Snowpack Distribution Across Yellowstone National Park

Phillip Farnes, Carolyn Heydon, Katherine Hansen
Earth Sciences Department
Montana State University
Bozeman, Montana
December 1999

SNOWPACK DISTRIBUTION ACROSS YELLOWSTONE NATIONAL PARK, WYOMING

Final Report
Proposal No. 97- 447
Cooperative Agreement Number CA 1268 -1 - 9017
Grant and Contract No. 291601

To
John Varley
Director, Yellowstone Center for Resources
National Park Service
Yellowstone National Park, Wyoming 82190

Report Prepared by
Phillip Farnes[1], Carolyn Heydon[2] and Dr. Katherine Hansen[3]
Montana State University
Department of Earth Sciences
Bozeman, Montana 59717

December 1999

[1]Research Scientist, [2]Research Associate,
and [3]Professor and Principal Investigator, Department of Earth Sciences, MSU

ACKNOWLEDGMENTS

We appreciate the contributions of the following people and agencies: the Natural Resources and Conservation Service (formerly Soil Conservation Service), Grand Teton and Yellowstone National Parks, U.S. Bureau of Reclamation, U.S. Forest Service, and National Weather Service for collecting and archiving snow course, SNOTEL, and climatological records at sites in and adjacent to Yellowstone National Park dating back to the early 1900s; National Weather Service offices in Riverton, Wyoming, Great Falls, Montana, and Billings, Montana, and Chief Rangers office in Yellowstone National Park for providing preliminary data sheets for climatological stations; Dr. Bruce Smith, National Elk Refuge, for forage production data; John Varley and John Mack of Yellowstone National Park for providing administrative and financial support as well as background information and data essential to this project; Ann Rodman and Shannon Savage, Yellowstone National Park Spatial Analysis Center, for GIS products; Dr. Michael Coughenour of Colorado State University for developing the procedure to process this data using GIS; Dr. Bok Sowell, MSU, Department of Animal and Range Sciences, for data and review of forage processing by ungulates; Ann Parker, Department of Earth Sciences, for word processing associated with this report; Kim Rehm, Department of Earth Sciences, for administrative services; Judy O'Dwyer, Forestry Sciences Laboratory, for technical review of manuscript; Forestry Sciences Laboratory, U.S. Forest Service, Bozeman, Montana, for office space and technical support; and numerous individuals who have provided suggestions and comments on this manuscript.

TABLE OF CONTENTS

TABLE OF CONTENTS (cont.)

LIST OF FIGURES AND TABLES

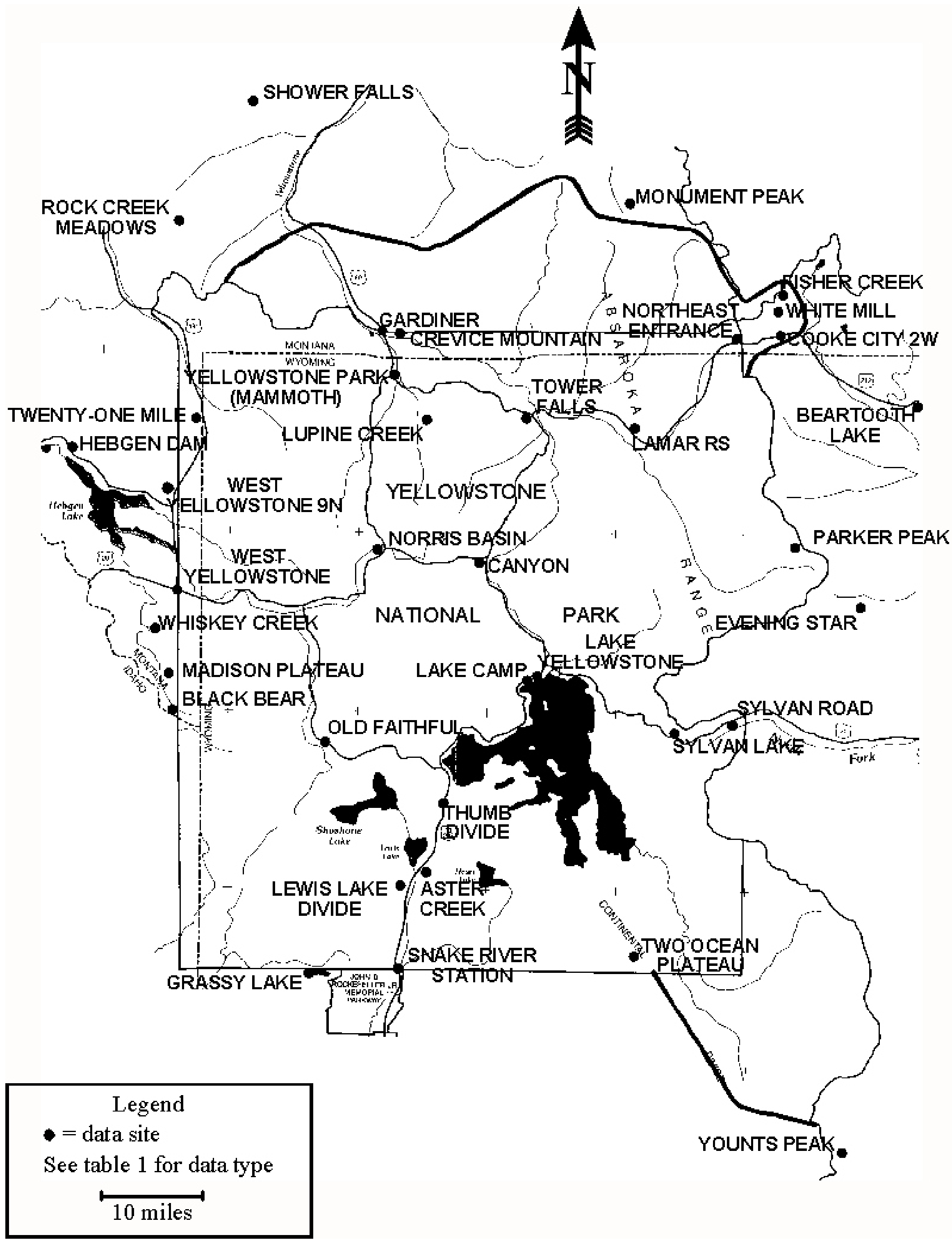

Figure 1. The study area includes Yellowstone National Park, Wyoming,and drainages that flow into Yellowstone National Park in Montana and Wyoming.

INTRODUCTION

This study's objective is to process historic data on snowpack distribution in and adjacent to Yellowstone National Park, Wyoming (Figure 1). Data on snowpack are related to the movement of bison (*Bison bison*), moose (*Alces alces shirasi*), elk (*Cervus elaphus*), and mule deer (*Odocoileus hemionus*) to winter ranges. In addition to snow data, daily precipitation and temperature data were processed for correlation with soil moisture, forage production, plant phenology and other plant/soil moisture/animal relationships. Variability in other natural processes, such as recovery from disturbance, may also be correlated to variations in snow, precipitation, and/or temperature.

Severity of winters based on snow, temperature and forage parameters relates to condition and mortality of ungulates, which is related to population dynamics. Ungulate carcasses provide carrion for grizzly bears (*Ursus arctos*) and other animals. The condition of ungulates also is related to predation by wolves (*Canis lupus)* and other predators during the winter and early spring.

HISTORY OF SNOW AND CLIMATOLOGICAL MEASUREMENTS

Within and adjacent to Yellowstone National Park, Wyoming, there are numerous sites where seasonal or daily data have been collected on snow, precipitation and temperature. A tabulation of data available at these sites is shown in Table 1.

Snow Courses

Snow courses (SC) are permanently marked locations where snow depth and snow water equivalent (SWE) measurements are manually collected on the first day of each month (usually from January through April). Five to ten snow samples are taken at a specific location, and the average of these measurements is recorded as the measurement for that snow course. This program is coordinated by the Natural Resources Conservation Service (NRCS), formerly the Soil Conservation Service (SCS). Many agencies and individuals help obtain these data, including the U.S. Bureau of Reclamation (USBR), US Forest Service (USFS), NRCS, and National Park Service. Data are reported and archived by NRCS and are available through the NRCS computer in Portland, Oregon, or the State NRCS Snow Survey offices in Casper, Wyoming, and Bozeman, Montana. The first snow course measurements within the study area were made in 1919 in the Snake River drainage to forecast runoff into Jackson Lake, Wyoming. Many other snow courses were established in the 1930s, primarily for forecasting irrigation water supplies.

Presently, nine snow courses are measured in and adjacent to Yellowstone National Park (Table 2). Average snow water equivalent at snow courses for the winter months of the 1961-1990 base period have been tabulated in Appendix 1. SNOTEL sites have replaced snow courses in some locations. At these sites, the manual snow course measurements have been reduced or eliminated and historic data has been transferred to the SNOTEL site.

Table 1. Data sites in and near Yellowstone National Park, Wyoming, and snow water equivalent records available.

Site Name and Data Type	Elev (ft)	Coordinates UTME	UTMN	Data and Years Available
Aster Creek (SC)	7750	529.7	4902.8	1-4, 1919-present
Beartooth Lake (SNOTEL)	9280	613.0	4977.4	Daily, 1981-present
Black Bear (SNOTEL)	8170	489.8	4928.1	Daily, 1972-present
Black Bear (SC; Disc)	8150	489.8	4928.1	3-5, 1972-1988
Canyon (SNOTEL)	7940	538.8	4951.7	Daily, 1981-present
Canyon (SC; Disc)	8090	540.3	4953.1	1-5, 1937-1991
Cooke City 2W (CLIM)	7460	581.0	4984.6	Daily, 1968-present
Cooke Station (SC; Disc)	8150	586.4	4986.9	3-5,1966-1989
Coulter Creek (SNOTEL; Disc)	7020	534.0	4890.5	Daily, 1981-1996
Coulter Creek (SC; Disc)	7020	534.0	4890.5	2-4, 1919-1993
Crevice Mountain (SC)	8240	531.5	4986.5	2-4, 1935-present
East Entrance (SC; Disc)	6960	579.4	4926.7	1-5, 1949-1987
Evening Star (SNOTEL)	9200	596.4	4944.8	Daily, 1983-present
Fisher Creek (SNOTEL)	9100	582.7	4990.7	Daily, 1967-present
Fisher Creek (SC; Disc)	9100	582.7	4990.7	3-5, 1966-1990
Gardiner (CLIM)	5275	523.3	4986.4	Daily, 1956-present
Grassy Lake (SNOTEL)	7265	514.2	4885.8	Daily, 1981-present
Grassy Lake (SC; Disc)	7270	514.3	4886.0	1-6, 1940-1992
Hebgen Dam (CLIM)	6489	473.5	4967.8	Daily, 1949-present
Hebgen Dam (SC)	6550	472.8	4968.5	1-5, 1934-present
Jardine (CLIM; Disc)	6450	528.9	4990.7	Daily, 1952-1971
Lake Camp (SC)	7780	547.4	4933.5	1-5, 1936-present
Lake Yellowstone (CLIM)	7770	548.1	4933.6	Daily, 1949-present
Lamar RS (CLIM)	6470	560.4	4971.4	Daily, 1949-1976[1]
Lewis Lake Divide (SNOTEL)	7860	526.8	4894.5	Daily, 1981-present
Lewis Lake Divide (SC; Disc)	7850	526.8	4894.5	1-6, 1919-1992
Lupine Creek (SC)	7380	530.8	4973.1	1-5, 1938-present
Madison Plateau (SNOTEL)	7750	490.7	4936.5	Daily, 1968-present
Madison Plateau (SC; Disc)	7750	490.7	4936.5	3-5, 1968-1990
Monument Peak (SNOTEL)	8850	559.9	5007.2	Daily, 1981-present
Monument Peak (SC; Disc)	8850	559.9	5007.2	3-5, 1961-1992
Norris Basin (SC)	7480	524.1	4953.0	1-5, 1936-present
Northeast Entrance (SNOTEL)	7350	577.7	4983.9	Daily, 1967-present
Northeast Entrance (SC)	7350	577.7	4983.9	1-5, 1937-present
Old Faithful (CLIM)	7358	513.6	4922.3	Daily, 1979-present
Old Faithful (SC)	7400	513.9	4922.1	1-5, 1975-present
Parker Peak (SNOTEL)	9400	586.0	4946.3	Daily, 1982-present
Parker Peak (AM; Disc)	9400	586.0	4946.3	2-4, 1965-1985

Pitchstone Plateau (AM; Disc)	8520	521.6	4898.2	2-4, 1965-1982
Rock Creek Meadows (SC)	8160	493.5	5003.1	3-5, 1976-present
Shower Falls (SNOTEL)	8100	503.3	5027.3	Daily, 1966-present
Snake River (CLIM)	6882	526.7	4886.6	Daily, 1949-present
Snake River Station (SNOTEL)	6920	526.7	4886.6	Daily, 1990-present
Snake River Station (SC)	6920	526.7	4886.6	1-4, 1919-present
Star Lake E (AM; Disc)	9650	585.6	4993.8	4-5, 1971-1990
Sylvan Lake (SNOTEL)	8420	567.1	4925.0	Daily, 1981-present
Sylvan Pass (SC; Disc)	7100	575.7	4924.8	1-5, 1937-1991
Sylvan Road (SNOTEL)	7120	576.5	4925.3	Daily, 1988-present
Thumb Divide (SNOTEL)	7980	534.0	4912.5	Daily, 1988-present
Thumb Divide (SC)	7980	534.0	4912.5	1-4, 1938-present
Tower Falls (CLIM)	6264	545.9	4973.7	Daily, 1949-present
Twenty-one Mile (SC)	7150	495.6	4973.6	1-5, 1937-present
Two Ocean Plateau (SNOTEL)	9240	562.3	4888.8	Daily, 1981-present
West Yellowstone (CLIM; Disc)	6670	492.0	4945.1	Daily, 1924-1995
West Yellowstone (SNOTEL)	6700	492.8	4944.8	Daily, 1967-present
West Yellowstone (SC)	6700	492.8	4944.8	1-5, 1934-present
West Yellowstone 9N (CLIM)	6572	489.5	4959.1	Daily, 1996-present
Whiskey Creek (SNOTEL)	6800	488.1	4939.5	Daily, 1972-present
Whiskey Creek (SC; Disc)	6800	488.1	4939.5	3-5, 1967-1990
White Mill (SNOTEL)	8700	585.8	4988.3	Daily, 1974-present
White Mill (SC; Disc)	8700	585.8	4988.3	3-5, 1967-1995
Yellowstone Park (Mammoth)(CLIM)	6230	524.0	4980.2	Daily, 1949-present
Yellowstone Park NE (CLIM; Disc)	7200	578.0	4983.7	Daily, 1949-1967
Younts Peak (SNOTEL)	8350	594.9	4864.8	Daily, 1981-present

Data Types: Disc = Discontinued; SC= Snow Course; SNOTEL = Snow Survey Telemetry; CLIM = Climatological Station; AM = Aerial Marker; 1-4 indicates monthly readings on January 1, February 1, March 1, and April 1; [1] = winter records only are available 1992 - present.

Table 2. Active snow courses in and adjacent to Yellowstone National Park.

Site No.	Site Name	Elev (ft)	Coordinates UTME	UTMN	LAT	LONG
10E08	Aster Creek	7750	529.7	4902.8	44-17	110-38
10D05	Crevice Mountain	8240	531.5	4986.5	45-02	110-36
11E05	Hebgen Dam	6550	472.8	4968.5	44-52	111-21
10E04	Lake Camp	7780	547.4	4933.5	44-33	110-24
10E01	Lupine Creek	7380	530.8	4973.1	44-55	110-37
10E19	Norris Basin	7480	524.1	4953.0	44-44	110-42
10E18	Old Faithful	7400	513.9	4922.1	44-27	110-49
11D21	Rock Creek Meadows	8160	493.5	5003.1	45-11	111-05
11E06	Twenty-one Mile	7150	495.6	4973.6	44-55	111-03

SNOTEL Sites

SNOTEL sites are automated stations that collect and transmit daily snow water equivalent (from snow pillows), total precipitation (accumulated from October 1 each year), and air temperatures year around (Table 3). Many are located at snow course sites and are operated and maintained by NRCS. Real-time and historic data for these sites are available through the NRCS computer in Portland, Oregon. Data collection at most sites began in the early 1980s. Monthly snow water equivalent at most of the snow pillows has been back-estimated from historic snow course data. There are twenty-one active SNOTEL sites in the study area. Average first-of-the-month SWE for snow pillow sites for 1961-1990 base period are shown in Appendix 1.

Table 3. Active SNOTEL snow pillow sites in and adjacent to Yellowstone National Park.

Site No.	Site Name	Elev	Coordinates			
		(ft)	UTME	UTMN	LAT	LONG
09E10S	Beartooth Lake	9280	613.0	4977.4	44-57	109-34
11E35S	Black Bear	8170	489.8	4928.1	44-30	111-08
10E03S	Canyon	7940	538.8	4951.7	44-43	110-31
09E11S	Evening Star	9200	596.4	4944.9	44-39	109-47
09D06S	Fisher Creek	9100	582.7	4990.7	45-04	109-57
10E15S	Grassy Lake	7270	514.2	4885.8	44-08	110-50
10E09S	Lewis Lake Divide	7860	526.8	4894.5	44-12	110-40
11E31S	Madison Plateau	7750	490.7	4936.5	44-35	111-07
10D12S	Monument Peak	8850	559.9	5007.2	45-13	110-14
10D07S	Northeast Entrance*	7350	577.7	4983.9	45-00	110-01
09E07S	Parker Peak	9400	586.0	4946.3	44-40	109-55
10D16S	Shower Falls	8100	503.3	5027.3	45-24	110-57
10E12S	Snake River Station	6920	526.7	4886.6	44-08	110-40
10E06S	Sylvan Lake	8420	567.1	4925.0	44-29	110-09
10E20S	Sylvan Road	7120	576.5	4925.3	44-29	110-02
10E07S	Thumb Divide	7980	534.0	4912.5	44-22	110-34
10E19S	Two Ocean Plateau	9240	562.3	4888.8	44-09	110-13
11E07S	West Yellowstone**	6700	492.8	4944.8	44-39	111-05
11E30S	Whiskey Creek	6800	488.1	4939.5	44-37	111-09
09D08S	White Mill	8700	505.8	4988.3	45-03	109-55
09F18S	Younts Peak	8350	594.9	4864.8	43-56	109-49

*The snow pillow at the Northeast Entrance was relocated prior to the 1999 water year and back records recalculated to represent the present location. Data used in this report represent the current location. **A new SNOTEL site was established at West Yellowstone prior to the 1999 water year and data being reported by NRCS through the Portland computer are for the new location. Eventually the snow pillow data prior to 1999 will be correlated to the new location and back records of the snow pillow adjusted to represent conditions at the SNOTEL site. Data included in this report are for the old snow pillow location. Check with the NRCS snow survey office in Bozeman, Montana, for the relationship between the old snow pillow and the SNOTEL snow pillow.

