID	BOSTETTER R.S. S	42.17	-114.18	2286	7	3	20.70	0.90	-0.38	1.28
W	OR	BOURNE PILLOW	44.82	-118.20	1768	0	2	18.78	0.22	-0.25	0.47
W	WA	BOYER MOUNTAIN	48.20	-117.43	1600	0	0	25.80	-0.81	1.28	-2.09
W	ID	BRUNDAGE RESERVOIR S	45.05	-116.13	1920	27	0	31.14	-0.81	1.12	-1.93
W	OR	CHEMULT ALT	43.22	-121.80	1451	20	4	8.77	0.03	-0.90	0.93
W	MT	COYOTE HILL	47.33	-113.58	1280	2	1	9.47	-0.55	-0.66	0.11
W	MT	DESERT MTN	48.42	-113.95	1707	0	2	15.45	0.04	1.10	-1.06
W	OR	DOOLEY MTN	44.50	-117.83	1655	2	2	8.47	-0.35	-0.73	0.38
W	OR	FISH CREEK SNOTEL	42.70	-118.63	2408	26	5	30.02	3.32	-0.63	3.95
W	MT	GIBBONS PASS	45.70	-113.95	2164	0	1	23.02	-0.18	1.25	-1.43
W	MT	GOLD CREEK LAKE	46.45	-113.07	2195	0	0	15.31	-0.81	1.42	-2.23
W	OR	HART MTN AM	42.48	-119.70	1935	0	7	1.64	-0.50	-1.22	0.72
W	MT	HELL ROARING DIVIDE	48.50	-114.35	1759	3	2	30.47	0.87	1.07	-0.20
W	OR	LAKE CREEK SNOTEL	44.18	-118.60	1585	5	4	11.28	0.43	-0.79	1.22
W	OR	LUCKY STRIKE SNOTEL	45.28	-118.85	1539	5	4	11.27	0.43	-0.92	1.35
W	OR	MARKS CREEK	44.48	-120.40	1384	0	3	1.61	-0.68	-1.22	0.54
W	ID	MOORES CREEK SUMMIT SNOTEL	43.92	-115.67	1859	36	4	35.64	3.12	0.28	2.84
W	WA	MUTTON CREEK NO 2	48.70	-119.87	1829	23	2	14.44	-0.02	-0.65	0.63
W	MT	NORTH FORK JOCKO PILLOW	47.27	-113.77	1929	31	0	45.81	-0.81	1.75	-2.56
W	OR	OCHOCO MEADOWS SNOTEL	44.43	-120.33	1585	0	6	9.09	0.69	-1.09	1.78
W	ID	PLACER CREEK	44.82	-116.70	1786	0	3	18.80	0.48	-0.46	0.94
W	OR	QUARTZ MTN	42.27	-120.78	1622	3	7	3.72	-0.09	-1.17	1.08
W	ID	SAVAGE PASS SNOTEL	46.47	-114.63	1881	0	2	27.48	0.70	-0.08	0.78
W	OR	SCHNEIDER MEADOWS	45.00	-117.15	1646	26	1	31.56	0.06	0.10	-0.04
W	MT	SLIDE ROCK MTN	46.58	-113.57	2164	0	1	16.13	-0.37	0.67	-1.04
W	ID	SMITH CREEK	48.87	-116.75	1463	30	1	45.48	-0.19	2.23	-2.42
W	OR	STARR RIDGE REV	44.27	-119.02	1570	0	5	3.97	-0.27	-1.12	0.85
W	OR	STINKING WATER	43.70	-118.53	1463	0	4	0.80	-0.72	-1.26	0.54
W	MT	STORM LAKE	46.08	-113.27	2371	12	0	14.17	-0.81	0.43	-1.24
W	OR	STRAWBERRY SNOTEL	42.10	-121.85	1756	9	4	5.50	-0.28	-1.05	0.77
W	OR	SUMMER RIM SNOTEL	42.70	-120.82	2164	3	6	19.66	2.44	-0.86	3.30
W	OR	TIPTON SNOTEL	44.67	-118.37	1570	23	2	15.28	0.03	-0.62	0.65

CHAPTER 4: DISCUSSION

While snow depths tend to be higher east of the Rocky Mountains, snow water equivalent values are, in general, higher west of the CD, and most significantly west of the CD in Montana. The most significant landscape feature that contributes to the distribution of SWE is the Rocky Mountains, which intercept moisture from the Pacific. In addition, high SWE values are related to both temperature and precipitation maximums (Serreze *et al*. 1999). Mean winter temperatures are higher overall west of the Rockies due to the moderating influence of marine air masses, which leads to higher water content in snow (Serreze *et al*. 1999). The seasonal precipitation maximum in the study area grades from November through December in most of Washington and western/central Oregon, to January through February in northeast Oregon, some locations in Idaho and western Montana, to May through June in western Idaho and central to eastern Montana (Mock 1996). For the region west of the CD, relatively warm and moist air from the Pacific dominates in the wintertime, which is best represented by April SWE (Cayan *et al.* 1999).

The results of SWE analysis demonstrated that in general, the Cascades and Northern Idaho/ northwestern Montana have the highest SWE (>30 inches). These regions overall have the highest elevations and are most likely to intercept moisture from the Pacific. These regions also have low historical bison populations. With increasing distance from the source of moisture, but high windward locations, the region from the Wallowa Mountains in northeastern Oregon to the Salmon Mountains in western Idaho have fairly high SWE values (20--25 inches). From central to southwest Oregon SWE values are the lowest (<10 inches), most likely due to the rainshadow effects of the Cascades. What is most interesting is the similarity in SWE values between the regions of central to northeastern Oregon and southwestern Montana. This component averages between 10 and 20 inches of April SWE. The reason for this is likely due to relatively high elevations (higher than SW Oregon, but lower than the Cascades and Northern Rockies), but in leeward locations.

Because SWE is highest west of the CD in western Montana and northern Idaho (excluding the Cascades Range), winter range conditions are likely the most severe in the valleys of this region, precluding bison populations from large abundance as their counterparts east of the Divide. Based on SWE values alone, and because SWE values between southwest Montana (relatively high historical bison abundance) and northeastern-central Oregon (lower historical bison abundance) are comparable, it would seem that - given all other conditions are equal - winter range conditions in the grassland/steppe of Oregon should be suitable for bison success.

At the regional scale, the cause of greater drought frequency west of the CD is most likely affected by a combination of topography and synoptic processes such as the high pressure over the Pacific and the PDO (Knapp *et al*. 2004). During the summer, precipitation is at a minimum west of the CD due to the blocking action of a high pressure system over the Pacific, which steers moisture to the north (Serreze *et al*. 1999, Knapp *et al*. 2004). In the autumn, the high pressure system begins to weaken, allowing marine air masses to penetrate the region. Knapp *et al.* (2004) found that sustained droughts are more common during the warm phase of the PDO, which is likely a greater synoptic control on precipitation variability during the summer west of the CD. Drought frequency east of the CD has been shown to be controlled by the transport of moisture from the Gulf of Mexico in the summertime, which is influenced by decadal-scale fluctuations in the North Atlantic sea surface temperatures (the North Atlantic Oscillation) and ENSO (Enfield *et al*. 2001, Woodhouse *et al.* 2002).

A comparison of inter- and intra-annual drought frequencies across the study area reveals that the most significant difference in drought frequency between locations east and west of the CD occurs in the summertime. Single-year droughts are a dominant climatic feature of western Montana, compared to multiple-year persistent drought across the region west of the Divide. Both variables were used to develop the CSI. Studies have shown that summertime drought conditions preceding a winter of heavy snowfall are particularly deleterious to bison populations (Frank and McNaughton 1992, Woodhouse *et al*. 2002). The combination of SWE and drought frequency variables provides a more complete analysis of how climate in the region may have

affected historical bison success. The results presented here indicate a relationship between areas of low historic bison occurrence and severe climate conditions. CSI values for single-year drought frequencies are slightly higher in northwestern Montana just west of the CD, and more significantly, CSI for sustained drought frequencies are the highest in central Washington and Oregon, all locations of low bison occurrence. Thus, the combined effects of high SWE and greater drought frequency create a two-dimensional form of climatic stress that may preclude bison from residing in certain areas.