Climatological Stations

Currently, there are ten climatological (CLIM) stations within the study area (Table 4). Data are manually collected at these sites and include daily precipitation, maximum and minimum air temperatures, snowfall and depth of snow on the ground. Historic data for these climatological sites are available from 1949 to the present through the NRCS computer in Portland. Records prior to 1949 exist for some of these stations, but daily data are not currently available through electronic means.

Table 4. Active climatological stations in and adjacent to Yellowstone National Park.

Site No.	Site Name	Elev (ft)	Coordinates UTME	UTMN	LAT	LONG
MT1995	Cooke City 2W	7460	581.0	4984.6	45-01	109-58
MT3378	Gardiner	5275	533.3	4986.4	45-02	110-41
MT4038	Hebgen Dam	6489	473.5	4967.8	44-52	111-20
WY5345	Lake Yellowstone	7770	548.1	4933.6	44-33	110-24
WY5355	Lamar RS	6470	560.4	4971.4	44-54	110-14
WY6845	Old Faithful	7358	513.6	4922.3	44-27	110-50
WY8315	Snake River	6882	526.7	4886.6	44-08	110-40
WY9025	Tower Falls	6264	545.8	4973.6	44-55	110-25
WY8859	West Yellowstone 9N	6572	489.5	4959.1	44-47	111-08
WY9905	Yellowstone Park (Mammoth)	6230	524.0	4980.2	44-58	110-42

Estimates were made of the daily SWE using data from the climatological stations. If the mean daily temperatures were below 32°F, precipitation was recorded as snow. When the mean daily temperatures were above 32°F, the degree-days (above 32°F) were calculated and multiplied by a melt-rate to estimate the daily melt. Melt-rates (based on unpublished studies at snow pillows in this area) in inches per degree-day (°F) were estimated to be 0.05 for October, 0.03 for November, December, January, and February, 0.06 for the first 15 days of March, and 0.09 for the last 16 days of March, 0.11 for the first 15 days of April, 0.12 for last 15 days in April, 0.14 for first 15 days in May, and 0.16 for last 16 days in May. The late-season melt-rate was calculated by dividing the SWE at the time melt started plus any precipitation received between start of melt and melt-out, by the sum of the degree-days from start of melt to melt-out. This calculated melt-rate diminishes the snow at a rate whereby the SWE drops to zero on the day the snow depth is zero.

For most valley stations, unpublished data from Yellowstone National Park and data from Grand Teton National Park (Farnes et al.,1999) indicates that the SWE values estimated from climatological records are comparable to the SWE values from the manual snow measurements for sites not affected by wind. Based on unpublished studies (Farnes, 1999) for data sites in and near the study area, the amount of under-catch of precipitation in the form of snow is primarily a function of exposure of the precipitation gage. Gages in protected areas not exposed to wind appear to catch snowfall comparable to that which is measured by snow pillows or snow courses. Sites that are exposed and experience some wind show under-catch of snowfall by up to 10 percent. Exposed, windier sites, under-catch snowfall between 10 and 20 percent of the winter precipitation. The amount of under-catch appears to be unrelated to either elevation or the amount of average annual precipitation. However, sublimation reduces the water content of the snowpack throughout the winter, thereby compensating for a portion of the precipitation gage's under-catch..

SWE was estimated for climatological stations shown in Table 4 except for Cooke City 2W and Gardiner. The SWE measured at Northeast Entrance is nearly the same as for Cooke City 2W. At Gardiner, the snowpack is transitional through the winter and snow depth measurements are intermittent. There was a climatological station at Northeast Entrance prior to SNOTEL (1968). Daily SWE was estimated for this early record and made part of the Northeast Entrance SNOTEL record. At Old Faithful, prior to about 1995, the weather station was moved from its summer location to a winter location that was more protected from the wind; since 1995, both summer and winter observations have been made at the same location. Wind affects snow depths at the climatological station and appears to increase under-catch of precipitation through the entire year. For the Old Faithful site, the snow water equivalent estimated from the CLIM stations needs to be multiplied by 1.22 to be compatible to the snow course. This is based on double-mass analysis with the snow course SWE and estimated CLIM SWE for the accumulation period. From 1979 to1994 the snow depths reported for the CLIM station (taken at the protected location) were near those measured at the snow course. However, since the winter records have been taken at the more exposed weather station, the snow depths reported at the CLIM stations are about 20 percent less than those measured at the snow course.

At Snake River, there is a snow course, SNOTEL and a CLIM site. Snow water equivalent values from 1949 to1989 were estimated from CLIM records and then adjusted to first-of-the-month snow course values so the data will be comparable to that collected at the present snow pillow location. Starting in 1990, SWE was obtained from the snow pillow. At West Yellowstone, there was a CLIM station and snow course. A snow pillow with on-site recorder was installed in 1967; however, SNOTEL electronics and a new snow pillow were installed near the original pillow site at the beginning of the 1999 water year. Snow water equivalent was estimated from 1949 to 1966 using data from the CLIM station and then adjusted so the data will be comparable to that collected at the original snow pillow location. Temperatures and precipitation from the West Yellowstone climatological station (adjusted for station moves) were used prior to 1999 WY to provide the historic record for the West Yellowstone SNOTEL site. The West Yellowstone climatological station was located in and around West Yellowstone from 1924 through August 1995. Starting in September 1995, the West Yellowstone station was moved approximately 9 miles north of town. Data for years prior to 1995 were adjusted to represent the current location (West Yellowstone 9N).

ADJUSTMENTS TO SNOW WATER EQUIVALENT

Snow water equivalent (SWE) measurements represent the amount of water stored in the snowpack at a specific time and location. At some sites, more than one type of snow measurement has been collected and different methods may yield different values of SWE. In the data analyses for this study, all SWE values were adjusted to represent near "true" SWE. No adjustments were made to snow pillow data as tests have shown that the butyl or hypalon snow pillows produce near "true" SWE. Manual snow samplers have an over-measurement bias related to the cutter design (Farnes et al., 1983). SWE values obtained with a manual snow sampler having a standard federal cutter (all Montana measurements and Wyoming measurements through 1977) were multiplied by 0.91 to obtain a "true" SWE. SWE obtained with snow tubes having a sharpened federal cutter (most of the Wyoming measurements including most measurements in Yellowstone National Park after 1977) were multiplied by 0.94 to obtain a "true" SWE. The SWE values shown in Appendix 1 have been adjusted to represent "true" SWE.

Estimates of SWE from climatological data are assumed to be near "true" SWE, due to a combination of under-catch of snow by precipitation gages and sublimation loss from the snowpack. SWE calculated from precipitation data at climatological stations was assumed to be approximate "true" SWE for this study (see previous section on climatological stations) for stations where the precipitation gage is not exposed to wind.

Typical long-term climate measuring stations are located in level and open areas that are not influenced by forest canopy. Therefore, to determine SWE on areas that are not level and/or that are forested required adjustments to the station data. A relationship between slope/aspect and SWE for non-forested portions of the Northern Range in Yellowstone National Park was developed by Farnes and Romme (1993). Data from the 1996 Grand Teton National Park supplemental snow measurements (Farnes et al., 1999) and additional Yellowstone data were incorporated into the original Yellowstone data to develop a revised relationship between snowpack in non-forested areas and slope/aspect for this area (Figure 2). The SWE for a flat and open pixel is determined by using the SWE at regular measuring sites and the appropriate algorithm to account for each pixel's location and elevation. The SWE is then adjusted to account for the slope and aspect of that pixel using the equations from Table 5. The equations represent the mean for each 30 degree azimuth sector.

Snowpack under a forest canopy is less than the snowpack in non-forested areas during the snow accumulation period due to snow interception in the forest canopy and subsequent sublimation of the snow caught in the canopy. How much less is dependent on the type of trees and the density of the forest canopy. Snow accumulates differently in lodgepole pine (*Pinus cortorta*) stands than in spruce/fir (*Picea engelmanni/Abies lasiocarpa*) stands. Studies by Codd (1959), Farnes (1971, 1978, 1989), Hardy and Hansen-Bristow (1990), McCaughey et al. (1997), Moore and McCaughey (1997), and Skidmore et al. (1994) have been used to relate snowpack accumulation to cover types as described by Despain (1990). The relationship of snowpack accumulation for lodgepole pine (Figure 3) and for spruce/fir (Figure 4) have been developed. Aspen (*Populus tremuloides*) and cottonwood (*Populus spp*.) stands are treated as openings since little snow is retained in the leafless winter canopy. Whitebark pine (*Pinus albicaulis*) forests usually have a less dense canopy than lodgepole pine or spruce/fir and are typically in more wind-swept areas. Losses of SWE in snowpack due to canopy interception by whitebark pine are assumed to be about 50 percent of that for spruce/fir.

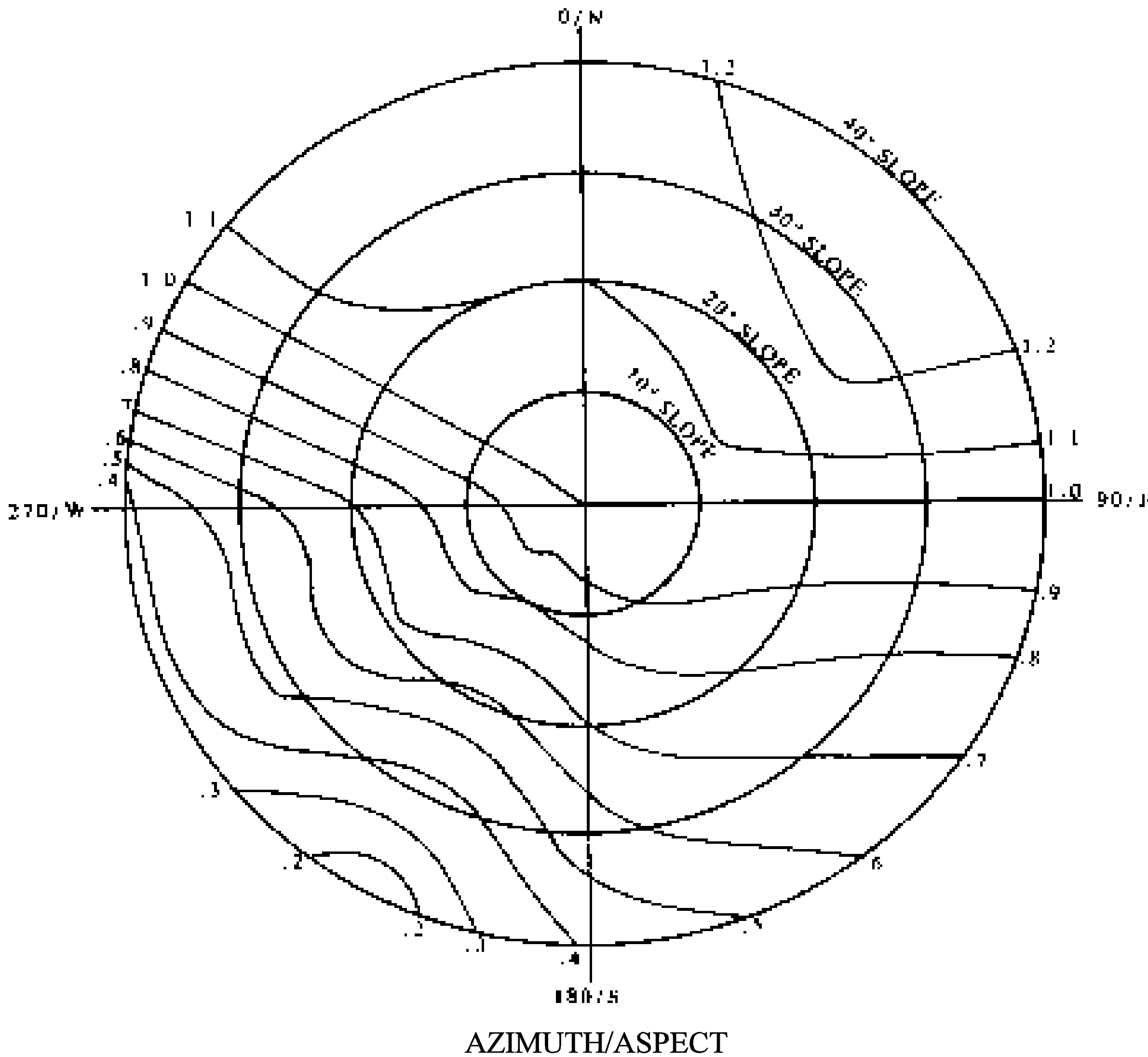

Figure 2. Snowpack and slope/aspect relationship for non-forested areas in the Yellowstone National Park study area.

Table 5. Approximating equations for obtaining factors to adjust SWE in non-forested areas to account for slope and aspect by 30 degree azimuth sectors from Figure 2.

Azimuth Range°	Equation
15 - 44	F = 1.0 + .0070 x S
45 - 74	F = 1.0 + .0082 x S (max F = 1.2)
75 - 104	F = 1.0
105 - 134	F = 1.0 - .0070 x S
135 - 164	F = 1.0 - .0115 x S
165 - 194	F = 1.0 - .0155 x S
195 - 224	F = 1.0 - .0222 x S
225 - 254	F = 1.0 - .0155 x S
255 - 284	F = 1.0 - .0155 x S
285 - 314	F = 1.0
315 - 344	F = 1.0 + .0047 x S
345 - 14	F = 1.0 + .0050 x S

F = Factor
S = Slope in degrees
Multiply SWE for flat, open location by factor to adjust for slope and aspect. True North equals 0° azimuth; True East equals 90° azimuth; True South equals 180° azimuth; True West equals 270° azimuth.

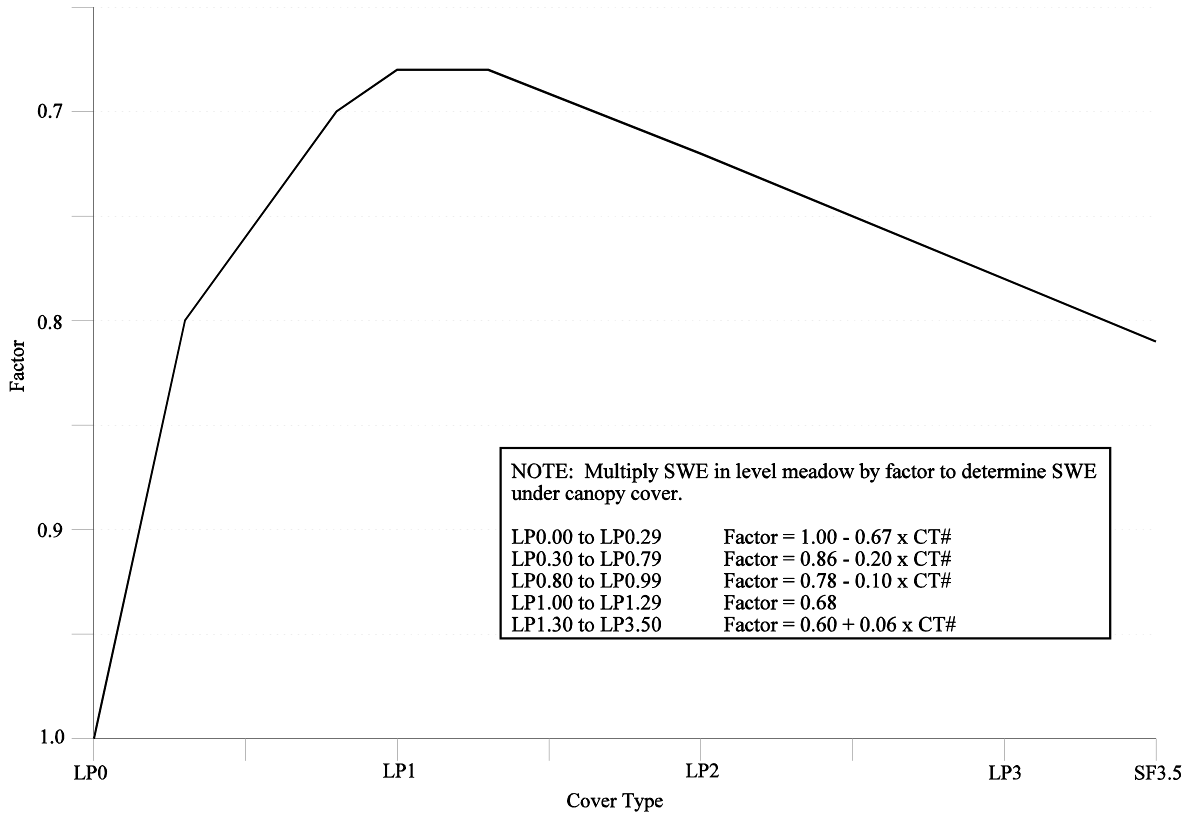

Figure 3. Relationship between snowpack accumulation and lodgepole pine cover types. (LP0 to LP3.5 refer to cover types described by Despain, 1990).