The spatial patterning of the CSI data suggest that the abundance of bison may be significantly influenced by the inter-annual reliability of forage as opposed to long-term averages of plant productivity that would suggest otherwise. Thus, in areas where SWE is low and summer droughts the least frequent, such as the eastern Rocky Mountain foothills of Montana, a reliable source of forage supported abundant bison herds. Conversely, greater SWE and more frequent droughts have historically posed challenges for bison to obtain forage during the winter and summer, respectively, and may have limited herd populations in western Idaho, eastern Oregon, and eastern Washington.

Conclusion

Using monthly average data collected at SNOTEL/snow course and NWS/Cooperative weather stations for the past several decades, average April SWE and summertime drought frequency were analyzed at sites across the northwest United States. An index of climate severity was developed by combining average SWE and drought frequency for sites within 50 km of grassland/steppe, as these are the climate factors that will most likely affect bison success. The results of the climate severity index (CSI) revealed that in general, locations west of the continental divide experience heavier snowfall and a greater frequency of sustained droughts, thus presenting a "double whammy" of climate conditions that bison populations would have to endure. The locations of highest combined snow and drought frequencies coincide with locations of low bison occurrence.

It is likely that climate conditions in concert with other factors have affected bison success across the Northwest United States, but it is also likely that CSI is critically important. In addition to this and other theories offered, consideration of migration filters and barriers in the northwest United States deserves more attention. Van Vuren (1987) suggests that the complex topography of mountains and canyons west of the continental divide is an impediment to open migration. It is also possible that rivers may be an important migration filter. Because of a lack of snow stations in northern Oregon and southern Washington along the Columbia River, it is not feasible to evaluate winter severity conditions in this area. But compared to locations further south in Oregon, this area has relatively low drought frequency, which is probably due to more frequent incursions of marine air through the Columbia Gorge, which would moderate the frequency of drought (Ferguson, 1999). The Columbia and Snake rivers essentially isolate Oregon from the rest of the region, so although bison can swim, and can cross rivers (Figure 34), migration across these rivers would only be possible along narrow stretches, during periods of low flow, or when the rivers freeze.

Figure 34. Bison crossing Yellowstone River. NPS Photo by Jim Peaco, September 2001.

While Bison have occurred west of the Rockies throughout the Holocene, the consensus is that they were never as abundant as east of the continental divide (Mack and Thompson 1982, Daubenmire 1985, Van Vuren 1987, Flores 1991, Garret 2001, Martin and Szuter 1999 and 2002, Lyman and Wolverton 2002, Moore 2002). These previous studies have examined human predation, carrying capacity of the landscape, forage quality, and snow depth. The results of this study of climate severity and bison distribution enhances previous work by providing evidence that there are significant differences between snow and drought conditions of the northwest United States, that coincide with areas with historically low bison occurrence. In addition, it illustrates that the role of climatic variability over what are otherwise considered to be defined ecoregions may be more important than previously identified for bison. This consideration of multi-dimensional climate variability as a factor of bison ecology from a geographical perspective should compel further research of mammalian biogeography with enhanced regard to the geographic and temporal scales of climate.

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APPENDIX I

SNOTEL Station Inventory

State	Station ID	Station Type	Station Name	Elev (meters)	Lat (North)	Long (West)
ID	11E20S	Snotel	Island Park Snotel	1917	44.42	-111.38
ID	11E37S	Snotel	Crab Creek Snotel	2091	44.43	-112.00
ID	11G01S	Snotel	Somsen Ranch Snotel	2073	42.95	-111.37
ID	11G05S	Snotel	Slug Creek Divide Snotel	2202	42.57	-111.30
ID	11G06S	Snotel	Emigrant Summit Snotel	2252	42.37	-111.57
ID	11G30S	Snotel	Sedgewick Peak Snotel	2393	42.53	-111.97
ID	11G32S	Snotel	Franklin Basin Snotel	2490	42.05	-111.60
ID	13D16S	Snotel	Moose Creek Snotel	1890	45.00	-113.95
ID	14C04S	Snotel	Savage Pass Snotel	1881	46.47	-114.63
ID	14E01S	Snotel	Mill Creek Summit Snotel	2682	44.47	-114.47
ID	14F02S	Snotel	Stickney Mill Snotel	2265	43.87	-114.22
ID	14F11S	Snotel	Soldier Rs Snotel	1750	43.48	-114.82
ID	14F19S	Snotel	Chocolate Gulch Snotel	1963	43.77	-114.42
ID	14G01S	Snotel	Bostetter R.S. Snotel	2286	42.17	-114.18
ID	14G02S	Snotel	Magic Mountain Snotel	2097	42.18	-114.30
ID	15C04S	Snotel	Shanghai Summit Snotel	1393	46.57	-115.75
ID	15E02S	Snotel	Big Creek Summit Snotel	2006	44.63	-115.80
ID	15E04S	Snotel	Deadwood Summit Snotel	2091	44.55	-115.57
ID	15F01S	Snotel	Moores Creek Summit Snotel	1859	43.92	-115.67
ID	15F04S	Snotel	Atlanta Summit S	2310	43.75	-115.23
ID	15F05S	Snotel	Trinity Mtn Snotel	2368	43.63	-115.43
ID	16A04S	Snotel	Mosquito Ridge Snotel	1585	48.05	-116.23
ID	16D08S	Snotel	West Branch Snotel	1695	45.07	-116.43
ID	16D09S	Snotel	Brundage Reservoir Snotel	1920	45.05	-116.13
ID	16G01S	Snotel	South Mtn Snotel	1981	42.77	-116.90
ID	11E022	Snow course	Kilgore	1926	44.40	-111.90
ID	11E08	Snow course	Valley View	2036	44.63	-111.32
ID	11E09	Snow course	Big Springs	1951	44.48	-111.27
ID	11E11	Snow course	Blue Ledge Mine	2103	44.43	-112.00
ID	11F01	Snow course	State Line	2030	43.55	-111.05
ID	11GO3	Snow course	Austin Bros Ranch	1951	42.78	-111.43
ID	12E03	Snow course	Camp Creek	2006	44.45	-112.23
ID	12G08	Snow course	Sublett	1814	42.38	-112.97
ID	13F02	Snow course	Copper Basin	2329	43.82	-113.92
ID	14D03	Snow course	Kit Carson Pasture	1509	45.70	-114.62
ID	14F05	Snow course	Graham Ranch	1911	43.78	-114.42
ID	14F07	Snow course	Mascot Mine	2371	43.70	-114.10
ID	15B03	Snow course	Fourty-Nine Meadows	1472	47.10	-115.88
ID	15D02	Snow course	Squaw Meadow	1798	45.15	-116.00
ID	15E011	Snow course	Lake Fork	1612	44.92	-115.95
ID	15E03	Snow course	Crawford	1481	44.53	-115.98
ID	16A01	Snow course	Smith Creek	1463	48.87	-116.75
ID	16A02	Snow course	Benton Meadow	722	48.35	-116.83
ID	16A03	Snow course	Benton Spring	1500	48.35	-116.77
ID	16B01	Snow course	Lower Sands Creek	951	47.73	-116.48

ID	16B02	Snow course	Copper Ridge D	1469	47.72	-116.50
ID	16D01	Snow course	Boulder Creek	1658	45.07	-116.45
ID	16E02	Snow course	Placer Creek	1786	44.82	-116.70
ID	16F02	Snow course	Bogus Basin	1932	43.77	-116.10
MT	09C01S	Snotel	Crystal Lake Pillow	1844	46.78	-109.50
MT	10C03S	Snotel	Porcupine Pillow	1981	46.12	-110.47
MT	10D07S	Snotel	Northeast Entrance Pillow	2240	45.00	-110.00
MT	10D16S	Snotel	Shower Falls Pillow	2469	45.40	-110.95
MT	11E07S	Snotel	Twenty-One Mile	2179	44.90	-111.05
MT	12C21S	Snotel	Neveda Creek Pillow	1975	46.83	-112.52
MT	13A24S	Snotel	Emery Creek Pillow	1326	48.43	-113.93
MT	13A26S	Snotel	Pike Creek Pillow	1807	48.30	-113.33
MT	13B07S	Snotel	North Fork Jocko Pillow	1929	47.27	-113.77
MT	13B24S	Snotel	Moss Peak Pillow	2067	47.68	-113.97
MT	13C03S	Snotel	Skalkaho Summit Pillow	2210	46.25	-113.77
MT	13C44S	Snotel	Barker Lake Pillow	2515	46.10	-113.13
MT	14D02S	Snotel	Nez Perce Camp Pillow	1722	45.73	-114.48
MT	15A08S	Snotel	Banfield Mtn Pillow	1707	48.57	-115.45
MT	09A01	Snow course	Rocky Boy	1433	48.18	-109.65
MT	09D01	Snow course	Camp Senia	2405	45.17	-109.47
MT	10C01	Snow course	Kings Hill	2286	46.85	-110.70
MT	10C02	Snow course	Grasshopper	2134	46.52	-110.77
MT	10D01	Snow course	New World	2103	45.57	-110.92
MT	10D03	Snow course	Hood Meadow	2012	45.48	-110.97
MT	10D04	Snow course	Devils Slide	2469	45.40	-110.95
MT	10D05	Snow course	Crevice Mtn	2560	45.03	-110.60
MT	10D06	Snow course	Independence	2393	45.22	-110.25
MT	10D07	Snow course	Northeast Entrance	2240	45.00	-110.00
MT	11E08	Snow course	West Yellostone	2042	44.67	-111.32
MT	11EO6	Snow course	Hebgen Dam	1996	44.87	-111.33
MT	12A01	Snow course	Freight Creek	1829	48.02	-112.83
MT	12B07	Snow course	Goat Mountain	2134	47.65	-112.92
MT	12B09	Snow course	Five Bull	1737	47.45	-112.82
MT	12C01	Snow course	Stemple Pass	2012	46.88	-112.48
MT	12C02	Snow course	Ten Mile Lower	2012	46.45	-112.28
MT	12C03	Snow course	Ten Mile Middle	2073	46.43	-112.30
MT	12C04	Snow course	Ten Mile Upper	2438	46.42	-112.28
MT	12C05	Snow course	Chessman Res	1890	46.47	-112.18
MT	12D01	Snow course	Pipestone Pass	2195	45.85	-112.45
MT	13A02	Snow course	Desert Mtn	1707	48.42	-113.95
MT	13A05	Snow course	Marias Pass	1600	48.32	-113.35
MT	13A16	Snow course	Mineral Creek	1219	48.77	-113.82
MT	13B03	Snow course	Big Creek	2057	47.68	-113.95
MT	13B10	Snow course	Coyote Hill	1280	47.33	-113.58
MT	13C01	Snow course	Stuart Mtn	2256	47.00	-113.92
MT	13C02	Snow course	Slide Rock Mtn	2164	46.58	-113.57
MT	13C04	Snow course	Intergaard	1966	46.22	-113.28
MT	13C06	Snow course	Stuart Mill	1981	46.17	-113.27
MT	13C07	Snow course	Storm Lake	2371	46.08	-113.27
MT	13C09	Snow course	El Dorado Mine	2377	46.43	-113.07
MT	13C10	Snow course	Gold Creek Lake	2195	46.45	-113.07
MT	13D01	Snow course	East Fork	1646	45.92	-113.72
MT	13D02	Snow course	Gibbons Pass	2164	45.70	-113.95
MT	13D09	Snow course	Gold Stone	2469	45.15	-113.53
MT	13D15	Snow course	Elk Horn Springs	2377	45.47	-113.10
MT	13D27	Snow course	Jahnke Lake Trail	2195	45.22	-113.50
MT	14A03	Snow course	Hell Roaring Divide	1759	48.50	-114.35

MT	14A05	Snow course	Logan Creek	1311	48.33	-114.65
MT	14A06	Snow course	Kishenehn	1186	48.97	-114.42
MT	14A07	Snow course	Weasel Divide	1661	48.95	-114.73
MT	14D01	Snow course	Nez Perce Pass	2003	45.72	-114.50
MT	15A01	Snow course	Red Mountain	1829	48.92	-115.35
MT	15B11	Snow course	Baree Creek	1676	47.97	-115.53
MT	15C01	Snow course	Hoodoo Creek	1798	46.98	-115.02
OR	17D02S	Snotel	Aneroid Lake #2 Snotel	2225	45.22	-117.20
OR	18D04S	Snotel	Emigrant Springs Snotel	1196	45.55	-118.45
OR	18D06S	Snotel	Lucky Strike Snotel	1539	45.28	-118.85
OR	18D09S	Snotel	Beaver Resev Snotel	1570	45.13	-118.22
OR	18D19S	Snotel	High Ridge Pillow	1518	45.68	-118.10
OR	18D20S	Snotel	Bowman Spr Snotel	1396	45.37	-118.45
OR	18E03S	Snotel	Eilertson Mead Snotel	1646	44.85	-118.12
OR	18E05S	Snotel	Bourne Pillow	1768	44.82	-118.20
OR	18E08S	Snotel	Gold Center Snotel	1628	44.77	-118.28
OR	18E09S	Snotel	Tipton Snotel	1570	44.67	-118.37
OR	18E16S	Snotel	Blue Mtn Springs Snotel	1798	44.25	-118.50
OR	18E18S	Snotel	Lake Creek Snotel	1585	44.18	-118.60
OR	18G01S	Snotel	Silvies Snotel	2103	42.75	-118.68
OR	18G02S	Snotel	Fish Creek Snotel	2408	42.70	-118.63
OR	19E03S	Snotel	Derr Snotel	1728	44.45	-119.93
OR	20E02S	Snotel	Ochoco Meadows Snotel	1585	44.43	-120.33
OR	20G02S	Snotel	Summer Rim Snotel	2164	42.70	-120.82
OR	20G09S	Snotel	Strawberry Snotel	1756	42.10	-121.85
OR	21D01S	Snotel	Greenpoint Snotel	975	45.62	-121.70
OR	21D14S	Snotel	Peavine Ridge Snotel	1067	45.05	-121.93
OR	21E04S	Snotel	Marion Forks Pillow	792	44.58	-121.97
OR	21E05S	Snotel	Santiam Jct Snotel	1143	44.43	-121.93
OR	21E06S	Snotel	Hogg Pass Snotel	1451	44.42	-121.87
OR	21E07S	Snotel	Mckenzie Snotel	1463	44.20	-121.87
OR	21E13S	Snotel	Three Creeks Meadow Snotel	1722	44.15	-121.63
OR	21F12S	Snotel	Silver Creek Pillow	1743	42.95	-121.18
OR	21F21S	Snotel	Irish Taylor Snotel	1676	43.82	-121.95
OR	22E07S	Snotel	Jump Off Joe Snotel	1067	44.38	-122.17
OR	22F03S	Snotel	Cascade Summit Snotel	1487	43.58	-122.02
OR	22F14S	Snotel	Summit Lake Snotel	1707	43.45	-122.13
OR	22F18S	Snotel	Diamond Lake Snotel	1620	43.18	-122.13
OR	22F43S	Snotel	Roaring River Pillow	1494	43.90	-122.03
OR	22FO4S	Snotel	Salt Creek Falls Snotel	1219	43.60	-122.07
OR	22G12S	Snotel	Fourmile Lake Snotel	1829	42.40	-122.22
OR	22G13S	Snotel	Billie Creek Snotel	1615	42.42	-122.28
OR	22G14S	Snotel	Fish Lake Snotel	1422	42.38	-122.42
OR	22G21S	Snotel	Big Red Mtn Pillow	1905	42.05	-122.85
OR	17D06	Snow course	Moss Springs	1783	45.27	-117.68
OR	17D08	Snow course	Schneider Meadows	1646	45.00	-117.15
OR	17E05	Snow course	Dooley Mtn	1655	44.50	-117.83
OR	18D03	Snow course	Tollgate	1545	45.83	-118.13
OR	18D05	Snow course	Meacham	1311	45.50	-118.42
OR	18E02	Snow course	Anthony Lake	2173	44.97	-118.23
OR	18F01	Snow course	Rock Springs	1554	43.98	-118.98
OR	18F04	Snow course	Stinking Water	1463	43.70	-118.53
OR	19D02	Snow course	Arbuckle Mtn	2377	45.18	-119.25
OR	19E08	Snow course	Starr Ridge	1570	44.27	-119.02
OR	19G01	Snow course	Hart Mtn Am	1935	42.48	-119.70
OR	20E02	Snow course	Marks Creek	1384	44.48	-120.40
OR	20G06	Snow course	Quartz Mtn	1622	42.27	-120.78