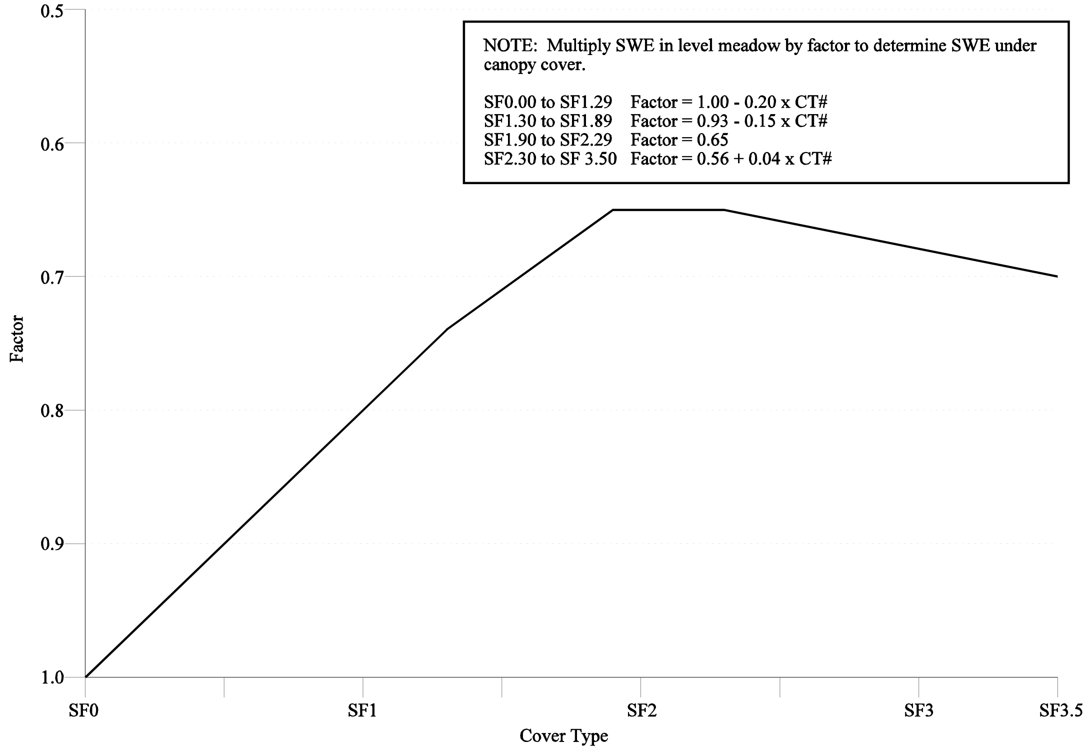

Figure 4. Relationship between snowpack accumulation and spruce/fir cover types. (SF0 to SF3.5 refer to cover types described by Despain, 1990).

DATA FORMAT

Data from daily SNOTEL and climatological stations for all stations in this study area are on file at the Spatial Analysis Center, Yellowstone Center for Resources, Yellowstone National Park (Mammoth), Wyoming. Each station's data is in a consistent format on disk (Figure 5). All data is in water year (WY) format (October 1 through September 30). For example, October 15, 1990, data is shown as 10 15 1991 (1991 WY) and January 15, 1992 is shown as 1 15 1992 (1992 WY).

Appendix 2 summarizes monthly data, useful for comparisons between various locations, and includes snow water equivalent, Keetch-Byram Drought Index (KBDI) values, and accumulated growing degree-days.

INFLUENCE OF OROGRAPHIC BARRIERS AND ELEVATION

Orographic uplifting of storms crossing mountain ranges results in increased precipitation on the upwind or windward side and just over the crest of mountain ranges, and less precipitation on the downwind or leeward side. Increases in SWE are magnified even more as air temperatures are lower at the higher elevations (so more precipitation falls in the form of snow), and melt occurs later and more slowly at higher elevations than at lower elevations. In the southwestern corner of Yellowstone National Park, storms do not undergo major orographic uplift until they reach the Madison Plateau, Pitchstone Plateau and the Red Mountains. Considerably more precipitation falls along the windward side and just past the crest of these barriers compared to leeward areas. For example, the Thumb Divide site (a leeward site) on the Continental Divide is slightly higher in elevation than the Lewis Lake Divide site (a windward site), but the average April 1 snow water equivalent at Lewis Lake Divide is over twice that at Thumb Divide. A more detailed description of climatic patterns across Yellowstone National Park is presented by Despain (1990). Monthly precipitation patterns change with elevation through the year (Farnes, 1995). In general, lower elevations receive a smaller percentage of their annual precipitation in the winter months and the most in the spring months; conversely, higher elevations receive most of their annual precipitation in the winter months with lower percentages in the spring and summer months.

To accurately estimate the SWE at specific locations in the study area using long-term station data, it is necessary to understand the physical processes associated with orographic uplifting and rain shadow effects. To have GIS models accurately represent these areas, it may be necessary to generate data for supplemental sites in order to replicate the natural processes that are occurring. Average annual precipitation maps have been developed by Farnes to assist with this interpretation.

STATION	MONTH	DAY	H2O YR	WATER YEAR DAY	TMIN F	TMAX F	TAVG F	PPT in.	SWE in.	SNOW DEPTH in.	DENSITY %	KBDI	GROWING DEGDAY F	ACCUM. GROWING DEGDAY F
WY5345	4	20	1951	202	10	42	26	0.00	5.19	25	20		0	0
WY5345	4	21	1951	203	11	38	24	0.17	5.36	27	19		0	0
WY5345	4	22	1951	204	2	40	21	0.00	5.36	25	21		0	0
WY5345	4	23	1951	205	27	40	34	0.00	5.12	24	21		0	0
WY5345	4	24	1951	206	25	42	34	0.00	4.88	23	21		0	0
WY5345	4	25	1951	207	27	47	37	0.00	4.28	22	19		0	0
WY5345	4	26	1951	208	21	48	34	0.02	4.06	22	18		0	0
WY5345	4	27	1951	209	31	44	37	0.10	3.56	21	16		0	0
WY5345	4	28	1951	210	27	49	38	0.00	2.84	21	13		0	0
WY5345	4	29	1951	211	28	38	33	0.21	2.93	21	13		0	0
WY5345	4	30	1951	212	26	39	32	0.21	3.14	21	14		0	0
WY5345	5	1	1951	213	21	33	27	0.04	3.18	21	15		0	0
WY5345	5	2	1951	214	19	39	29	0.08	3.26	21	15		0	0
WY5345	5	3	1951	215	18	49	34	0.00	3.17	20	15		0	0
WY5345	5	4	1951	216	20	62	41	0.00	2.76	19	14		0	0
WY5345	5	5	1951	217	23	63	43	0.00	2.27	17	13		2	0
WY5345	5	6	1951	218	31	61	46	0.00	1.64	16	10		5	0
WY5345	5	7	1951	219	24	45	34	0.06	1.61	16	10		0	0
WY5345	5	8	1951	220	31	45	38	0.57	1.91	15	12		0	0
WY5345	5	9	1951	221	24	48	36	0.00	1.73	15	11		0	0
WY5345	5	10	1951	222	20	53	36	0.00	1.55	15	10		0	0
WY5345	5	11	1951	223	21	61	41	0.00	1.14	14	8		0	0
WY5345	5	12	1951	224	31	54	42	0.10	0.79	14	5		1	0
WY5345	5	13	1951	225	21	38	30	0.02	0.81	13	6		0	0
WY5345	5	14	1951	226	16	50	33	0.00	0.77	12	6		0	0
WY5345	5	15	1951	227	19	59	39	0.00	0.45	6	7		0	0
WY5345	5	16	1951	228	23	60	42	0.00	0.00	0	0	1	1	0
WY5345	5	17	1951	229	25	62	44	0.00		0		3	3	0
WY5345	5	18	1951	230	34	55	44	0.05		0		4	3	0
WY5345	5	19	1951	231	26	55	40	0.00		0		5	0	0
WY5345	5	20	1951	232	34	50	42	0.06		0		5	1	1
WY5345	5	21	1951	233	32	56	44	0.00		0		6	3	4
WY5345	5	22	1951	234	25	63	44	0.00		0		8	3	7
WY5345	5	23	1951	235	27	64	46	0.00		0		10	5	12
WY5345	5	24	1951	236	31	55	43	0.10		0		11	2	14
WY5345	5	25	1951	237	35	53	44	0.00		0		12	3	17
WY5345	5	26	1951	238	34	62	48	0.00		0		14	7	24
WY5345	5	27	1951	239	29	65	47	0.02		0		16	6	30
WY5345	5	28	1951	240	36	55	46	0.35		0		1	5	35
WY5345	5	29	1951	241	22	59	40	0.00		0		2	0	35

Figure 5. Format of daily data on disk for SNOTEL and climatological stations.

AVERAGE ANNUAL PRECIPITATION MAPS

The average annual precipitation was calculated for SNOTEL and CLIM stations for the 30-year base period from 1961-1990 (Table 6). The standard for comparing climatic and hydrologic data is to use a 30-year period updated every 10 years. Starting in 2001, the base period will be 1971-2000. The annual precipitation at snow courses was estimated using the April 1 SWE versus annual precipitation curve obtained from data at SNOTEL and CLIM stations. Elevation versus average annual precipitation curves was used to determine the elevation at which equal increments of precipitation would occur using various profiles across the drainage (Farnes, 1971). Isohyetal lines (lines of equal precipitation) were drawn connecting known points of annual precipitation. Isohyetal maps for the 1961 to 1990 period were developed for Yellowstone National Park and surrounding areas on base maps with a scale of 1:250,000 scale and digitized and incorporated into Yellowstone National Park GIS. These maps are available from the Spatial Analysis Center, Yellowstone Center for Resources, Yellowstone National Park (Figure 6).

In general, the area near the north entrance along the Yellowstone River near Gardiner has around 10 inches of average annual precipitation. Higher elevations in the southwest area of the Park have over 70 inches average annual precipitation. The average annual (1961 through 1990) precipitation across Yellowstone National Park is 39 inches. In the lower elevations, 30 to 35 percent of the average annual precipitation falls as snow while in the higher elevations, up to 70 percent of the average annual precipitation falls as snow. The annual precipitation in any given year can be as low as 60 percent of the average to as high as 150 percent of average.

KEETCH-BYRAM DROUGHT INDEX

The Keetch-Byram Drought Index (KBDI) (Keetch and Byram 1988) is a stand-alone drought indicator representing the net effect of evapotranspiration and precipitation in producing cumulative moisture deficiency in deep duff or litter and in upper soil layers. It was initially developed for, and is primarily used for, fire danger ratings. In this study, however, the KBDI is used to represent soil moisture deficiency. KBDI values are important in evaluating forage production by identifying periods of moisture stress and availability of soil moisture through the critical portion of the growing season.

The KBDI varies from 0 to 800, with 0 representing field capacity. The numbers represent 100 times the number of inches of precipitation required to achieve a zero KBDI (or to increase the soil moisture to field capacity). For example, a KBDI of 300 would require approximately 3 inches of rainfall to restore the soil moisture to field capacity.

Table 6. Average annual precipitation and April 1 SWE (1961-1990) for stations in and near Yellowstone National Park, Wyoming.

Site Name	Station Type	Elevation (ft)	Average Precip	Average Annual April 1, SWE (true)
Aster Creek	SC	7750	47.0[E]	28.9
Beartooth Lake	SNOTEL	9280	32.9	23.8
Black Bear	SNOTEL	8170	61.7	38.5
Canyon	SNOTEL	7940	27.7	13.8
Cooke City 2W	CLIM	7460	25.54	9.3[E]
Cooke Station	SC (DISC)	8150	40.0[E]	22.6
Coulter Creek	SNOTEL (DISC)	7020	40.9	22.9
Crevice Mountain	SC	8240	27.0[E]	10.0
East Entrance	SC (DISC)	6960	23.0[E]	6.7
Evening Star	SNOTEL	9200	45.1	27.2
Fisher Creek	SNOTEL	9100	59.0	36.1
Gardiner	CLIM	5280	10.03	-
Grassy Lake	SNOTEL	7265	56.0	36.3
Hebgen Dam	CLIM SC	6550	30.21	11.0
Jardine	CLIM (DISC)	6450	14.99	-
Lake Yellowstone/Camp	CLIM, SC	7780	20.41	9.3
Lamar RS	CLIM	6470	14.06	2.9
Lewis Lake Divide	SNOTEL	7860	57.0	35.7
Lupine Creek	SC	7380	27.0[E]	9.9
Madison Plateau	SNOTEL	7750	42.7	24.8
Monument Peak	SNOTEL	8850	38.8	21.4
Norris Basin	SC	74.80	32.0[E]	13.5
Northeast Entrance	SNOTEL	7350	25.2	11.6
Old Faithful	CLIM, SC	7358	28.04	13.9
Parker Peak	SNOTEL	9400	31.8	21.8
Pitchstone Plateau	AM (DISC)	8520	70.5[E]	46.5
Rock Creek Meadows	SC	8160	31.6	20.0
Shower Falls	SNOTEL	8100	51.9	23.8
Snake River Station	CLIM/SNOTEL	6920	31.5	18.8
Star Lake	AM (DISC)	9650	63.5[E]	38.9
Sylvan Lake	SNOTEL	8420	37.3	22.3
Sylvan Road	SNOTEL	7120	32.5	12.5
Thumb Divide	SNOTEL	7980	36.6	17.2
Tower Falls	CLIM	6264	16.94	3.8
Twentyone Mile	SC	7150	41.0[E]	18.4
Two Ocean Plateau	SNOTEL	9240	46.9	25.3
West Yellowstone	CLIM/SNOTEL	6700	22.21	9.7
West Yellowstone 9N	CLIM	6572	20.96	-
Whiskey Creek	SNOTEL	6800	36.6	17.5
White Mill	SNOTEL	8700	47.0	25.1
Yellowstone Park (Mammoth)	CLIM	6230	15.39	0.8
Younts Peak	SNOTEL	8350	31.4	17.3

SC = Snow Courses; SNOTEL = SNOTEL Site; AM = Aerial Marker; CLIM = Climatological Station; Disc = Discontinued; [E] = Average annual precipitation estimated from April 1 SWE versus annual precipitation curve.

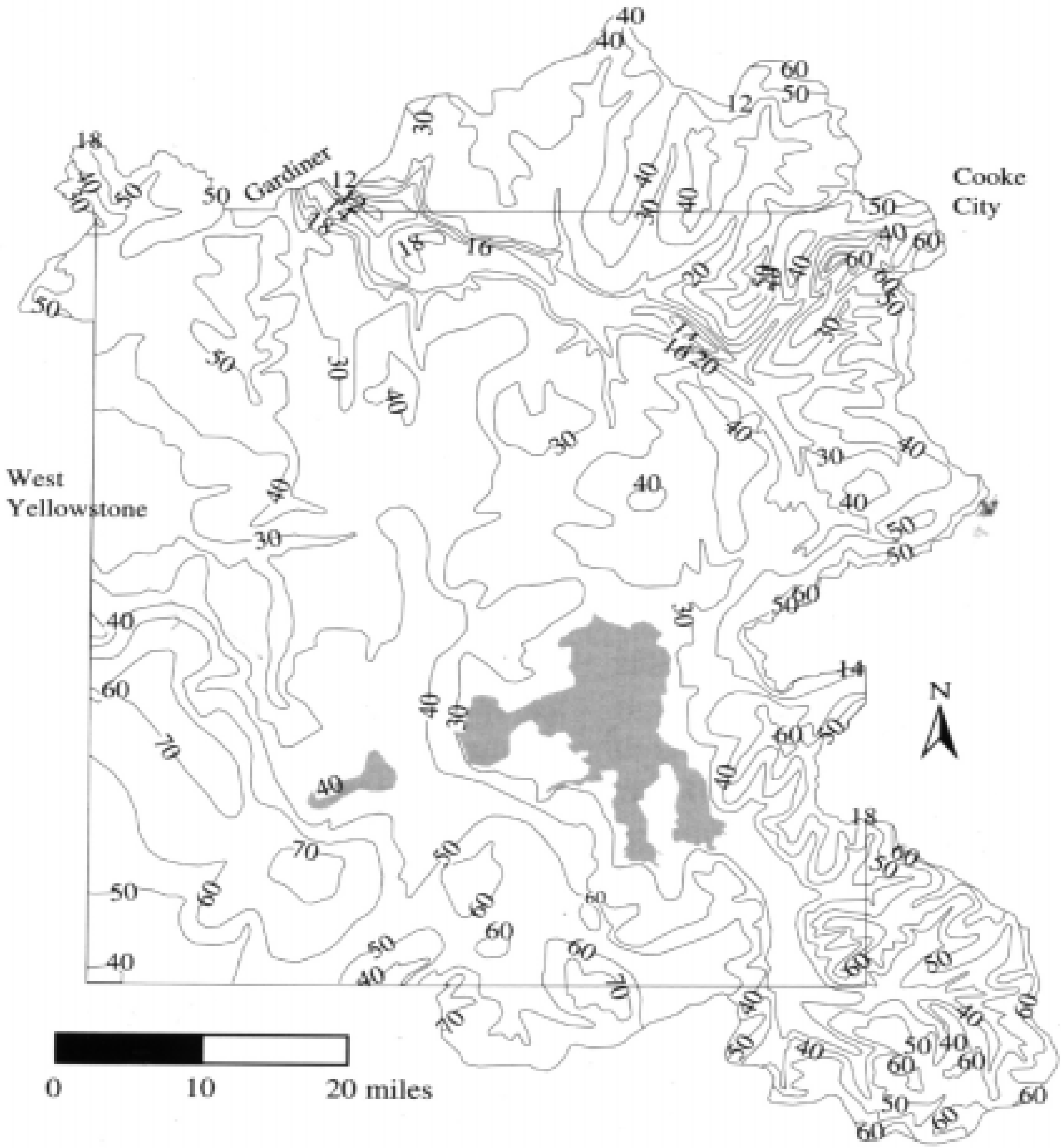

Figure 6. Average annual precipitation, in inches, for the 1961-1990 base period for Yellowstone National Park, Wyoming, by Farnes.

The procedure uses daily precipitation and daily maximum temperature, average annual precipitation, latitude, and KBDI on the previous day as input parameters. For this study, the KBDI is assumed to be zero on the day the snowpack melts to zero. Daily KBDI values are calculated from the time snow melts to zero in the spring until the snow begins to accumulate in the fall or early winter. The value on the day the snow begins to accumulate represents the moisture deficiency in the soil under the snowpack and is assumed to persist until melt begins in the spring. At Gardiner, the KBDI program is run year around since the winter precipitation in many years is not adequate to eliminate the soil moisture deficit from the previous fall.

The KBDI is one of the variables used in the forage production component of the Index of Winter Severity (IWS) and to estimate forage production on the summer ranges.

GROWING DEGREE-DAYS

Growing Degree-Days (GDD) are calculated as the number of degrees that the mean daily air temperature (TMax + TMin divided by 2) is above 41°F or 5°C (the temperature considered to be biological zero for many plants). For this study, it is assumed that sedges, grasses, and forbs break dormancy after three consecutive days where the mean daily temperatures are above 41°F after the snowpack has melted to zero (Farnes et al., 1995). Trees are assumed to break dormancy after three consecutive days where the mean daily temperatures are above 41°F and may occur when there is still snow on the ground. Shrubs are assumed to break dormancy after three consecutive days above 41°F after snow has melted to about one-half the plant height.

Degree-days are calculated daily from March 1 through September 30 for each year and are accumulated from the time plants (grasses, sedges, and forbs) are assumed to break dormancy (i.e., three consecutive days where TAvg is above 41°F after the snow becomes zero). GDD are related to phenological stages of plants. GDD are also used in determining the forage production component of the Index of Winter Severity. For this study, it is assumed that the majority of plant growth of native range forage plants (grasses, sedges, and forbs) occur in the first 750 GDD (Walker et al., 1994).

DEPTH/SWE RELATIONSHIPS

It is more accurate to estimate total snow depth using SWE and the date than it is to estimate snow depth independently due to variability resulting from new snow depth, settlement within the snowpack, the snowpack's prior temperature, and other factors. Historic records of snow course measurements were analyzed to obtain date, density, SWE and depth relationships. Multipliers were developed to calculate snow depth from SWE based on the first-of-the-month snow surveys from January through June and were extrapolated to other dates (Table 7). These multipliers can be applied across the entire study area. Density values can be calculated by dividing the SWE by the snow depth for any specific date at any specific pixel.

Table 7. Multipliers* for calculating snow depth from SWE through the snow season for Yellowstone National Park and surrounding areas.

SWE Inches	DATE Prior to Oct 15	Oct 16 to Nov 15	Nov 16 to Dec 15	Dec 16 to Jan 15	Jan 16 to Feb 14	Feb 15 to Mar 15	Mar 16 to Apr 15	Apr 16 to May 7	May 8 to May 22	May 23 to Jun 7	After Jun 8
Less 4.99	6.4	6.2	6.0	6.0	5.6	5.2	4.8	4.2	3.6	3.2	2.8
5 - 9.99	4.9	4.8	4.7	4.7	4.4	4.2	4.0	3.6	3.2	3.1	2.7
10 - 14.99	4.3	4.2	4.2	4.1	3.9	3.8	3.7	3.3	2.9	2.6	2.5
15 - 19.99	3.9	3.9	3.8	3.8	3.7	3.6	3.4	3.1	2.7	2.5	2.4
20 -24.99	3.7	3.6	3.6	3.5	3.4	3.4	3.2	3.0	2.6	2.4	2.3
25 - 29.99	3.5	3.4	3.4	3.3	3.3	3.2	3.1	2.8	2.5	2.3	2.2
30 - 34.99	3.4	3.3	3.2	3.2	3.1	3.1	3.0	2.8	2.5	2.2	2.1
35 - 39.99	3.2	3.2	3.1	3.1	3.0	3.0	2.9	2.7	2.4	2.1	2.0
40 - 44.99	3.1	3.1	3.0	3.0	2.9	2.9	2.8	2.6	2.3	2.1	2.0
45 - 49.99	3.0	3.0	2.9	2.9	2.9	2.8	2.8	2.5	2.3	2.0	2.0
50 - 54.99	3.0	3.0	2.9	2.9	2.9	2.8	2.8	2.5	2.3	2.0	2.0
55 - 59.99	3.0	3.0	2.9	2.9	2.9	2.8	2.8	2.5	2.3	2.0	2.0
60 - 64.99		3.0	2.9	2.9	2.9	2.8	2.8	2.5	2.3	2.0	2.0
65 - 69.99			2.9	2.9	2.9	2.8	2.8	2.5	2.3	2.0	2.0
70 - 74.99				2.9	2.9	2.8	2.8	2.5	2.3	2.0	2.0
75 - 79.99					2.9	2.8	2.8	2.5	2.3	2.0	2.0
80 - 84.99						2.8	2.8	2.5	2.3	2.0	2.0
85 - 89.99							2.8	2.5	2.3	2.0	2.0
90 - 94.99								2.5	2.3	2.0	2.0
95 - 99.99									2.3	2.0	2.0

*SWE (in inches) x multiplier = snow depth in inches

ANIMALS' TOLERANCE OF SNOW

Many larger ungulates can travel and forage in deeper snow than can smaller animals; however, these larger animals sink further into the snowpack than do most predators and smaller mammals. Most larger mammals (elk, moose, bison) actually sink nearly to the ground surface except when the snow is extremely dense. Because there is less snow under a forest canopy, larger mammals typically use these areas for more efficient travel routes. Also, because south-facing slopes have less snow (due to radiation-induced losses) than do level, non-forested areas and north-facing slopes, animals may utilize south-facing areas when travel becomes difficult in deeper snow. Early in the season, most foraging generally occurs in the relatively flat and non-forested areas with the most abundant forage. Later in the season, these areas may not be accessible due to deeper snow or to the dense snow created by the animals (feeding craters) as they move snow to gain access to forage. Once snow has been disturbed, such as in and around the "craters", it becomes very dense. These areas usually cannot be utilized again until the snow is softened by warm temperatures in the spring. As the winter season progresses, foraging animals are usually forced to move to locations where there is less snow, such as south-facing slopes or lower elevations. Typically, the south-facing slopes produce less forage per unit area than do the level sites because lower elevations have deeper soils, more nutrients available and more favorable soil moisture. Generally, these animals will utilize this sparse forage on the south-facing slopes quite quickly and then will move to lower elevations.

Using aerial count data from 1968 to 1981, SWE maps for the northern range in Yellowstone National Park, and snow tube measurements near animal sightings, for the past few years Farnes has observed that where bison and elk can move to lower snow areas, they will generally forage in areas that have less than 6 inches of SWE. Generally, accumulations of 1 or 2 inches of snow water equivalent are enough to initiate movement of at least part of the herd to lower elevations or areas with less snow. Threshold values for mule deer may be about one-half those for elk.

Values reported in the literature appear to substantiate these observations. Most studies report snow depth, rather than snow water equivalent, as a determinant in mammal's habitat use. Where possible, snow depth values were converted to estimated SWE so comparisons between SWE and animal observances could be added to the present data base.

Generally, animals tend to start moving to lower elevations when snow depth reaches mid-calf height on the leg of a mature animal (estimated 2 to 3 inches SWE for elk) (Halfpenny and Ozanne, 1989), and a primary stimulus for autumn migration from a summer home range is a snow depth of approximately 25 cm (SWE estimated 1.5 to 2 inches) depending on snow consistency (Skovlin 1982; Rudd et al., 1983; Fischer and Gosson, 1987; see references in Schmidt, 1993). Previous studies in the USSR, Canada, and the United States have found snow depths exceeding 40 to 50 cm (SWE estimated 2.5 to 4 inches) impede the movements of wolves and white-tailed deer (Formozov, 1946; Kelsall, 1969; Mech, 1970; Kelsall and Prescott, 1971).

When snow depths exceed 40 cm (SWE estimated 3 to 4 inches) and basal metabolism is depressed, white-tail deer select forest stands with dense canopy covers and depauperate understories (Pauley et al., 1993). Mule deer use mostly old forest stands (>140 years) as snow depths exceeded 26 cm (SWE estimated 1.5 to 2.5 inches) (Armleder et al., 1994). Moose selection of early winter canopy cover was influenced by both forage and snow depth in a study in British Columbia by Schwab and Pitt (1991). Mean sinking depths were found to be lowest, and thus movement by deer most favorable, in 80-year-old, second growth forest stands (estimated SWE about half of that in openings) (Bunnell et al., 1990).

Increased cost of locomotion when sinking depths in snow exceed 25 cm (SWE estimated 1.5 to 2.5 inches) made energy expenditure the primary determining factor in body condition and mass of Sitka black-tailed deer (*Odocoileus hemionus sitkensis*) (Parker et al., 1999).

During periods of snow cover, bighorn sheep in Colorado shifted their feeding areas from open sites to shrub-covered areas, and as snow depth increased, the percentage of green material in their diet declined (Goodson et al., 1991). Larter and Gates (1991) suggest in their bison study that snow depth influences habitat use. Snow depth, summed over three consecutive years, was suggested as an important influence on the population parameters of moose in Michigan (Mech et al., 1987).

Huggard (1993) found snow depth could add substantial, density-independent variations to wolf-prey interactions and could affect which classes of prey were killed. Snow depth was determined to be significantly greater during successful coyote kills in Yellowstone National Park (Gese and Grothe, 1995).

When low air temperatures (-20° to -50°F) occur during periods without snowfall, a weak layer of snow crystals may develop at the base of the snowpack. The layer is referred to as depth hoar or temperature gradient snow. The surface layer generally breaks rather easily under weight and this weak, low density layer makes the forage more available to grazing animals than when the entire snowpack is stronger and denser. Animals that obtain forage under this weak layer expend less energy than when they must move denser snow. The lower air temperatures at this time, however, require the animals to expend more energy to maintain body heat.

Snow crusting can also affect foraging animals. Crusts are formed when warmer air temperatures create melt on the snow surface or when there is rainfall on the snowpack followed by freezing air temperatures. Crusts are also formed by wind erosion and deposition. Usually these conditions are highly variable and only portions of the area develop crusts. The impact on wintering wildlife depends on the time of season, the crust hardness and depth, the extent of the area that is crusted, the duration of these crusts, as well as forage availability.

There may be localized variations in the snowpack due to wind scour or deposition, melt, and avalanches. These variables are difficult to predict. For this study, it was acknowledged that these conditions may exist, but the affected areas are probably less than 5 percent of the total area. A refined model to account for all variations would require a much greater data base and extensive on-site measurements that are beyond the capability of this study. Also, these affected areas may be insignificant when looking at the overall area.

INDEX OF WINTER SEVERITY

The Index of Winter Severity (IWS) is obtained by combining SWE, accumulated TMin temperatures below the effective critical temperature for each species, and forage availability on the winter range. Even with adequate natural forage, most ungulates in this area cannot maintain body weight through the winter months, even in mild winters (Parker et al., 1999). Loss of body weight is greater in winters with heavier snowpack, colder temperatures, or an extended snow season. A combination of severe conditions usually result in significant mortality. However, less severe conditions may not result in mortality, but may affect reproduction, survival of young of the year and predation. The IWS has a scale from +4 to -4, with +4 representing the mildest conditions and -4 indicating the most severe conditions. IWS is calculated for each winter range and each species to represent the variability from the norm for that area. The response of individual animals, or groups of animals, may vary depending on topography and vegetation. The IWS is intended to estimate the animals' responses to climatic and vegetative conditions on the winter range. It does not necessarily represent migration response. On the other hand, the snow component used in the IWS is one of the variables relating to movement to lower elevations. The amount of forage produced on the summer range is related to the animals' weight and condition in the fall. During years of good summer forage, the animals are in better physical condition and they are better able to withstand the effects of winter. The amount of forage produced on the winter range determines the effort and time required to obtain adequate daily forage intake.

Snow Water Equivalent

SWE is obtained from SNOTEL or CLIM stations and snow courses. Usually stations on or near each winter range are used for the IWS. As SWE increases, areas available for foraging decrease, energy expended to obtain forage and to travel increases, and competition for forage may increase. Forage utilization is a function of snow pack. When snow accumulation exceeds 1½ to 2 inches of SWE, grazing animals create foraging craters as they move the snow to obtain food. Snow moved in the cratering process becomes very hard and typically prevents further utilization of forage under the deposited snow until snow softens in the spring, generally around mid-March. Area of deposited or disturbed snow may be three to four times the area where forage was removed, thereby reducing the forage utilization as observed in the spring to 25 to 35 percent of the area. In shallow snow or no snow areas, forage utilization can approach 100 percent. For example, forage utilization on National Elk Refuge at Jackson, Wyoming, generally varies from 47 to 82 percent, with a higher level of utilization on the lower snow years.

The snow water equivalent also determines the area of winter range available particularly the northern range. Preliminary data suggest that on low snow years (SWE that is 35 to 40 percent of average), nearly all the area identified as northern winter range both inside Yellowstone National Park and north of the Park in Montana is available (SWE is generally less than 6 inches). On average snow years, only about 55 percent of the winter range in the Park and 70 percent outside the park is available by early February. By February 1 on heavy snow years (SWE that is 170 to 180 percent average), only about 15 percent of the northern winter range in Yellowstone Park has less than 6 inches SWE, while about 30 percent of the winter range outside the Park has less than 6 inches SWE. It has been proposed that GIS be used to determine monthly SWE maps for the northern range for the previous 50 years using SWE values and algorithms generated for this report.

Effective Critical Temperatures

Each species has an effective critical temperature and when air temperatures are below this threshold, the animals must increase their basal metabolic rate to maintain body temperature (Table 8). These values are for non-active periods such as bedding or ruminating and are usually associated with periods having the lowest daily air temperatures. Most wildlife ruminants cannot process enough winter forage to maintain their fat reserves under mild temperature conditions. When air temperatures are below the effective critical temperature, animals must utilize energy from their fat reserves to maintain adequate body temperatures. These losses in fat reserves are cumulative through the winter. For moose and bison, there is no temperature variable in the IWS since their effective critical temperature is so low that only a few days each winter have any effect. However, there is an upper critical temperature where these two species must increase their metabolism in order to reduce their body temperatures. This effect was not considered in this report since they can generally utilize snow cover, shade or inactivity during the warmer part of the day to minimize this effect. Where available, thermal areas on the winter range have been utilized by some ungulates to counteract effects of cold air temperatures.

The critical temperature index used in the IWS is calculated by subtracting the effective critical temperature from TMin. If TMin is warmer than the critical temperature, the daily temperature index is zero. Daily values are accumulated from the beginning of the winter, usually weekly or monthly, to determine the season-to-date value. There is some variability within each species related to age, sex, and weight, but the values from Table 8 provide an index relative to each species.

Table 8. Effective critical temperature values for some mammals.

Mammal	°C	°F	Mammal	°C	°F
Pronghorn	0	32	Mountain goat	-20	-4
White-tail deer	-12	10	Bighorn sheep	-20	-4
Mule deer	-18	0	Moose	-32	-26
Elk	-18	0	Bison*	-34	-29

Chappel and Hudson, 1980; Krog and Monson,1954; Mautz et al., 1985; Nelson and Leege, 1982; Schwab and Pitt, 1991; Wesley et al., 1973.

* Metabolic rates for bison are similar at 0° and -30°C but are about 30 percent higher at +10°C. There was an increase in metabolic rate at -30°C with 3 mph wind, indicating a possible effective critical temperature around -34°C (Christopherson et al., 1979).

Forage Production

Forage production on the summer range is a critical component of winter survival. When forage production is good, females with young produce abundant milk, and the young of the year enter winter in good physical shape and at a heavier weight than on years with poorer summer forage. Likewise, adult animals also enter the winter in better physical condition.

The majority of forage utilized by grazers on the winter range is produced annually, and the amount produced in any year is a function of available spring moisture and temperature. Early growing season moisture comes from snow melt and rainfall, and it is usually adequate for initiating plant growth when temperatures are warm enough to break dormancy. Rainfall later in the growing season, however, is more variable and more significant to total forage production. Moisture falling after July may not be as important in producing forage, particularly if there has been a deficiency in moisture earlier in the season. For the IWS, the amount of forage produced in a given year on the winter range was originally indexed by the June and July precipitation for the summer preceeding the winter being indexed. Currently the average daily Keetch-Byram Drought Index (KBDI) for the first 750 growing degree days plus 0.2 times the maximum KBDI during the first 750 GDD is used to represent available soil moisture for forage production. It is assumed the major growth of native forage plants in the study area occurs during this period. Appendix 2 shows average date when measured sites reach 750 GDD and when herbaceous plants break dormancy.

Forage available on the winter ranges in this area generally has crude protein content that varies from about 3 percent for bluebunch wheatgrass (Wambolt, 1998), 5 to 7 percent at grassland sampling sites on the northern range (Wallace et al., 1995) and 3 to 5 percent for grasses and sedges on the northern range (Houston, 1982). To maintain body weight, crude protein levels of forage need to exceed 6 to 8 percent (Van Soest, 1982). Some ungulates may utilize sagebrush or other shrubs to increase the crude protein levels in forage intake to slow body weight loss through the winter. Houston (1982) reported that sagebrush and evergreen shrubs on the northern range had crude protein levels that averaged about 10 percent. Wambolt (1998) reported that Welch and McArthur found crude protein content of 21 big sagebrush accessions averaged 12.4 percent. Where available, lichens may be an important winter food source (Ward, 1999).

When crude protein levels are in the 3 to 4 percent range, ungulates take much longer to process this forage in their digestive systems than when crude protein levels are higher (Sowell, personal communication). The literature suggests that ungulates reduce their forage intake in the winter as a survival technique, whereas, in reality, their digestive systems may not be able to process any additional forage due to the slowing of their digestive processes. For years where there is good forage production on the winter range, energy expended obtaining forage under the snow is reduced, thereby helping to decrease the decline in body fat reserves.

Method

A method used by Shafer and Dezman (1982) was adapted to compare the range of variation in the snow, temperature, and forage in a specific area. This method allows the use of a common scale to compare different variables using the probability of non-exceedence (PN) and to calculate the IWS.