OR	20G08	Snow course	Camas Creek #1	1743	42.23	-120.28
OR	21D06	Snow course	Brooks Meadow	1311	45.40	-121.50
OR	21D08	Snow course	Mt Hood	1646	45.33	-121.72
OR	21D12	Snow course	Clear Lake	1067	45.20	-121.72
OR	21D13	Snow course	Clackamas Lake	1036	45.08	-121.75
OR	21E17	Snow course	New Dutchman Flat	1951	44.00	-121.70
OR	21F22	Snow course	Chemult Alt	1451	43.22	-121.80
OR	21G03	Snow course	Taylor Butte	1554	42.70	-121.40
OR	21G08	Snow course	Harriman Lodge	1265	42.45	-121.10
OR	22F16	Snow course	North Umpqua	1286	43.28	-122.15
OR	22F17	Snow course	Trap Creek	1158	43.25	-122.25
OR	22G02	Snow course	Silver Burn	1134	42.92	-121.40
OR	22G05	Snow course	Park Hq Rev	1996	42.90	-122.13
OR	22G06	Snow course	Annie Spring	1835	42.88	-122.17
OR	22G16	Snow course	Hyatt Prairie	1494	42.18	-122.47
OR	22G35	Snow course	Siskiyo Summit	1411	42.07	-122.62
OR	22G40	Snow course	Crystal	1265	42.67	-122.07
OR	22G41	Snow course	Fort Klamath	1280	42.72	-122.00
OR	23G04	Snow course	Althouse2	1786	44.77	-118.05
WA	19A02S	Snotel	Salmon Mdws Pillow	1372	48.67	-119.83
WA	20A05S	Snotel	Harts Pass Pillow	1981	48.72	-120.65
WA	20A09S	Snotel	Rainy Pass Pillow	1457	48.55	-120.72
WA	20A12S	Snotel	Park Creek Pillow	1402	48.45	-120.92
WA	20A23S	Snotel	Lyman Lake Pillow	1798	48.20	-120.92
WA	20A40S	Snotel	Miners Ridge Pillow	1890	48.17	-120.98
WA	20B02S	Snotel	Blewett Pass Pillow	1301	47.35	-120.68
WA	21B04S	Snotel	Fish Lake Pillow	1027	47.52	-121.07
WA	21B10S	Snotel	Stampede Pass Pillow	1177	47.28	-121.33
WA	21B55S	Snotel	Olallie Mdws Pillow	1128	47.37	-121.43
WA	21C35S	Snotel	Paradise Pillow	1561	46.83	-121.72
WA	17A01	Snow course	Bunchgrass Meadow	1524	48.27	-117.28
WA	17A02	Snow course	Boyer Mountain	1600	48.20	-117.43
WA	19A01	Snow course	Mutton Creek No 2	1829	48.70	-119.87
WA	19A03	Snow course	Rusty Creek	1219	48.53	-119.87
WA	1B13S	Snow course	Corral Pass Pillow	1829	47.02	-121.47
WA	20A01	Snow course	Freezeout Cr Tr	1067	48.95	-120.95
WA	20A08	Snow course	Meadow Cabins	579	48.58	-120.93
WA	20A12	Snow course	Park Creek Ridge	1402	48.45	-120.92
WA	20A22	Snow course	Cloudy Pass Am	1981	48.20	-120.92
WA	20A24	Snow course	Little Meadows Am	1608	48.20	-120.90
WA	21A01	Snow course	Beaver Pass	1122	48.88	-121.25
WA	21A04	Snow course	Beaver Creek Trail	671	48.83	-121.20
WA	21B01	Snow course	Stevens Pass	1281	47.73	-121.08
WA	21B08	Snow course	Tunnel Avenue	747	47.32	-121.35
WA	21B09	Snow course	Big Boulder Creek	975	47.43	-121.03
WA	21B14	Snow course	Lake Cleelum	671	47.23	-121.07
WA	21C06	Snow course	Cayuse Pass	1615	46.87	-121.53
WA	21C08	Snow course	Bumping Lake	1036	46.87	-121.30
WA	21C10	Snow course	Green Lake Pillow	1829	46.55	-121.17
WA	21C11	Snow course	Ahtanum Rs	945	46.52	-121.02
WA	21C13	Snow course	Surprise Lakes	1295	46.10	-121.75

APPENDIX II

Monthly Cooperative Precipitation Stations

State	Coop ID	Station Name	Elev (meters)	Lat (North)	Long (West)	Years of Data	% Missing Data
ID	100010	Aberdeen Experiment Stn	1342.6	42.95	-112.83	64	0
ID	100227	American Falls 3	1342.6	42.78	-112.92	64	0
ID	100282	Anderson Dam	1183.2	43.37	-115.45	61	0
ID	100375	Arco	1623.1	43.63	-113.30	63	11
ID	100448	Arrowrock Dam	998.2	43.60	-115.92	64	0
ID	100470	Ashton	1588.6	44.07	-111.45	64	0
ID	100667	Bayview Model Basin	632.5	47.98	-116.57	57	0
ID	100915	Blackfoot Fire Dept	1382.6	43.20	-112.35	64	11
ID	101002	Bliss 4 Nw	998.2	42.95	-115.02	57	0
ID	101079	Bonners Ferry	539.5	48.70	-116.32	64	0
ID	101408	Cambridge	807.7	44.57	-116.68	64	0
ID	101514	Cascade 1 Nw	1492.3	44.52	-116.05	62	0
ID	101663	Challis	1577.3	44.50	-114.23	56	0
ID	101671	Chilly Barton Flat	1908	43.98	-113.83	59	0
ID	101956	Coeur D’alene	650.1	47.68	-116.80	56	2
ID	102187	Council	899.2	44.73	-116.43	64	0
ID	102444	Deer Flat Dam	765	43.58	-116.75	64	0
ID	102676	Driggs	1865.4	43.73	-111.12	64	3
ID	102707	Dubois Experiment Stn	1661.2	44.25	-112.20	65	2
ID	102875	Elk City 1 NE	1236.9	45.83	-115.47	53	0
ID	102892	Elk River 1 S	889.4	46.77	-116.18	52	0
ID	102942	Emmett 2 E	728.5	43.85	-116.47	64	0
ID	103108	Fairfield Ranger Stn	1543.8	43.35	-114.78	57	5
ID	103143	Fenn Ranger Station	475.5	46.10	-115.53	69	7
ID	103297	Fort Hall 1	1360.9	43.05	-112.42	64	0
ID	103448	Garden Valley	944.9	44.10	-115.97	65	5
ID	103631	Glenns Ferry	751.6	42.93	-115.32	64	0
ID	103732	Grace	1691.6	42.58	-111.75	64	0
ID	103760	Grand View 4 Nw	731.5	43.02	-116.18	61	0
ID	103771	Grangeville	1021.1	45.93	-116.12	65	3
ID	103882	Grouse	1829.1	43.72	-113.55	64	5
ID	103964	Hamer 4 Nw	1460	43.97	-112.27	64	8
ID	104140	Hazelton	1237.5	42.60	-114.13	64	0
ID	104268	Hill City 1 W	1554.5	43.30	-115.07	64	0
ID	104295	Hollister	1379.2	42.35	-114.57	64	0
ID	104384	Howe	1469.1	43.78	-113.00	64	5
ID	104442	Idaho City	1208.5	43.83	-115.83	64	0
ID	104456	Idaho Falls 16	1776.4	43.35	-111.78	49	0
ID	104598	Island Park	1917.2	44.42	-111.37	64	0
ID	104670	Jerome	1140	42.73	-114.52	64	0
ID	105038	Kuna	819.9	43.48	-116.42	54	4