The probability of non-exceedence is obtained by subtracting the normal probability from 100. Using the probability of each variable provides a means to compare the variability among variables. To compress the range of probability of non-exceedence (1 - 99%) to a range of -4 to +4, subtract 50 from the probability and divide by 12.25:

$$\text{Index} = \frac{PN - 50}{12.25}$$

For example, an index for a probability of non-exceedence of 1%, or near lowest of record, would
be calculated as follows:

$$\frac{1-50}{12.25} = \frac{-49}{12.25} = -4$$

An index for a probability of non-exceedence of 50%, or about average, would be calculated as follows:

$$\frac{50-50}{12.25} = 0$$

And, an index for a probability of non-exceedence of 99%, or near mildest of record, would be calculated like this:

$$\frac{99-50}{12.25} = \frac{49}{12.25} = +4$$

For elk, the IWS for the winter season was calculated by weighting the snow variable as 45%, the temperature variable as 35%, and the winter forage variable (KBDI values) as 20%. These weightings come from discussions with researchers and wildlife managers which suggest the effects of snow should have the greatest weight, temperatures below the effective critical temperature somewhat less, and the total forage production on the winter range should have the least weight. Weightings may be changed to reflect the observations of wildlife managers or for areas not conforming to general wintering ranges. For both bison and moose, temperature is not used because their effective critical temperature is near or below the lowest temperatures recorded in this area. For bison, the suggested weighting of snow variable is 70% and the winter forage variable is 30%. For moose, where the winter forage is predominately willow or spruce boughs, the forage production may be weighted over a 2- to 5-year span rather than an index of annual production. Snow and forage weightings for moose are probably similar to bison or 70% snow and 30% forage. For mule deer, it is suggested the snow variable be weighted as 50%, the critical temperature variable as 30%, and the winter forage variable as 20%. For white-tailed deer, it is suggested the snow variable be weighted as 60%, the critical temperature variable as 25% and the winter forage variable as 15%. For pronghorn, it is suggested that the snow variable be weighed as 55%, the critical temperature variable as 30% and the winter forage variable as 15%.

From general observation of elk, values above 0 (all positive IWS) are comparable (i.e., winter kill is low, reproduction is good, recruitment is good, and predators must work harder to obtain prey). Values between -1 and -2 show some reduction in reproduction, but generally little mortality of older animals and yearlings occurs. IWS values below -2 usually indicate significant mortality, low reproduction rates, weaker calves and lower birth weights, smaller herd recruitment rates or even negative recruitment (i.e., more animals die than enter the population), and increased predation. IWS values calculated for elk for five winter ranges in and near Yellowstone National Park area (Figure 7) are shown in Appendix 3 and in Figures 8-12. The IWS values for four winter ranges for bison (Figure 13) are tabulated in Appendix 3 and in Figures 14-17.

The IWS values for one mule deer winter range (Figure 18) are tabulated in Appendix 3 and in Figure 19. The IWS values for one Pronghorn winter range (Figure 20) are tabulated in Appendix 3 and in Figure 21.

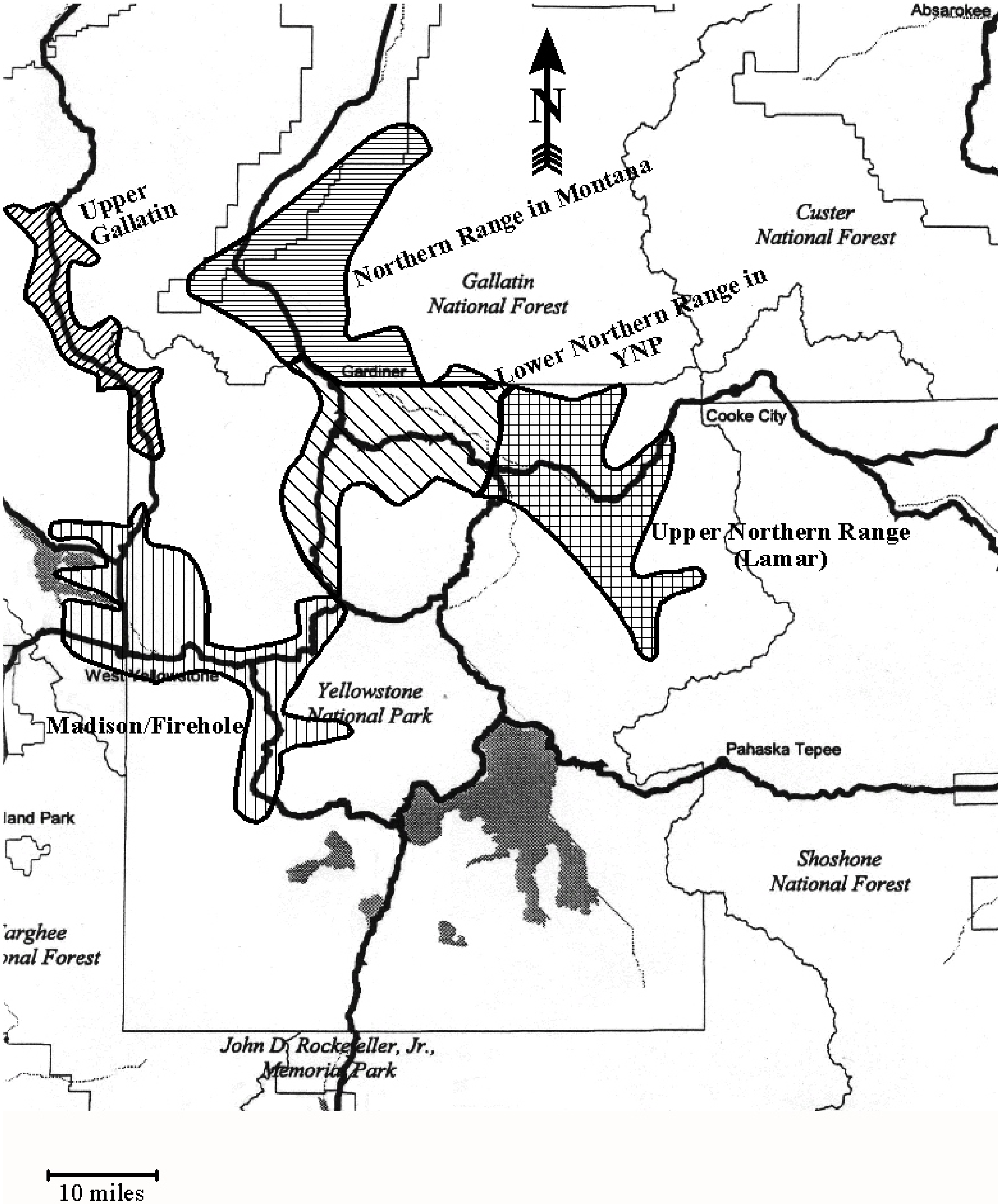

Figure 7. General location of elk winter ranges in and adjacent to Yellowstone National Park where index of winter severity is calculated.

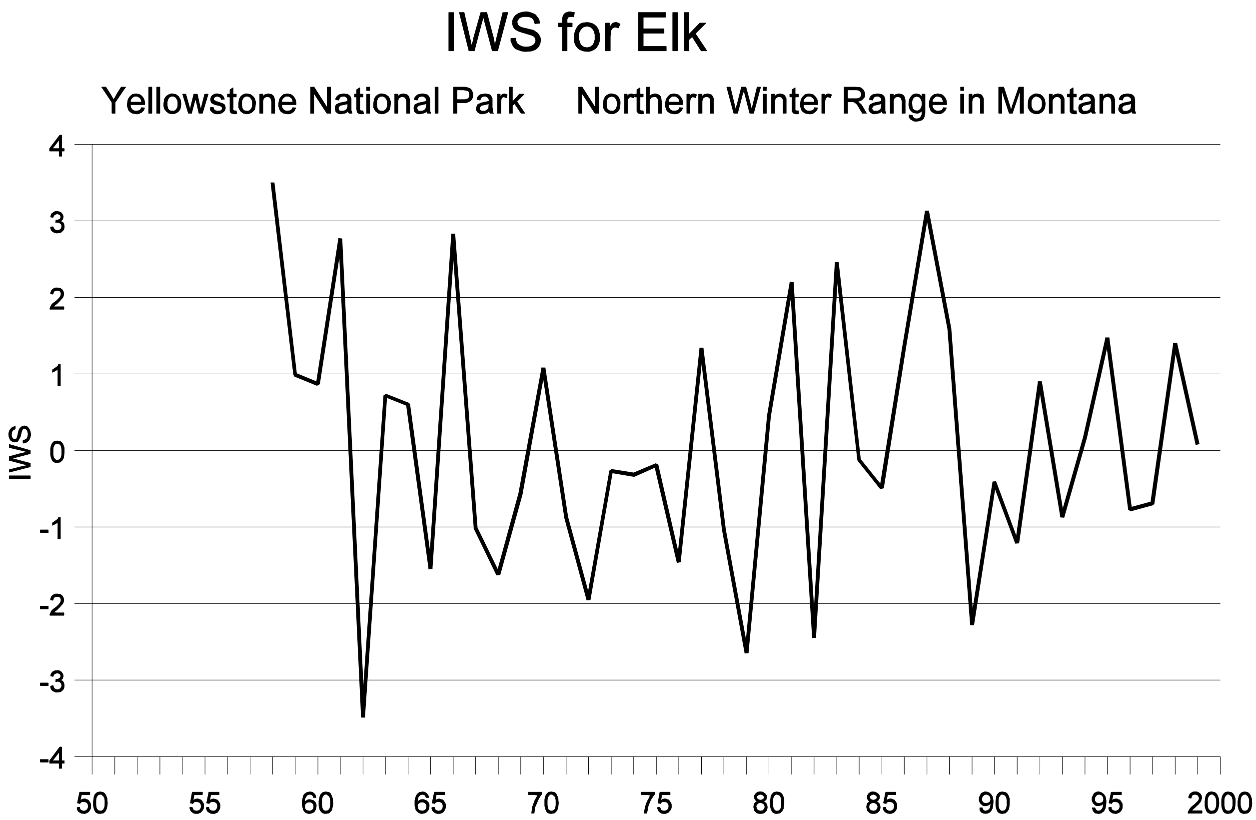

Figure 8. Index of winter severity (IWS) for elk for the winters of 1958-1999 for the Northern Winter Range in Montana north of Yellowstone National Park.

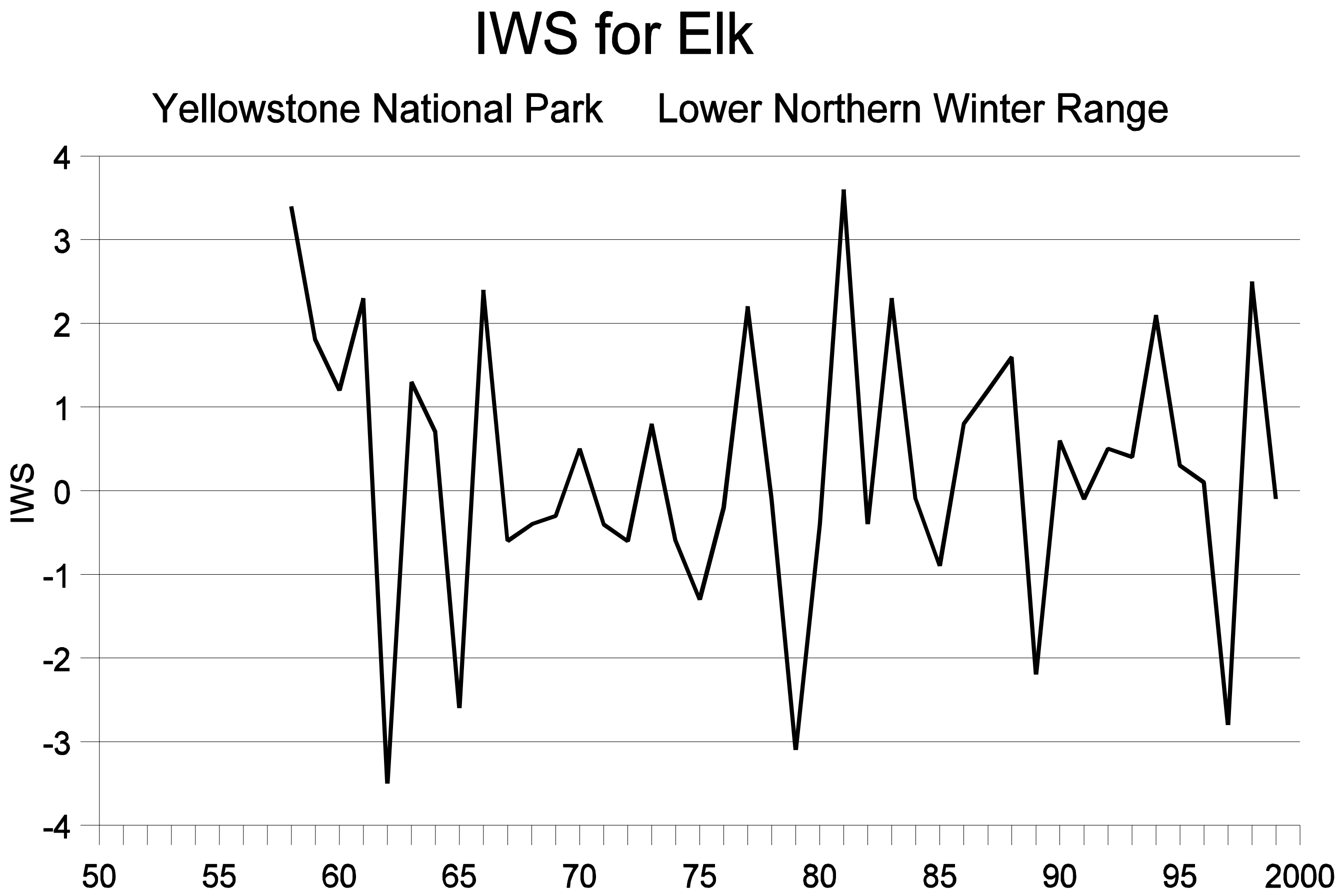

Figure 9. Index of winter severity (IWS) for elk for the winters of 1958-1999 for the Lower Northern Winter Range in Yellowstone National Park.

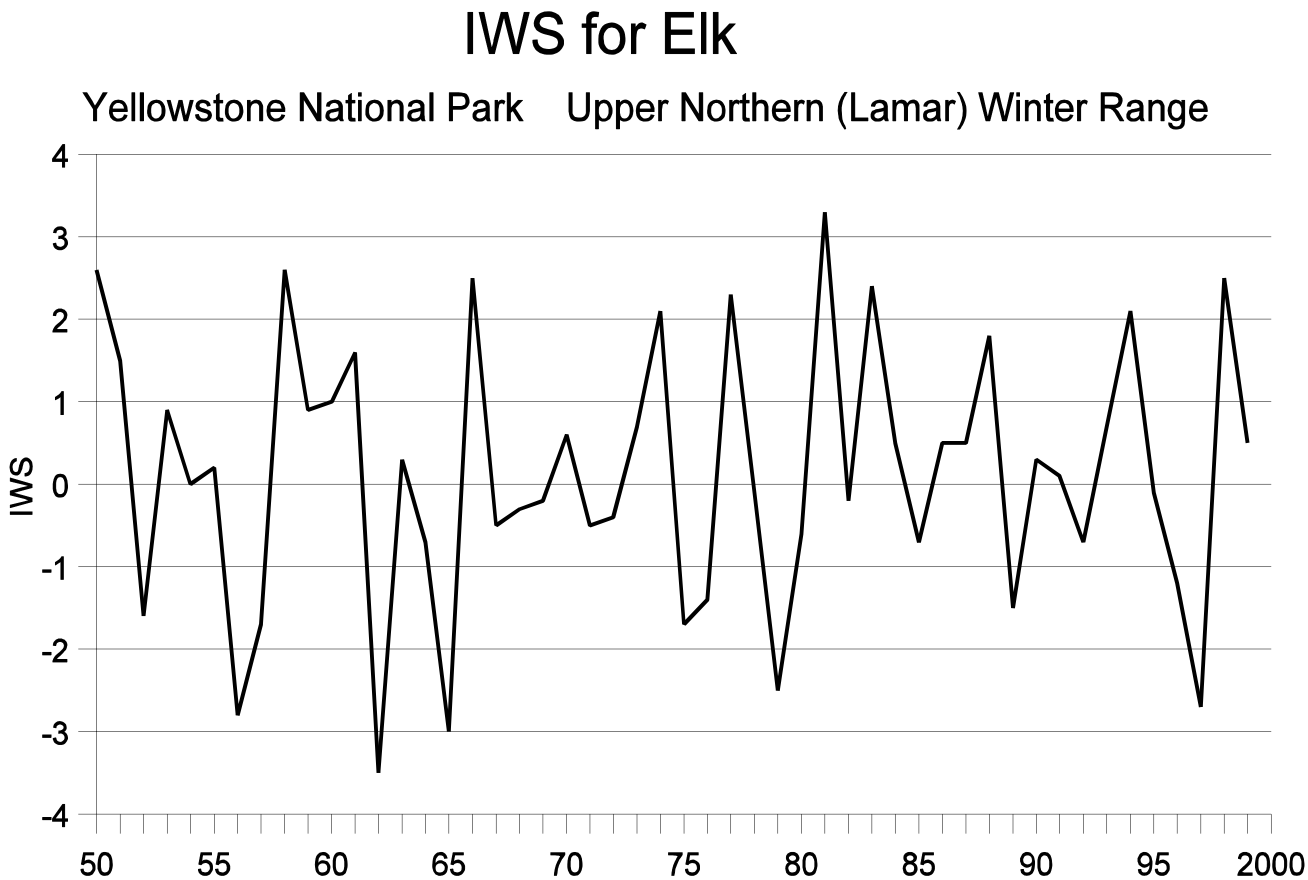

Figure 10. Index of winter severity (IWS) for elk for the winters of 1950-1999 for the Upper Northern (Lamar) Winter Range in Yellowstone National Park.

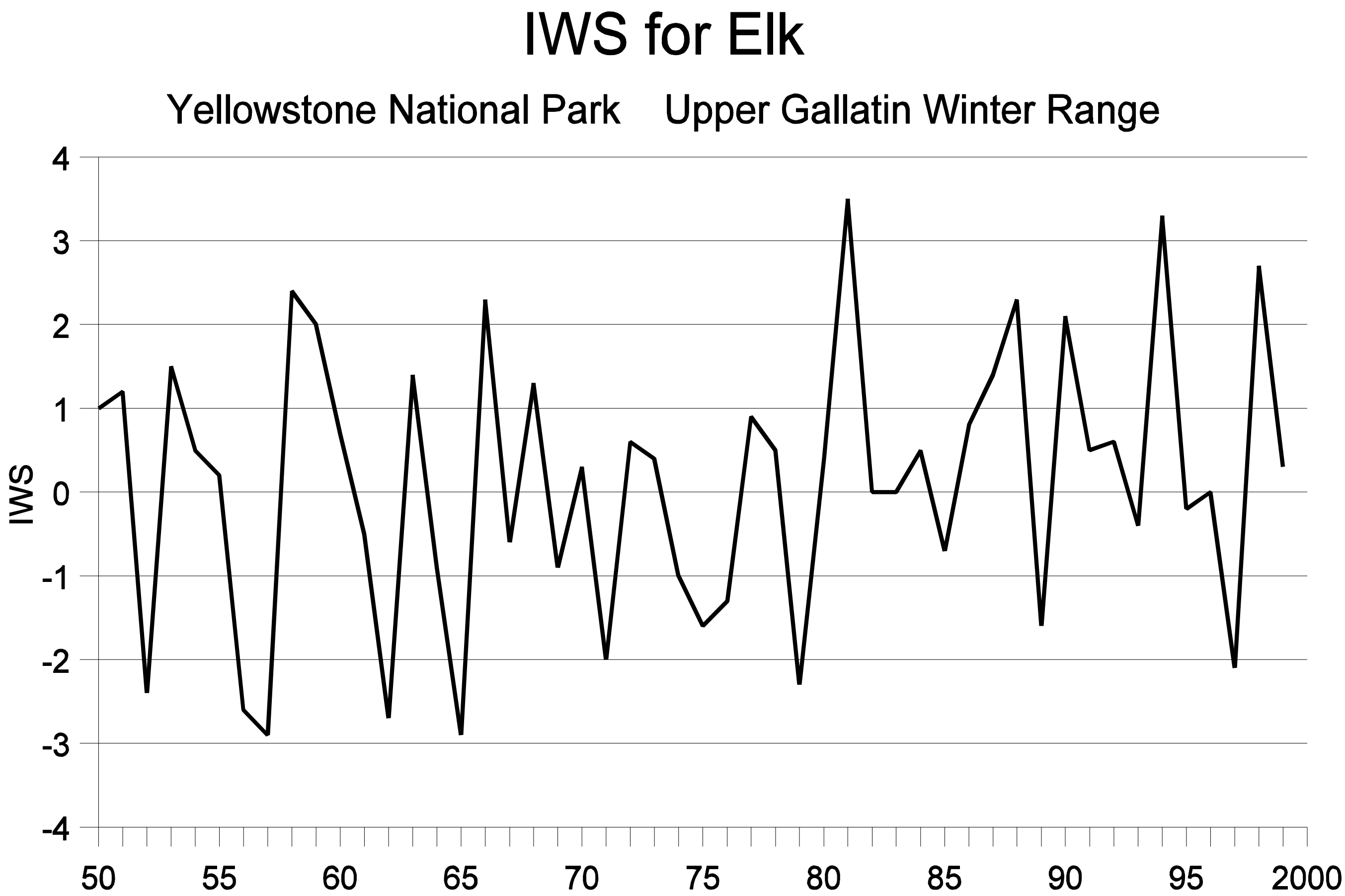

Figure 11. Index of winter severity (IWS) for elk for the winters of 1950-1999 for the Upper Gallatin Winter Range in and near Yellowstone National Park.

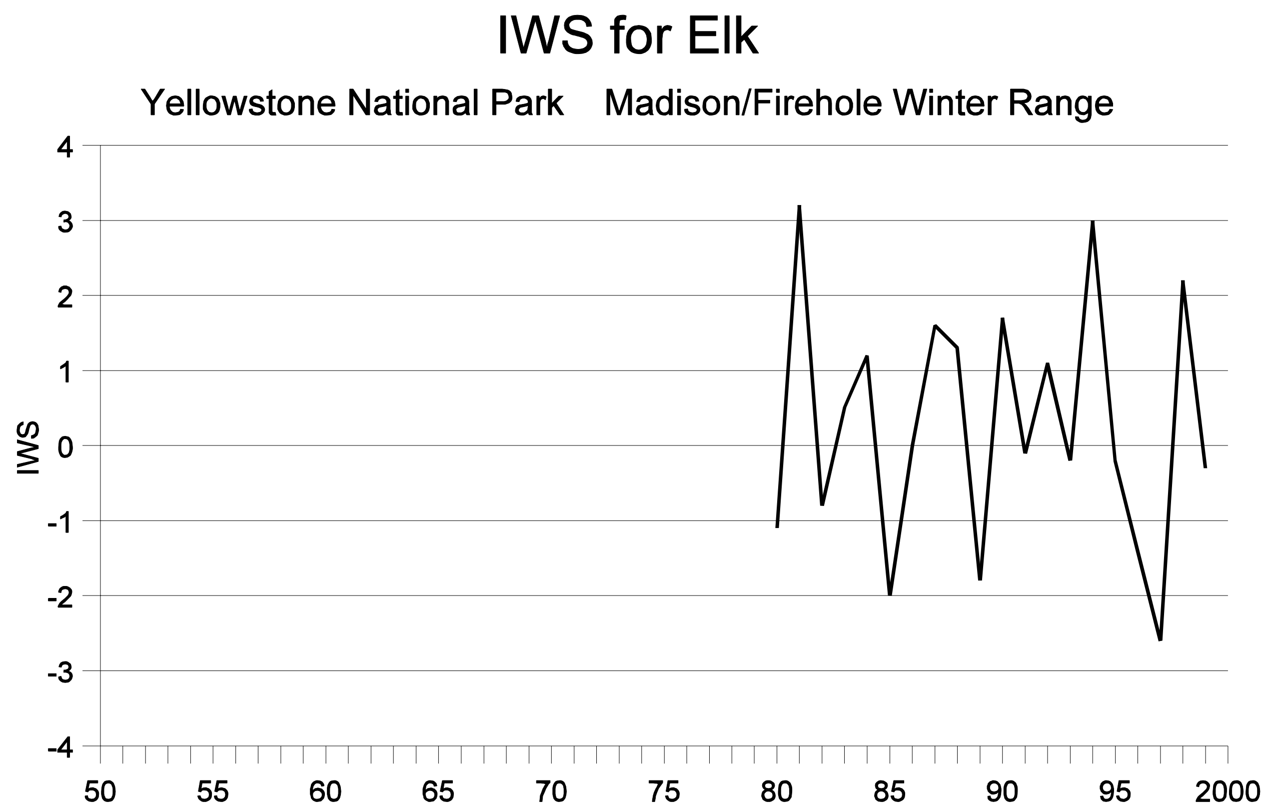

Figure 12. Index of winter severity (IWS) for elk for the winters of 1980-1999 for the Madison/Firehole Winter Range in and near Yellowstone National Park.

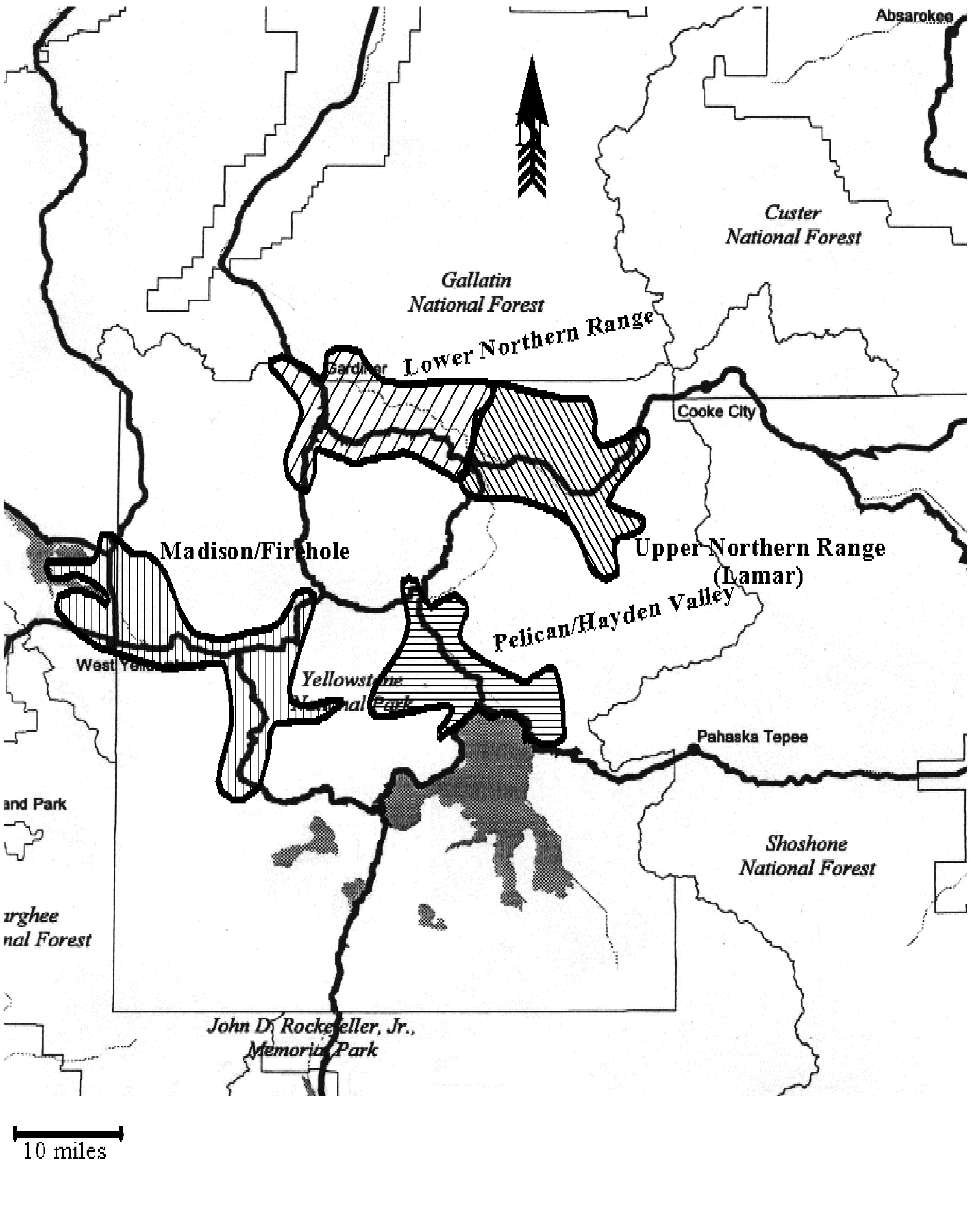

Figure 13. General location of bison winter ranges in Yellowstone National Park where index of winter severity is calculated.

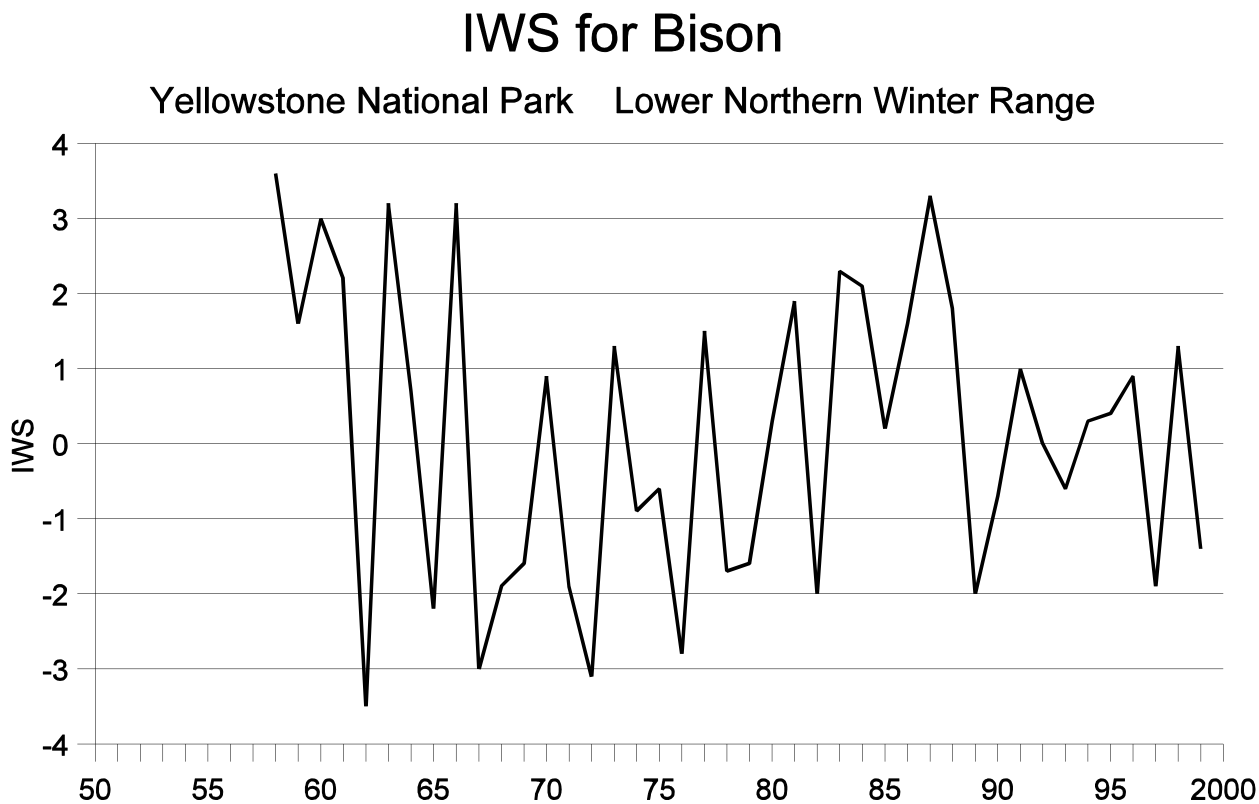

Figure 14. Index of winter severity (IWS) for bison for the winters of 1958-1999 for the Lower Northern Winter Range in Yellowstone National Park.

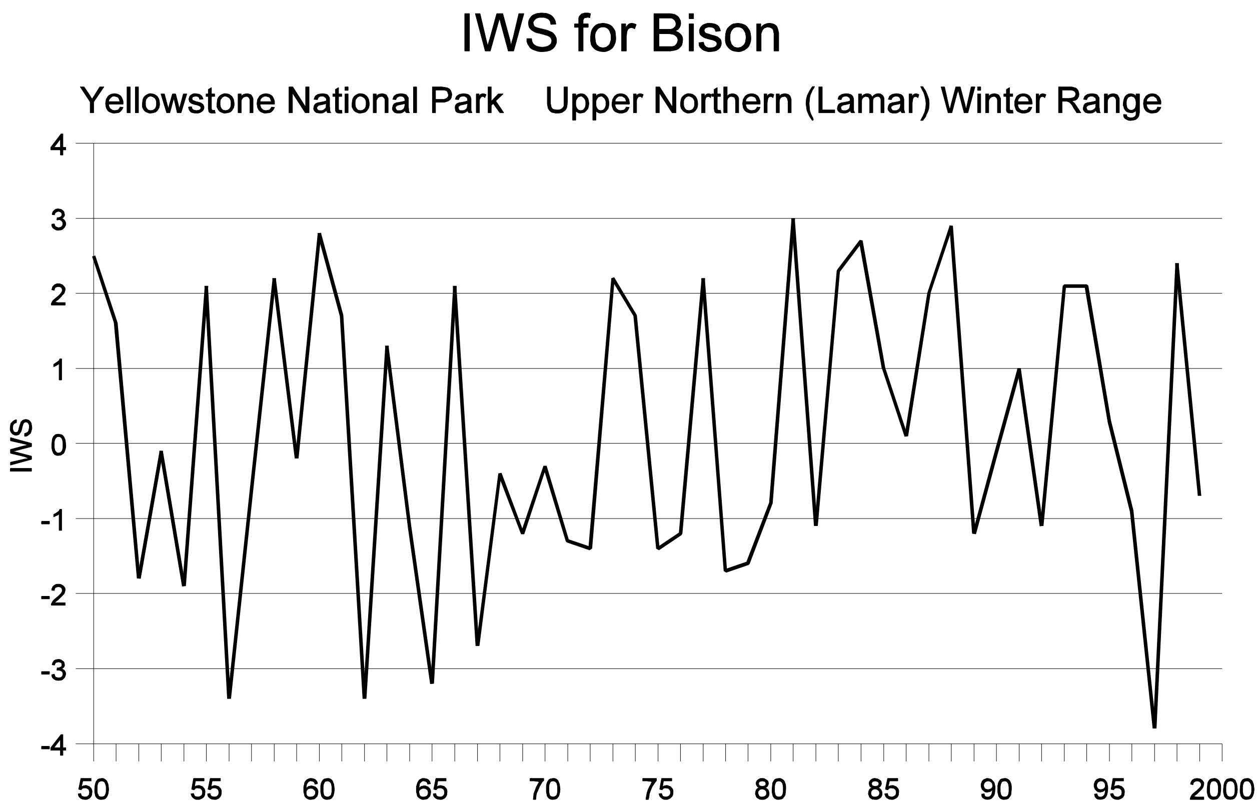

Figure 15. Index of winter severity (IWS) for bison for the winters of 1950-1999 for the Upper Northern (Lamar) Winter Range in Yellowstone National Park.