ID	105241	Lewiston Nez Perce Cnty Ap	437.7	46.37	-117.02	56	0
ID	105275	Lifton Pumping Stn	1806.2	42.12	-111.32	64	0
ID	105559	Malad City	1362.5	42.15	-112.28	60	0
ID	105685	May 2	1539.2	44.57	-113.90	54	0
ID	105708	Mccall	1531.6	44.88	-116.10	64	0
ID	105980	Minidoka Dam	1269.2	42.68	-113.50	57	0
ID	106152	Moscow U Of I	810.8	46.72	-116.97	64	0
ID	106174	Mountain Home	957.1	43.13	-115.72	65	0
ID	106424	Nezperce	987.6	46.23	-116.25	52	0
ID	106542	Oakley	1389.9	42.23	-113.90	64	0
ID	106764	Palisades	1641.3	43.35	-111.22	47	0
ID	106877	Paul 1	1264.9	42.63	-113.77	64	0
ID	106891	Payette	655.3	44.08	-116.93	64	0
ID	107211	Pocatello Regional Ap	1353.3	42.92	-112.57	55	0
ID	107301	Potlatch 3	792.5	46.95	-116.88	63	0
ID	107673	Richfield	1305.2	43.05	-114.15	64	0
ID	107706	Riggins	548.6	45.42	-116.32	64	0
ID	108022	Saint Anthony 1 Wnw	1508.8	43.97	-111.72	64	0
ID	108062	Saint Maries 1 W	707.1	47.32	-116.58	64	0
ID	108137	Sandpoint Exp Station	640.1	48.30	-116.55	64	0
ID	108380	Shoshone 1 Wnw	1204	42.93	-114.42	64	0
ID	108676	Stanley	1911.4	44.22	-114.93	40	0
ID	108928	Swan Falls P H	708.7	43.25	-116.38	64	0
ID	109498	Wallace Woodland Park	896.1	47.48	-115.92	64	0
ID	109560	Warren	1800.5	45.27	-115.68	45	0
MT	240364	Augusta	1240.5	47.50	-112.40	65	2
MT	240375	Austin 1 W	1460	46.63	-112.27	54	2
MT	240392	Babb 6 Ne	1310.6	48.93	-113.37	65	3
MT	240622	Bozeman Gallatin Field	1349.3	45.78	-111.17	62	0
MT	240755	Bigfork 13 S	887	47.88	-114.03	65	2
MT	240770	Big Sandy	844.3	48.13	-110.07	64	3
MT	240780	Big Timber	1249.7	45.83	-109.95	65	2
MT	240807	Billings Logan Int'l Arpt	1091.5	45.80	-108.55	63	0
MT	240877	Blackleaf	1290.8	48.02	-112.43	56	5
MT	241008	Boulder	1494.7	46.23	-112.12	65	2
MT	241044	Bozeman Montana St Univ	1497.5	45.67	-111.05	65	2
MT	241102	Bridger 2 N	1092.1	45.33	-108.92	63	5
MT	241318	Butte Bert Mooney Ap	1678.2	45.97	-112.50	63	2
MT	241552	Cascade 5 S	1024.1	47.22	-111.72	65	2
MT	241692	Chester	954.6	48.50	-110.97	63	5
MT	241722	Chinook	737.6	48.58	-109.23	65	3
MT	241737	Choteau	1172	47.82	-112.20	65	3
MT	241938	Columbus	1097.9	45.65	-109.27	65	2
MT	241974	Conrad	1082	48.18	-111.97	65	3
MT	242104	Creston	896.1	48.18	-114.13	56	2
MT	242173	Cut Bank Municipal Ap	1169.8	48.60	-112.38	64	2
MT	242221	Darby	1182.6	46.02	-114.18	65	2
MT	242347	Denton	1100.3	47.32	-109.93	65	3
MT	242409	Dillon Wmce	1593.5	45.22	-112.65	66	3
MT	242421	Divide	1630.7	45.75	-112.75	57	4

MT	242438	Dodson	694.9	48.40	-108.25	53	0
MT	242500	Drummond	1219.2	46.63	-113.18	41	0
MT	242793	Ennis	1509.7	45.35	-111.72	66	3
MT	242820	Ethridge	1080.2	48.55	-112.13	56	7
MT	242857	Fairfield	1214	47.62	-111.98	65	2
MT	242996	Fishtail	1371.6	45.45	-109.50	53	0
MT	243013	Flatwillow 4 Ene	954.9	46.85	-108.32	65	2
MT	243110	Fort Assinniboine	796.4	48.50	-109.80	67	4
MT	243113	Fort Benton	801.9	47.82	-110.67	65	2
MT	243139	Fortine 1 N	914.4	48.78	-114.90	65	6
MT	243157	Fort Logan 4 Ese	1435.6	46.65	-111.10	54	7
MT	243346	Galata 16 Ssw	944.9	48.25	-111.40	56	4
MT	243445	Geraldine	954	47.60	-110.27	54	0
MT	243489	Gibson Dam	1399	47.60	-112.75	66	3
MT	243617	Goldbutte 7 N	1066.2	48.98	-111.40	64	5
MT	243707	Grant 5 Se	1761.7	44.93	-113.03	52	8
MT	243727	Grass Range	1063.8	47.03	-108.80	65	2
MT	243751	Great Falls Intl Arpt	1116.8	47.47	-111.38	63	2
MT	243885	Hamilton	1075.6	46.23	-114.17	65	2
MT	243929	Harlem 4 W	719.9	48.55	-108.87	65	3
MT	243939	Harlowton	1268.6	46.43	-109.83	65	3
MT	244038	Hebgen Dam	1977.8	44.87	-111.33	66	5
MT	244055	Helena Regional Airport	1166.8	46.60	-111.97	65	2
MT	244084	Heron 2 Nw	682.8	48.08	-116.00	65	2
MT	244241	Holter Dam	1062.8	46.98	-112.02	65	2
MT	244328	Hungry Horse Dam	963.2	48.35	-114.02	58	0
MT	244345	Huntley Experiment Stn	924.8	45.92	-108.25	65	0
MT	244447	Jackson	1975.1	45.37	-113.42	54	13
MT	244512	Joplin	1013.5	48.57	-110.77	66	5
MT	244766	Kremlin	871.7	48.52	-110.10	53	0
MT	244820	Lakeview	2045.2	44.60	-111.82	63	3
MT	244978	Lewistown 11 Sse	1513.3	46.90	-109.42	56	0
MT	244985	Lewistown Municipal Ap	1263.4	47.05	-109.47	65	0
MT	245015	Libby 1 Ne Rs	638.9	48.40	-115.53	65	0
MT	245020	Libby 32 Sse	1097.3	47.97	-115.22	56	0
MT	245030	Lima	1912	44.63	-112.58	65	0
MT	245040	Lincoln Ranger Stn	1394.5	46.95	-112.65	58	0
MT	245080	Livingston 12 S	1484.4	45.48	-110.57	53	0
MT	245086	Livingston Mission Fld	1415.2	45.70	-110.43	65	0
MT	245153	Loma 1 Wnw	786.4	47.95	-110.53	55	0
MT	245387	Martinsdale 3 Nnw	1463	46.50	-110.33	63	0
MT	245608	Menard 3 Ne	1540.2	46.00	-111.13	51	0
MT	245745	Missoula International Ap	972.9	46.92	-114.10	63	0
MT	245961	Mystic Lake	1994.6	45.25	-109.73	65	0
MT	246157	Norris Madison Ph	1446.3	45.48	-111.63	65	0
MT	246472	Philipsburg R S	1606.3	46.32	-113.30	48	0
MT	246615	Polebridge	1072.9	48.77	-114.28	57	0
MT	246635	Polson	917.4	47.68	-114.18	60	0
MT	246747	Pryor	1239.9	45.43	-108.53	54	0
MT	246862	Rapelje 4 S	1257.3	45.92	-109.25	65	0