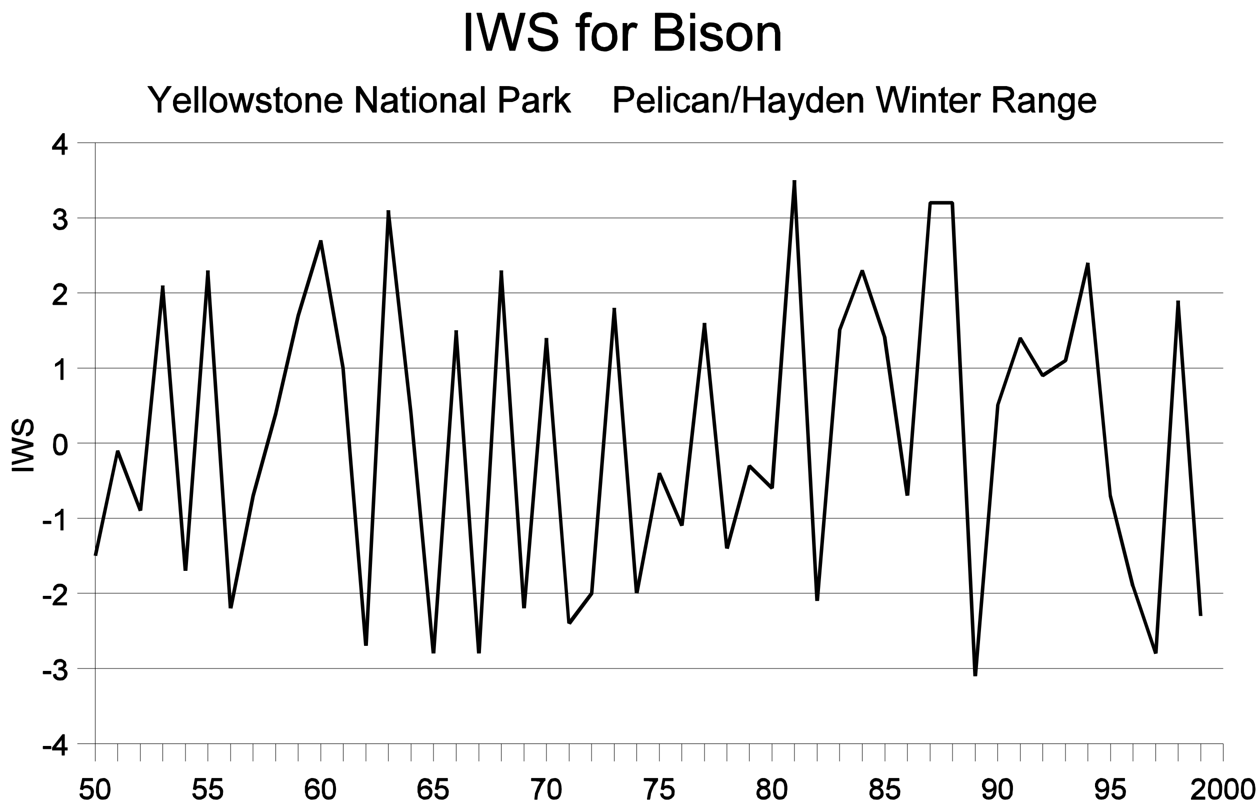

Figure 16. Index of winter severity (IWS) for bison for the winters of 1950-1999 for the Pelican/Hayden Valley Winter Range in Yellowstone National Park.

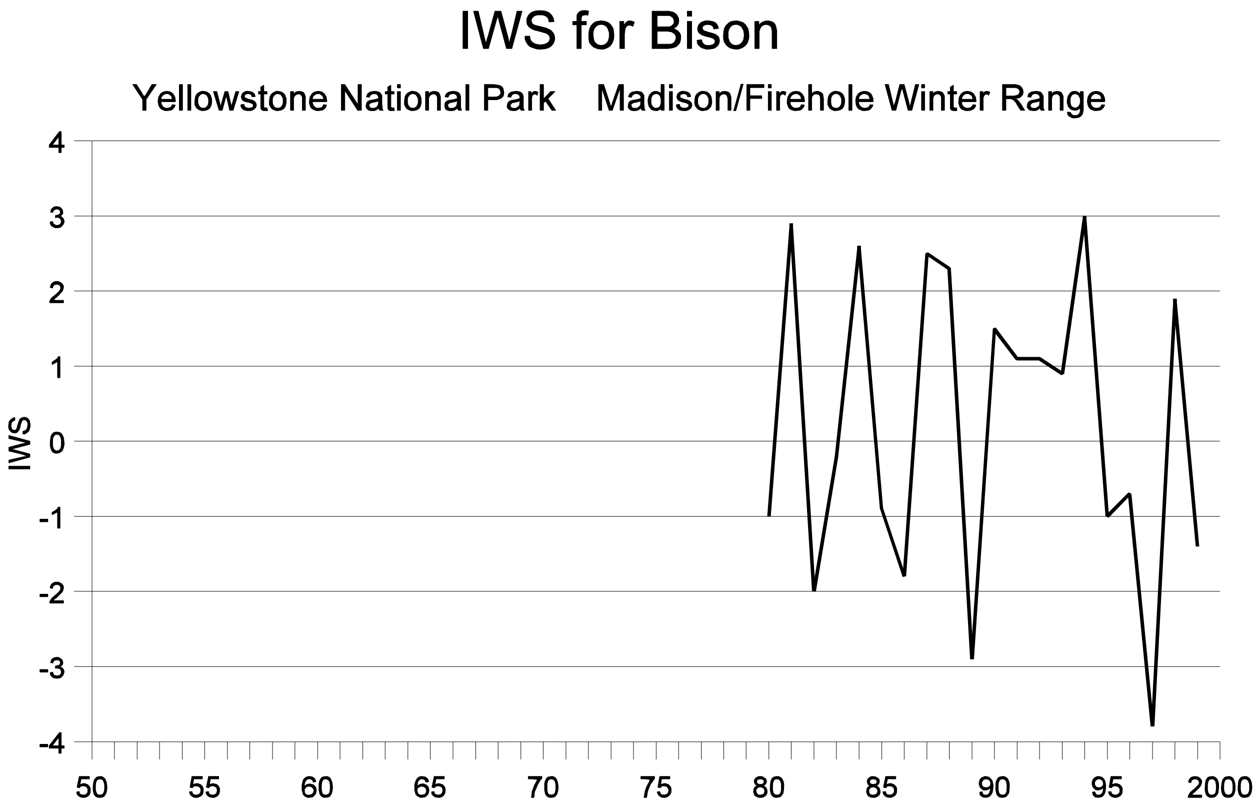

Figure 17. Index of winter severity (IWS) for bison for the winters of 1980-1999 for the Madison/Firehole Winter Range in and near Yellowstone National Park.

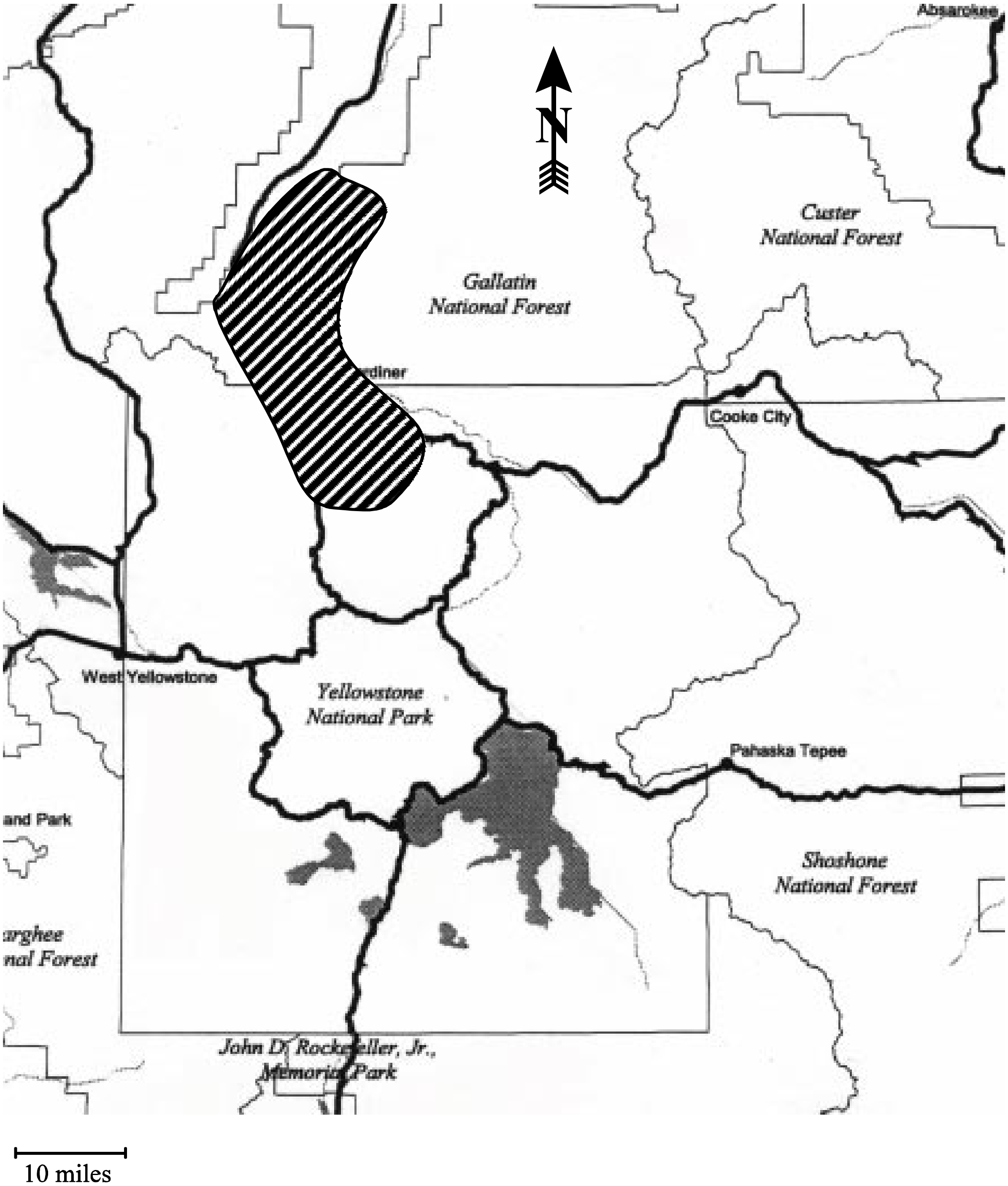

Figure 18. General location of mule deer northern winter range in and adjacent to Yellowstone National Park where index of winter severity (IWS) is calculated.

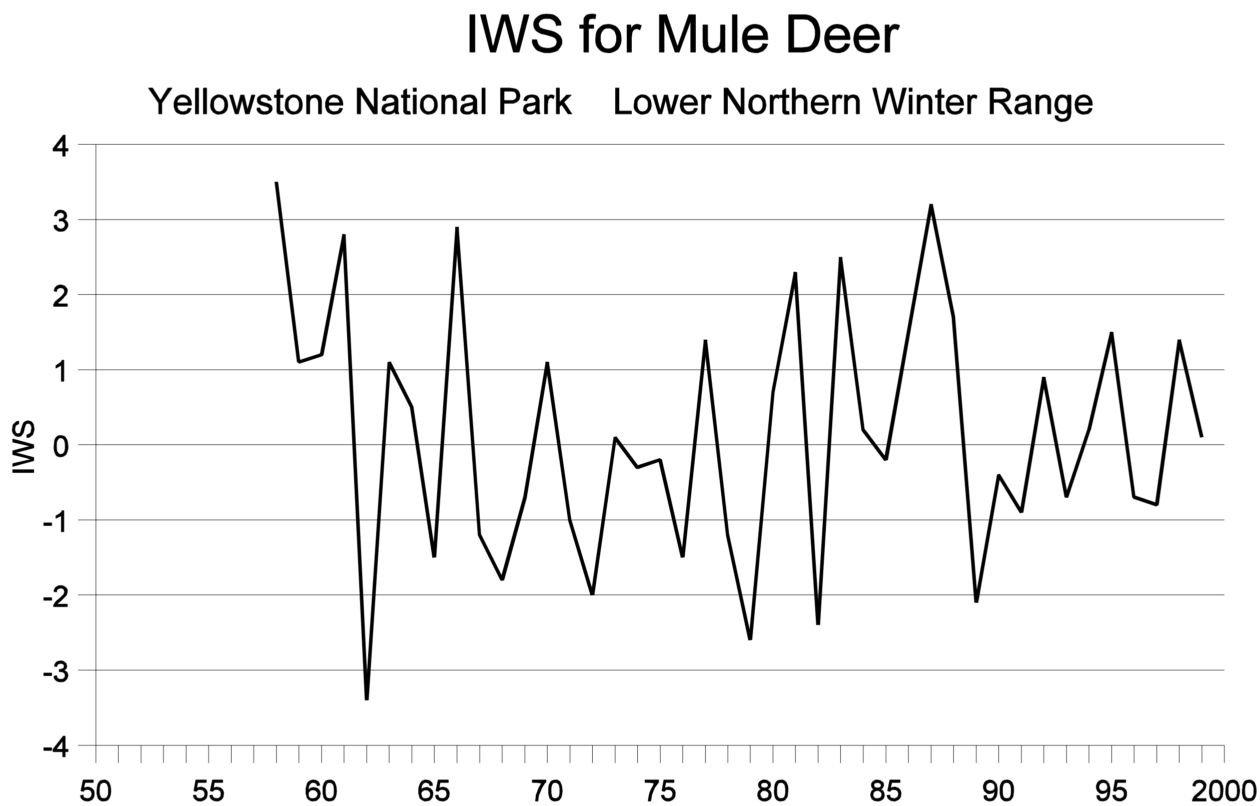

Figure 19. Index of winter severity (IWS) for mule deer for the winters of 1958-1999 for the Lower Northern Winter Range in and near Yellowstone National Park.

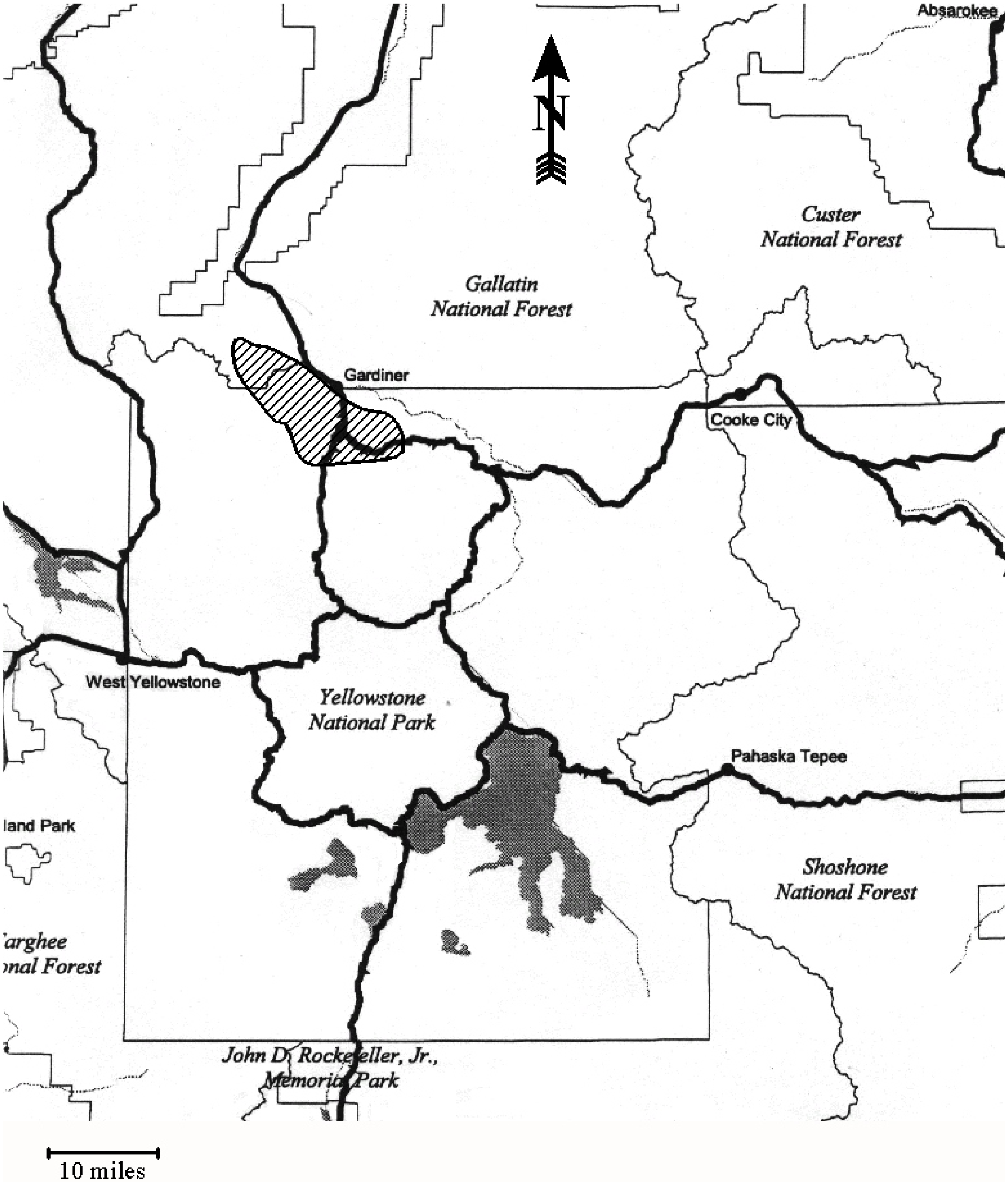

Figure 20. General location of pronghorn northern winter range in and adjacent to Yellowstone National Park where winter severity is calculated.