MT	247214	Roundup	973.2	46.43	-108.53	65	0
MT	247228	Roy 8 Ne	1050	47.43	-108.85	65	0
MT	247286	St Ignatius	883.9	47.32	-114.10	65	0
MT	247448	Seeley Lake R S	1249.7	47.22	-113.52	65	0
MT	247620	Simpson 6 N Wildhorse	858	49.00	-110.22	65	0
MT	247894	Stevensville	1028.7	46.52	-114.08	66	0
MT	247964	Sula 3 Ene	1364	45.85	-113.93	49	0
MT	247996	Sunburst 8 E	1127.8	48.88	-111.73	53	0
MT	248021	Sun River 4 S	1097.3	47.48	-111.73	64	0
MT	248043	Superior	826	47.20	-114.88	65	0
MT	248324	Townsend	1170.4	46.33	-111.53	65	0
MT	248363	Trident	1230.2	45.95	-111.47	65	0
MT	248430	Twin Bridges	1409.7	45.55	-112.33	54	0
MT	248501	Valier	1161.3	48.32	-112.25	65	0
MT	248809	West Glacier	961.3	48.50	-113.98	56	0
MT	248902	Whitefish	944.9	48.40	-114.37	62	0
MT	249033	Winifred	988.5	47.57	-109.38	65	0
MT	249067	Wisdom	1847.1	45.62	-113.45	66	0
MT	249082	Wise River 3 Wnw	1746.5	45.80	-113.02	59	0
OR	350197	Antelope 6 Ssw	923.5	44.82	-120.75	64	0
OR	350356	Austin 3 S	1284.1	44.57	-118.48	64	0
OR	350412	Baker City Muni Ap	1024.4	44.85	-117.82	61	0
OR	350694	Bend	1115.6	44.05	-121.28	64	0
OR	350723	Beulah	996.7	43.92	-118.15	62	0
OR	350897	Bonneville Dam	18.9	45.63	-121.95	64	0
OR	351067	Brothers	1414.3	43.82	-120.60	45	0
OR	351546	Chemult	1450.8	43.23	-121.78	64	5
OR	351765	Condon	865.6	45.23	-120.18	65	2
OR	352135	Danner	1287.8	42.95	-117.33	64	6
OR	352440	Dufur	405.4	45.45	-121.13	65	3
OR	353038	Fossil	807.7	45.00	-120.22	60	7
OR	353095	Fremont 5 Nw	1404.8	43.40	-121.22	58	9
OR	353542	Grizzly	1107.9	44.52	-120.93	66	6
OR	353604	Halfway	812.3	44.88	-117.12	64	6
OR	353692	Hart Mountain Refuge	1711.8	42.55	-119.65	65	2
OR	353827	Heppner	574.5	45.37	-119.57	65	2
OR	353847	Hermiston 1 Se	195.1	45.83	-119.27	60	5
OR	354003	Hood River Exp Stn	152.4	45.68	-121.52	65	2
OR	354098	Huntington	643.1	44.35	-117.25	65	5
OR	354291	John Day	933.6	44.42	-118.97	51	0
OR	354403	Keno	1254.6	42.13	-121.93	65	2
OR	354411	Kent	826	45.20	-120.70	65	2
OR	354506	Klamath Falls 2 Ssw	1249.1	42.20	-121.78	63	3
OR	354670	Lakeview 2 Nnw	1456.3	42.22	-120.37	66	5
OR	355162	Malheur Refuge Hdq	1252.4	43.27	-118.85	45	0
OR	355221	Marion Frks Fish Hatch	754.4	44.62	-121.95	55	0
OR	355335	Mc Dermitt 26 N	1360.6	42.42	-117.87	49	0
OR	355545	Mikkalo 6 W	472.4	45.47	-120.35	56	0
OR	355593	Milton Freewater	295.7	45.95	-118.42	65	0
OR	355641	Mitchell 2 Nw	806.2	44.58	-120.18	51	0

OR	356179	Nyssa	662.9	43.88	-116.98	65	0
OR	356243	Ochoco Ranger Station	1211.6	44.40	-120.43	65	0
OR	356302	O O Ranch	1260.7	43.28	-119.32	53	0
OR	356405	Owyhee Dam	731.5	43.65	-117.25	65	0
OR	356426	Paisley	1328.9	42.70	-120.53	65	0
OR	356634	Pilot Rock 1 Se	524.3	45.48	-118.83	65	0
OR	356853	P Ranch Refuge	1278.6	42.83	-118.88	63	0
OR	357062	Redmond Roberts Field	927.5	44.25	-121.13	55	0
OR	357208	Riverside 7 Ssw	1030.2	43.45	-118.22	42	0
OR	357310	Rome 2 Nw	1037.8	42.87	-117.65	53	0
OR	357675	Seneca	1420.4	44.13	-118.98	62	0
OR	357736	Sheaville 1 Se	1408.2	43.12	-117.03	52	0
OR	358029	Squaw Butte Exp Station	1420.4	43.48	-119.72	65	0
OR	358726	Ukiah	1036.3	45.13	-118.93	63	0
OR	358746	Union Experiment Stn	842.8	45.20	-117.88	66	0
OR	358780	Unity	1228.6	44.43	-118.18	67	0
OR	358797	Vale	682.8	43.98	-117.25	65	0
OR	358997	Wallowa	890.9	45.57	-117.53	65	0
OR	359316	Wickiup Dam	1328.3	43.68	-121.68	64	0
WA	450668	Bickleton	919	46.00	-120.30	64	8
WA	450945	Buckley 1 Ne	208.8	47.17	-122.00	64	0
WA	451395	Chewelah	509	48.28	-117.72	64	0
WA	451400	Chief Joseph Dam	249.9	48.00	-119.65	55	0
WA	451666	Conconully	707.1	48.55	-119.75	64	6
WA	451679	Concrete Ppl Fish Stn	59.4	48.53	-121.75	64	0
WA	451767	Coulee Dam 1 Sw	518.2	47.95	-119.00	58	0
WA	451968	The Dalles Muni Ap	71.6	45.62	-121.17	63	0
WA	451992	Darrington Ranger Stn	167.6	48.27	-121.60	64	0
WA	452007	Davenport	743.7	47.65	-118.15	64	0
WA	452030	Dayton 1 Wsw	474.6	46.32	-118.00	64	0
WA	452157	Diablo Dam	271.6	48.72	-121.13	64	0
WA	452505	Ellensburg	451.1	46.97	-120.53	52	4
WA	453529	Hartline	582.2	47.68	-119.12	64	8
WA	454077	Kahlotus 5 Ssw	473	46.58	-118.60	57	4
WA	454154	Kennewick	118.9	46.22	-119.10	64	0
WA	454338	Lacrosse	442	46.82	-117.88	64	0
WA	454446	Lake Wenatchee	611.1	47.83	-120.80	64	0
WA	454679	Lind 3 Ne	496.8	47.00	-118.57	64	0
WA	455525	Monroe	36.6	47.85	-121.98	64	0
WA	455659	Mount Adams Ranger Stn	594.4	46.00	-121.53	64	0
WA	455844	Newport	650.7	48.18	-117.05	64	0
WA	455946	Northport	411.5	48.90	-117.80	64	0
WA	456039	Odessa	466.3	47.33	-118.70	64	0
WA	456215	Othello 6 Ese	362.7	46.78	-119.05	62	0
WA	456262	Packwood	323.1	46.62	-121.67	62	0
WA	456610	Pomeroy	579.1	46.47	-117.58	64	0
WA	456880	Quincy 1 S	388.3	47.22	-119.85	63	0
WA	456909	Randle 1 E	274.3	46.53	-121.93	64	0
WA	456974	Republic	795.5	48.65	-118.73	61	0
WA	457059	Ritzville 1 Sse	557.8	47.12	-118.38	64	0

WA	457180	Rosalia	731.5	47.23	-117.37	64	0
WA	457727	Smyrna	170.7	46.83	-119.67	50	0
WA	457773	Snoqualmie Falls	134.1	47.53	-121.83	64	0
WA	457938	Spokane International Ap	717.2	47.62	-117.53	62	0
WA	458034	Startup 1 E	51.8	47.87	-121.72	65	0
WA	458059	Stehekin 4 Nw	387.1	48.35	-120.73	64	0
WA	458207	Sunnyside	227.7	46.32	-120.02	64	0
WA	459012	Waterville	798.6	47.65	-120.07	64	0
WA	459058	Wellpinit	759	47.90	-118.00	65	0
WA	459074	Wenatchee	195.1	47.42	-120.32	64	0
WA	459238	Wilbur	679.7	47.75	-118.68	64	0
WA	459376	Winthrop 1 Wsw	534.9	48.45	-120.20	64	0
WA	459465	Yakima Air Terminal	324.3	46.57	-120.55	56	0

APPENDIX III

Monthly Cooperative Stations for Snow

State	Coop ID	Station Name	Elev (meters)	Lat (North)	Long (West)	Years of Data	% Missing Data
WA	450668	Bickleton	919	46.00	-120.30	63	6.3
WA	450945	Buckley 1 Ne	208.8	47.17	-122.00	64	0.0
WA	451233	Cedar Lake	475.5	47.42	-121.75	64	0.0
WA	451395	Chewelah	509	48.28	-117.72	64	0.0
WA	451586	Colfax	603.5	46.88	-117.35	55	3.6
WA	451666	Conconully	707.1	48.55	-119.75	64	18.8
WA	451679	Concrete Ppl Fish Stn	59.4	48.53	-121.75	64	0.0
WA	451767	Coulee Dam 1 Sw	518.2	47.95	-119.00	58	0.0
WA	451968	The Dalles Muni Ap	71.6	45.62	-121.17	60	0.0
WA	451992	Darrington Ranger Stn	167.6	48.27	-121.60	64	0.0
WA	452007	Davenport	743.7	47.65	-118.15	64	3.1
WA	452030	Dayton 1 Wsw	474.6	46.32	-118.00	59	0.0
WA	452505	Ellensburg	451.1	46.97	-120.53	52	5.8
WA	452614	Ephrata Municipal Ap	381	47.30	-119.52	53	1.9
WA	453529	Hartline	582.2	47.68	-119.12	64	9.4
WA	453546	Hatton 9 Se	460.2	46.72	-118.65	64	0.0
WA	454077	Kahlotus 5 Ssw	473	46.58	-118.60	55	0.0
WA	454154	Kennewick	118.9	46.22	-119.10	63	0.0
WA	454338	Lacrosse	442	46.82	-117.88	64	0.0
WA	454446	Lake Wenatchee	611.1	47.83	-120.80	64	7.8
WA	454486	Landsburg	163.1	47.38	-121.97	64	0.0
WA	454572	Leavenworth 3 S	343.8	47.55	-120.68	64	0.0
WA	454679	Lind 3 Ne	496.8	47.00	-118.57	64	0.0
WA	455231	Mcnary Dam	110	45.93	-119.30	50	0.0
WA	455387	Mill Creek Dam	358.1	46.08	-118.27	56	0.0
WA	455525	Monroe	36.6	47.85	-121.98	64	3.1
WA	455659	Mount Adams Ranger Stn	594.4	46.00	-121.53	64	9.4
WA	456896	Rainier Ohanapecosh	594.4	46.73	-121.57	63	12.7
WA	457938	Spokane International Ap	717.2	47.62	-117.53	62	8.1
WA	458009	Stampede Pass	1206.4	47.30	-121.33	50	6.0
WA	458059	Stehekin 4 Nw	387.1	48.35	-120.73	62	9.7
WA	458089	Stevens Pass	1240.5	47.73	-121.08	53	11.3
WA	459012	Waterville	798.6	47.65	-120.07	60	16.7
WA	459376	Winthrop 1 Wsw	534.9	48.45	-120.20	64	0.0
WA	459465	Yakima Air Terminal	324.3	46.57	-120.55	56	8.9
OR	350197	Antelope 6 Ssw	923.5	44.82	-120.75	51	0.0
OR	350356	Austin 3 S	1284.1	44.57	-118.48	63	9.5
OR	350412	Baker City Muni Ap	1024.4	44.85	-117.82	59	6.8
OR	350723	Beulah	996.7	43.92	-118.15	62	11.3
OR	351546	Chemult	1450.8	43.23	-121.78	64	10.9

OR	353402	Government Camp	1213.1	45.30	-121.75	52	0.0
OR	354098	Huntington	643.1	44.35	-117.25	65	16.9
OR	354161	Ione 18 S	649.2	45.32	-119.85	65	18.5
OR	354291	John Day	933.6	44.42	-118.97	51	7.8
OR	354403	Keno	1254.6	42.13	-121.93	65	10.8
OR	354411	Kent	826	45.20	-120.70	65	13.8
OR	354506	Klamath Falls 2 Ssw	1249.1	42.20	-121.78	63	9.5
OR	354670	Lakeview 2 Nnw	1456.3	42.22	-120.37	63	7.9
OR	355139	Madras	679.7	44.62	-121.00	65	13.8
OR	355221	Marion Frks Fish Hatch	754.4	44.62	-121.95	56	8.9
OR	355734	Moro	570	45.48	-120.72	64	15.6
OR	356179	Nyssa	662.9	43.88	-116.98	64	18.8
OR	356243	Ochoco Ranger Station	1211.6	44.40	-120.43	65	12.3
OR	356426	Paisley	1328.9	42.70	-120.53	63	14.3
OR	356546	Pendleton E Or Regional Ap	452.9	45.70	-118.85	60	10.0
OR	356634	Pilot Rock 1 Se	524.3	45.48	-118.83	65	15.4
OR	356853	P Ranch Refuge	1278.6	42.83	-118.88	60	16.7
OR	356883	Prineville	888.5	44.30	-120.80	65	15.4
OR	357062	Redmond Roberts Field	927.5	44.25	-121.13	53	9.4
OR	357250	Rock Creek	1248.2	44.92	-118.07	65	7.7
OR	357310	Rome 2 Nw	1037.8	42.87	-117.65	51	13.7
OR	357354	Round Grove	1489.9	42.33	-120.88	50	14.0
OR	357675	Seneca	1420.4	44.13	-118.98	59	13.6
OR	357736	Sheaville 1 Se	1408.2	43.12	-117.03	52	19.2
OR	358029	Squaw Butte Exp Station	1420.4	43.48	-119.72	62	16.1
OR	358420	The Poplars	1313.7	43.27	-120.95	51	17.6
OR	358726	Ukiah	1036.3	45.13	-118.93	63	15.9
OR	358746	Union Experiment Stn	842.8	45.20	-117.88	66	9.1
OR	358780	Unity	1228.6	44.43	-118.18	61	18.0
OR	358797	Vale	682.8	43.98	-117.25	62	17.7
OR	358997	Wallowa	890.9	45.57	-117.53	64	14.1
OR	359316	Wickiup Dam	1328.3	43.68	-121.68	64	10.9
ID	100470	Ashton	1588.6	44.07	-111.45	64	0.0
ID	101022	Boise Air Terminal	857.7	43.57	-116.23	54	0.0
ID	101514	Cascade 1 Nw	1492.3	44.52	-116.05	62	0.0
ID	103882	Grouse	1829.1	43.72	-113.55	64	17.2
ID	104140	Hazelton	1237.5	42.60	-114.13	64	10.9
ID	104460	Idaho Falls 46 W	1505.1	43.53	-112.95	50	0.0
ID	104598	Island Park	1917.2	44.42	-111.37	64	4.7
ID	105275	Lifton Pumping Stn	1806.2	42.12	-111.32	64	0.0
ID	105414	Lowman	1194.8	44.08	-115.62	51	19.6
ID	105559	Malad City	1362.5	42.15	-112.28	60	6.7
ID	105685	May 2 Sse	1539.2	44.57	-113.90	54	13.0
ID	105708	Mccall	1531.6	44.88	-116.10	64	12.5
ID	105980	Minidoka Dam	1269.2	42.68	-113.50	57	8.8
ID	106152	Moscow U Of I	810.8	46.72	-116.97	64	10.9
ID	106542	Oakley	1389.9	42.23	-113.90	64	7.8
ID	107264	Porthill	541	49.00	-116.50	64	17.2
MT	240412	Baker 1 E	896.1	46.37	-104.27	65	10.8
MT	240807	Billings Logan Int'l Arpt	1091.5	45.80	-108.55	63	1.6

MT	241044	Bozeman Montana St Univ	1497.5	45.67	-111.05	65	4.6
MT	241088	Bredette	804.1	48.55	-105.27	53	5.7
MT	241102	Bridger 2 N	1092.1	45.33	-108.92	63	6.3
MT	241127	Broadus	924.2	45.45	-105.40	65	3.1
MT	241231	Brusett 3 N	906.5	47.47	-107.32	65	4.6
MT	241297	Busby	1045.5	45.53	-106.97	65	9.2
MT	241318	Butte Bert Mooney Ap	1678.2	45.97	-112.50	61	1.6
MT	241552	Cascade 5 S	1024.1	47.22	-111.72	65	1.5
MT	242104	Creston	896.1	48.18	-114.13	56	8.9
MT	242173	Cut Bank Municipal Ap	1169.8	48.60	-112.38	62	1.6
MT	242404	Dillon Airport	1585	45.25	-112.55	54	3.7
MT	242421	Divide	1630.7	45.75	-112.75	57	3.5
MT	242629	East Glacier	1464.9	48.45	-113.22	51	5.9
MT	242857	Fairfield	1214	47.62	-111.98	65	7.7
MT	243013	Flatwillow 4 Ene	954.9	46.85	-108.32	65	3.1
MT	243089	Forks 4 Nne	792.2	48.78	-107.45	58	10.3
MT	243113	Fort Benton	801.9	47.82	-110.67	65	6.2
MT	243139	Fortine 1 N	914.4	48.78	-114.90	65	3.1
MT	243157	Fort Logan 4 Ese	1435.6	46.65	-111.10	54	7.4
MT	243445	Geraldine	954	47.60	-110.27	54	1.9
MT	243489	Gibson Dam	1399	47.60	-112.75	66	6.1
MT	243581	Glendive	632.8	47.10	-104.72	65	9.2
MT	243617	Goldbutte 7 N	1066.2	48.98	-111.40	63	4.8
MT	243707	Grant 5 Se	1761.7	44.93	-113.03	51	5.9
MT	243727	Grass Range	1063.8	47.03	-108.80	65	7.7
MT	243751	Great Falls Intl Arpt	1116.8	47.47	-111.38	63	1.6
MT	243929	Harlem 4 W	719.9	48.55	-108.87	64	14.1
MT	243939	Harlowton	1268.6	46.43	-109.83	65	3.1
MT	244038	Hebgen Dam	1977.8	44.87	-111.33	65	3.1
MT	244055	Helena Regional Airport	1166.8	46.60	-111.97	57	1.8
MT	244084	Heron 2 Nw	682.8	48.08	-116.00	65	3.1
MT	244386	Ingomar 14 Ne	851.9	46.73	-107.20	51	5.9
MT	244512	Joplin	1013.5	48.57	-110.77	65	10.8
MT	244985	Lewistown Municipal Ap	1263.4	47.05	-109.47	62	1.6
MT	245020	Libby 32 Sse	1097.3	47.97	-115.22	56	5.4
MT	245045	Lindsay	819.9	47.23	-105.15	54	7.4
MT	245080	Livingston 12 S	1484.4	45.48	-110.57	53	3.8
MT	245086	Livingston Mission Fld	1415.2	45.70	-110.43	62	1.6
MT	245153	Loma 1 Wnw	786.4	47.95	-110.53	54	5.6
MT	245285	Lustre 4 Nnw	890.9	48.45	-105.93	55	3.6
MT	245387	Martinsdale 3 Nnw	1463	46.50	-110.33	62	6.5
MT	245572	Medicine Lake 3 Se	591.9	48.48	-104.45	66	6.1
MT	245596	Melstone	890	46.60	-107.87	65	6.2
MT	245690	Miles City F Wiley Fld	799.8	46.43	-105.88	63	3.2
MT	245745	Missoula International Ap	972.9	46.92	-114.10	63	1.6
MT	245754	Mizpah 4 Nnw	755.9	46.28	-105.30	56	7.1
MT	245961	Mystic Lake	1994.6	45.25	-109.73	65	3.1
MT	246238	Opheim 12 Sse	894.9	48.70	-106.32	61	1.6
MT	246615	Polebridge	1072.9	48.77	-114.28	57	12.3
MT	246747	Pryor	1239.9	45.43	-108.53	54	9.3

MT	246862	Rapelje 4 S	1257.3	45.92	-109.25	65	7.7
MT	246918	Red Lodge 2 N	1676.4	45.22	-109.23	65	3.1
MT	247034	Ridgeway 1 S	1010.7	45.50	-104.45	52	0.0
MT	247228	Roy 8 Ne	1050	47.43	-108.85	65	1.5
MT	247286	St Ignatius	883.9	47.32	-114.10	65	3.1
MT	247382	Savage	602	47.45	-104.33	65	3.1
MT	247448	Seeley Lake R S	1249.7	47.22	-113.52	65	4.6
MT	247540	Shonkin 7 S	1310.6	47.53	-110.58	51	9.8
MT	247560	Sidney	588.6	47.73	-104.15	56	5.4
MT	247620	Simpson 6 N Wildhorse	858	49.00	-110.22	65	3.1
MT	248363	Trident	1230.2	45.95	-111.47	65	9.2
MT	248569	Vida 6 Ne	696.2	47.88	-105.37	65	7.7
MT	248809	West Glacier	961.3	48.50	-113.98	56	3.6
MT	248857	West Yellowstone	2042.1	44.67	-111.82	58	12.1
MT	248939	Whitewater	711.1	48.77	-107.63	54	3.7
MT	249175	Wyola 1 Sw	1136.9	45.12	-107.40	65	7.7

APPENDIX IV

FAUNMAP Holocene Bison Sites

Site ID	Site Name	Unit Name	State	ResAge	Lat	Long
1522	Bison Rockshelter	Layer	ID	Lhol	44.08	-112.92
1511	Challis Bison Jump	Layer	ID	Hist	44.37	-114.12
1506	Five Fingers Buffalo Jump	Assemblage	ID	Mhol	42.37	-116.00
1502	Malad Hill	Occupation	ID	Lhol	42.25	-112.12
55	Middle Butte Cave	Assemblage	ID	LMHol	43.37	-112.62
18	Moonshiner	Assemblage	ID	Ehol	43.37	-112.62
1497	Owl Cave	Layer	ID	Mhol	43.50	-112.38
1510	Quill Cave	Layer	ID	Hol	44.37	-114.12
1523	Veratic Rock Shelter	Layers	ID	Hist	44.08	-112.92
1498	Western Canyon Rockshelter	Layer	ID	Mhol	42.00	112.00
37	Wilson Butte Cave	Stratum	ID	Mhol	42.77	-114.22
2849	24CA287	Assemblage	MT	Hol	47.50	-111.25
345	24GF250	Assemblage	MT	Lhol	47.50	-106.75
641	Antonsen	Areas	MT	Lhol	45.66	-111.16
709	Ash Coulee	Assemblage	MT	Hhol	46.75	-105.25
570	Big Lip	Assemblage	MT	Lhol	45.00	-108.25
346	Birdtail Butte	Assemblage	MT	Lhol	48.12	-109.00
588	Blacktail Cave	Alcove/Cave	MT	Mhol	47.08	-112.28
575	Bootlegger Trail	Units	MT	Lhol	48.25	-111.25
572	County Line	Assemblage	MT	Lhol	46.87	-113.75
590	Drake	Levels	MT	Lhol	45.75	-108.62
574	Ellisons Rock	Midden	MT	Lhol	45.87	-106.62
577	False Cougar Cave	Natural Stratum	MT	LMHol	45.12	-108.25
591	Hagen	Assemblage	MT	Hol	47.00	-104.62
374	Hoffer	Areas	MT	Lhol	47.75	-109.87
569	Holmes Terrace		MT	Hhol	47.62	-109.62
343	Kobold	Level/Rockshelter	MT	Lhol	45.25	-107.00
707	Mangus	Occupation	MT	Lhol	45.25	-107.87
571	Montana Ice Cave	Assemblage	MT	Hol	46.75	-109.00
579	Morse Creek #1	Assemblage	MT	Hol	46.62	-113.12
592	Pictograph Cave	Units	MT	LMHol	45.62	-108.37
2850	Red Rock Springs	Assemblage	MT	Lhol	44.87	-112.75
2248	Risley Bison Kill	Assemblage	MT	Hhol	47.37	-112.37
576	Shield Trap	Stratum	MT	MHol	45.12	-108.25
708	Sorenson	Occupation	MT	Mhol	45.25	-107.87
1065	Connley Cave No. 3	Stratum	OR	Hhol	43.25	-121.00
1066	Connley Cave No. 4	Stratum 1-4	OR	EMHol	43.25	-121.00
1067	Connley Cave No. 5	Stratum 1-3	OR	EMHol	43.25	-121.00
1543	Ray	Assemblage	OR	Hol	44.87	-116.87

1542	Robinette Rockshelter	Assemblage	OR	Hhol	44.75	-117.00
1050	45AD2	Levels	WA	Hhol	47.00	-118.37
1147	45AS80	House	WA	Lhol	46.37	-117.12
2891	Aveys Orchard	Assemblage	WA	Lhol	47.37	-120.25
1036	Berrians Island	Assemblage	WA	Hist	46.00	-119.37
1425	Chief Joseph dam Site	Hudnut and Kartar Component	WA	Mhol	48.12	-119.12
1053	Ferry County salvage sites	Burials	WA	Hhol	48.62	-118.12
1038	Lind Coulee	Bed	WA	EMHol	47.15	-119.00
1148	Pig Farm	House	WA	Hhol	46.37	-117.12
1146	Timothy’s Village		WA	Mhol	46.37	-117.12
2911	Willow Creek	Assemblage	WA	Hol	46.75	-118.00