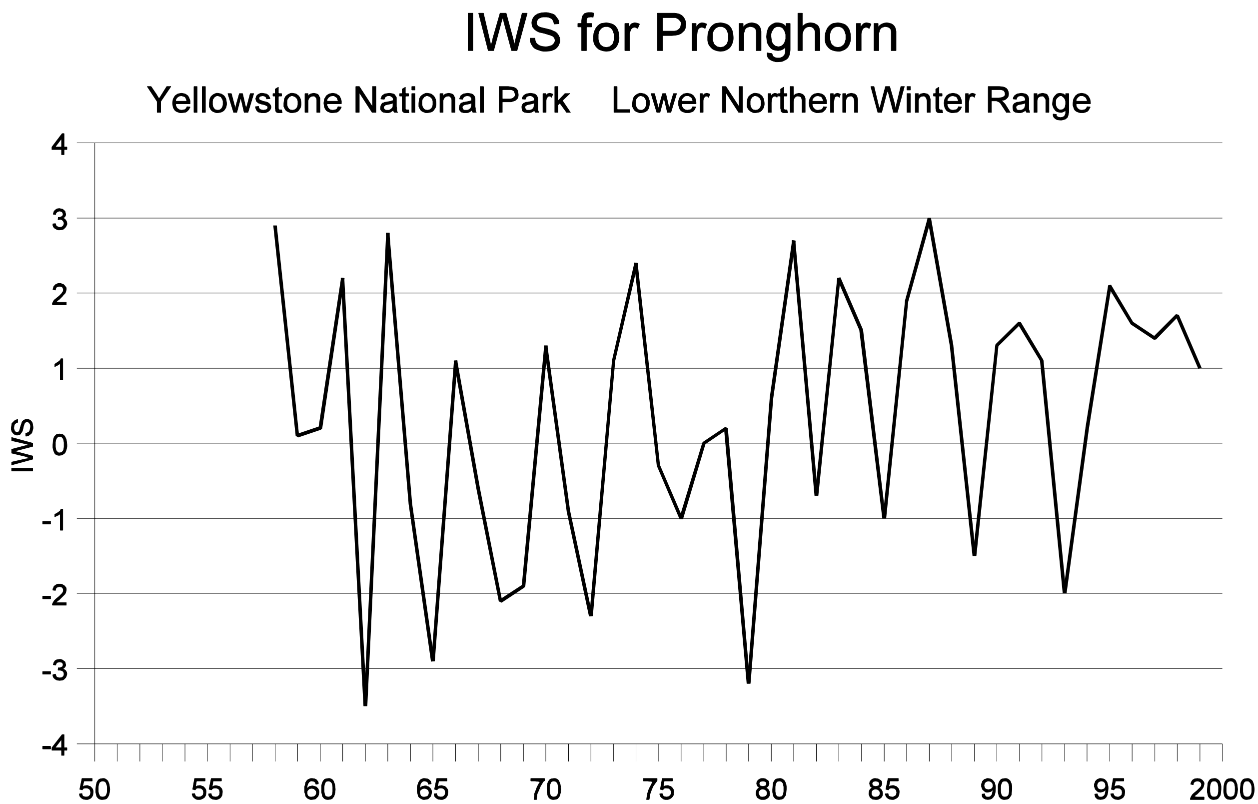

Figure 21. Index of winter severity (IWS) for pronghorn for the winters of 1958-1999 for the Lower Northern Winter Range in and near Yellowstone National Park.

PROCESSING CURRENT DATA

Data Sources

SNOTEL, snow course, and historical climatological data can be downloaded from the NRCS computer in Portland, Oregon. A no-cost agreement and password are needed from the NRCS State Conservationist in Casper, Wyoming, or Bozeman, Montana. Arrangements for this agreement can be made through the Wyoming NRCS state office by contacting Dave Taylor or Terry Gonzolas (phone: 307-261-6496) in Casper or through the Montana NRCS state office by contacting Roy Kaiser (phone: 406-587-6991) or Jerry Beard (phone: 406-587-6844). Near real-time daily data is available for the SNOTEL sites. It should be noted that daily SNOTEL data in the Portland database are for the previous 24-hour period. Current snow course data can be downloaded soon after the first-of-the-month surveys from January through May (not all of these sites are measured in January, February, and May). SWE is measured and reported for SNOTEL sites and snow courses, and values are reported in inches. Air temperatures at SNOTEL sites are in ^{o}C.

Climatological (CLIM) station data is observed daily and recorded manually on B-91 forms. At the end of each month, B-91s for sites within the study area are mailed to NWS in Riverton, Wyoming, Billings, Montana, or Great Falls, Montana. For stations within Yellowstone National Park, copies are also sent to the Chief Ranger’s office in Mammoth (YNP). This data is not usually available electronically until approximately a year after collection. Because of near-real-time availability of SNOTEL records, it is recommended that Snake River Station SNOTEL data be used instead of the data from the CLIM station at Snake River. To use current data from the B-91s, it is necessary to input this raw data into electronic form. CLIM station data are also available from Western Regional Climate Center in Reno, Nevada. SWE must be calculated at CLIM sites using snow depth, precipitation, and temperature observations. Observations at CLIM stations are reported in inches and ^{o}F.

Estimating Missing Data

SNOTEL records were usually complete with estimates of any missing values and edits made by NRCS. For CLIM sites, missing values were not estimated by NWS. Correlations have been run between stations, and missing values were estimated from these relationships for temperature and precipitation.

Generally, estimates of snow depth at CLIM sites were made using records before and after the missing period and extrapolating values based on trends at adjacent stations.

Conversion to Degree Fahrenheit

SNOTEL sites currently report temperature values in $^{\circ}$C. All TMax and TMin values for SNOTEL sites were converted to $^{\circ}$F using the standard conversion equation ($^{\circ}F = 1.8 \times {}^{\circ}C + 32$). This was done to ensure compatibility with CLIM station data, which is in $^{\circ}$F.

TAvg reported for SNOTEL sites is the average of 96 temperature observations (every 15 minutes) over a 24-hour period. To be compatible with CLIM station temperature data, TAvg for SNOTEL sites was calculated as the average of the TMax and TMin values rather than using the reported TAvg values.

Calculating Estimated SWE at CLIM Stations

A program has been written to calculate SWE and densities using data obtained at CLIM stations (Table 4). These calculations were made after all missing data had been estimated. See page 11 for procedure used to estimate SWE.

REFERENCES

Armleder, H. M.; Waterhouse, M. J.; Keisker, D. G.; Dawson, R. J. 1994. Winter habitat use by mule deer in the center interior of British Columbia. Can. J. Zool. 72: 1721-1725.

Bunnell, F. L.; Hovey, F. W.; NcNay, R. S.; Parker, K. L. 1990. Forest cover, snow conditions, and black-tailed deer sinking depths. Can. J. Zool. 68: 2403-2408.

Chappel, R. W.; Hudson, R. J. 1980. Prediction of energy expenditure by Rocky Mountain bighorn sheep. Can. J. Zool. 58: 1908-1912.

Christopherson, R. J.; Hudson, R. J.; Christophersen, M. K. 1979. Seasonal energy expenditures and thermoregulatory response of bison and cattle. Can. J. Anim. Sci. 59: 611-617.

Codd, A. R. 1959. The Photocanopyometer. In: Stockwell, H. J.; Van de Erve, J.; Mayo, F. T.; Hall, N. S., Publ. Comm. Proceedings: 27th Annual Western Snow Conference; 21-23 April 1959; Reno, NV. Fort Collins, CO: Colorado State University: 17-22.

Despain, D. G. 1990. Yellowstone vegetation consequences of environment and history in a natural setting. Boulder, CO: Roberts-Rinehart. 239 p.

Farnes, P. E. 1971. Mountain precipitation and hydrology from snow surveys. In: Washichek, J. N.; Peak, G.; Davis, R. T., eds. Proceedings: 39th Annual Western Snow Conference; 20-22 April 1971; Billings, MT. Fort Collins, CO: Colorado State University: 44-49.

Farnes, P. E. 1978. Preliminary report: hydrology of mountain watersheds. Bozeman, MT: U.S. Department of Agriculture, Soil Conservation Service. 7 p.

Farnes, P. E. 1989. Relationships between snow water equivalents in burned and unburned areas, cover types, canopy cover, and basal area. Unpublished data on file at Forestry Sciences Laboratory, Bozeman, MT.

Farnes, P. E. 1995. Estimating distribution of average annual precipitation in mountainous areas of Montana. In: Troendle, C.; Marron, J.K., eds. Proceedings: 63rd Annual Western Snow Conference; 17-20 April 1995; Sparks, Nevada. Fort Collins, CO: Colorado State University: 78-87.

Farnes, P. E. 1999. Unpublished data on file at USDA, Natural Resources and Conservation Service, Snow Survey, Bozeman, MT.

Farnes, P. E.; Goodison, B. E.; Peterson, N. R.; Richards, R. P. 1983. Metrication of manual snow sampling equipment - Final Report. Portland, OR: Western Snow Conference. 106 p.

Farnes, P. E.; Romme, W. H. 1993. Estimating localized SWE on the Yellowstone Northern Range. In: Ferrick, M.; Pangburn, T., eds. Presented at the Joint Eastern-Western Snow Conference; 8-10 June 1993; Quebec City, Quebec: 59-65.

Farnes, P. E.; Shearer, R. C.; Hansen, K. J. 1995. Correlating weather with survival and maturity of western larch cones. Bozeman, MT: Montana State University, Department of Earth Sciences, Final Report INT-94895-RJVA. 49 p.

Farnes, P. E.; Heydon, C. L.; Hansen, K. J. 1999. Snowpack distribution in Grand Teton National Park and Snake River drainage above Jackson, Wyoming. Bozeman, MT: Montana State University, Department of Earth Sciences; Final Report Cooperative Agreement CA 1268-1-9017. 55 p.

Fischer, A.; Gosson, H. 1987. Untersuchungen zur Raum-Zeit-Nutzung des Rotwildes angesichts menschlicher Storeinflusse, unter besonderer Berucksichtigung der Wintersituation: Fallstudie St. Anton am Arlberg. Centralbl; Gesamte Forstwes, 104: 191-218.

Formozov, A. N. 1946. Snow cover as an integral factor of the environment and its importance in the ecology of mammals and birds (translated from Russian). In: Fauna and Flora of the USSR. N.S. Zool. No. 5 (XX), 1946. Occas. Pap. No. 1, Boreal Institute, University of Alberta, Edmonton.

Gese, E. M.; Grothe, S. 1995. Analysis of coyote predation on deer and elk during winter in Yellowstone National Park, WY. Am. Midl. Nat. 133: 36-43.

Goodson, N. J.; Stevens, D. R.; Bailey, J. A. 1991. Effects of snow on foraging ecology and nutrition of bighorn sheep. J. Wildl. Manage. 55(2): 214-222.

Halfpenny, J. C.; Ozanne, R. D. 1989. Winter: An Ecology Handbook. Boulder, CO: Johnson Publishing Co. 273 p.

Hardy, J. P.; Hansen-Bristow, K. J. 1990. Temporal accumulation and ablation patterns of the seasonal snowpack in forest representing varying stages of growth. In: Shafer, B.; Marron, J. K.; Troendle, C., eds. Proceedings: 58th Annual Western Snow Conference; 17-19 April 1990; Sacramento, CA. Fort Collins, CO: Colorado State University: 23-24.

Houston, D. B. 1982. The Northern Yellowstone Elk, Ecology and Management. New York, NY: MacMillan Publishing Co. Inc. 474 p.

Huggard, D. J. 1993. Effect of snow depth on predation and scavenging by gray wolves. J. Wildl. Manage. 57(2): 382-388.

Keetch, J. J.; Byram, G. M. 1988. A drought index for forest fire control. Res. Pap. SE-32. Ashland, SC: U.S. Department of Agriculture, Forest Service, Southern Forest and Experiment Station. 32 p.

Kelsall, J. P. 1969. Structural adaptations of moose and deer for snow. J. of Mammology. 50: 302-310.

Kelsall, J. P.; Prescott, W. 1971. Moose and deer behavior in snow in Fundy National Park, New Brunswick. Can. Wildl. Serv. Rep. Ser. No. 15. 41 p.

Krog, H.; Monson, M. 1954. Notes on the metabolism of a mountain goat. Am. J. Physiol. 178: 515-516.

Larter, N. C.; Gates, C. C. 1991. Diet and habitat selection of wood bison in relation to seasonal changes in forage quantity and quality. Can. J. Zool. 69: 2677-2685.

Mautz, W. W.; Perkins, P. J.; Warren, J.A. 1985. Cold temperature effects on metabolic rate of white-tailed, mule, and black-tailed deer in winter coat. Biology of Deer Production, The Royal Society of New Zealand, Bulletin 22: 453-457.

McCaughey, W. W.; Farnes, P. E.; Hansen, K. J. 1997. Historic role of fire in determining annual water yield from Tenderfoot Creek Experimental Forest, Montana, USA. In: Proceedings: 65th Annual Western Snow Conference; 4-8 May 1997; Banff, Alberta. Hydrology C6U: 52-60.

Mech, L. D. 1970. The wolf: ecology and behavior of an endangered species. New York, NY: Doubleday Press. 384 p.

Mech, L. D.; McRoberts, R. E.; Peterson, R. O.; Page, R. E. 1987. Relationship of deer and moose populations to previous winters' snow. J. of Animal Ecol. 56: 615-627.

Moore, C. A.; McCaughey, W. W. 1997. Snow accumulation under various forest stand densities at Tenderfoot Creek Experimental Forest, Montana, USA. In: Proceedings: 65th Annual Western Snow Conference; 4-8 May 1997; Banff, Alberta. Hydrology C6U: 42-51.

Nelson, J. R.; Leege, T. A. 1982. Nutritional requirements and food habits. In: Thomas, J. W.; Toweill, D. E., eds. Elk of North America, Ecology and Management. Harrisburg, PA: Stockpole Books: 323-367.

Parker, K. L.; Gillingham, M. P.; Hanley, T.A.; Robbins, C. T. 1999. Energy and protein balance of free-ranging black-tailed deer in a natural forest environment. Wildlife Monographs 143. The Wildlife Society. 48 p.

Pauley, G. R.; Peek, J. M.; Zager, P. 1993. Predicting white-tailed deer habitat use in northern Idaho. J. Wildl. Manage. 57(4): 904-913.

Rudd, W. J., Ward, A. L., and Irwin, L. 1983. Do split hunting seasons influence elk migrations from Yellowstone National Park? Wildl. Soc. Bull. 11: 328-331.

Schmidt, K. 1993. Winter ecology of nonmigratory alpine red deer. Oecologia. 95: 226-233.

Schwab, F. E.; Pitt, M. O. 1991. Moose selection of canopy cover types related to operative temperature forage, and snow depth. Can J. Zool. 69: 3071-3077.

Shafer, B. A.; Dezman, L. E. 1982. Development of a surface water supply index (SWSI) to assess the severity of drought conditions in snowpack runoff areas. In: Shafer, B. A.; Davis, R. T.; Meiman, J. R., eds. Proceedings: 50th Annual Western Snow Conference; 19-23 April 1982; Reno, NV. Fort Collins, CO: Colorado State University: 164-175.

Skidmore, P.; Hansen, K. J.; Quimby, W. 1994. Snow accumulation and ablation under fire-altered lodgepole pine forest canopies. In: Troendle, C.; Marron, J. K., eds. Proceedings: 62nd Annual Western Snow Conference; 18-21 April 1994; Santa Fe, NM. Fort Collins, CO: Colorado State University: 43-52.

Skovlin, J. M. 1982. Habitat requirements and evaluations. In: Thomas, J. W. and Toweill, D. E., eds., Elk of North America, Ecology and Management. Wildlife Management Institute Book. Harrisburg, PA: Stockpole Books: 219-277.

Sowell, B. 1999. (Personal communication). March 4. Bozeman, MT: Montana State University Department of Animal and Range Sciences.

Van Soest, P. J. 1982. Nutritional ecology of ruminants. Corvallis, OR: O and B Books: 350 pp.

Walker, M. D.; Webber, P. J.; Arnold, E. H.; Ebert-May, D. 1994. Effects of interannual climate variation on above ground phytomass in alpine vegetation. Ecology. 75(2): 393-408.

Wallace, L. L., Turner, M. G., Romme, W. H., O'Neil, R. V., and Wu, Y. 1995. Scale of heterogeneity of forage production and winter foraging by elk and bison. Landscape Ecology. 10(2): 75-83.

Wambolt, C. L. 1998. Sage brush and ungulate relationships on Yellowstone's northern range. Wildlife Society Bulletin. 26(3): 429-437.

Ward, R. L. 1999. The occurrence of two genera of arboreal licken and their utilization by deer and elk on selected winter ranges in west-central Montana. Missoula, MT: University of Montana. 88 p. Thesis.

Wesley, D. E.; Knox, K. L.; Nagy, J. G. 1973. Energy metabolism of pronghorn antelopes. J. Wildl. Manage. 37(4): 563-573.

APPENDIX

Appendix 1. Average January 1, February 1, March 1, April 1, and May 1 snow water equivalent for active snow pillows, snow courses and climatological stations in and adjacent to Yellowstone National Park, Wyoming, for 1961-1990 base period.

Site No.	Site Name	1961-1990 Average SWE inches				
		Jan 1	Feb 1	Mar 1	Apr 1	May 1
SNOW PILLOWS						
09E10S	Beartooth Lake	11.5	16.0	19.9	23.8	26.0
11E35S	Black Bear	15.6	24.5	31.7	38.5	39.8
10E03S	Canyon	5.6	8.8	11.3	13.8	11.5
09E11S	Evening Star	12.9	17.8	22.5	27.2	30.8
09D06S	Fisher Creek	15.6	24.2	30.3	36.1	38.7
10E15S	Grassy Lake	14.3	23.0	29.6	36.3	33.9
10E09S	Lewis Lake Divide	13.8	22.8	29.5	35.7	34.4
11E31S	Madison Plateau	10.1	16.1	20.6	24.8	23.8
10D12S	Monument Peak	9.5	13.9	17.8	21.4	23.8
10D07S	Northeast Entrance	5.0	8.0	10.0	11.3	7.1
09E07S	Parker Peak	10.6	14.3	18.0	21.8	23.7
10D16S	Shower Falls	10.4	14.8	18.8	23.8	28.0
10E12S	Snake River Station	7.9	12.6	15.7	17.6	9.3
10E06S	Sylvan Lake	10.8	14.9	18.5	22.3	23.8
10E20S	Sylvan Road	5.8	8.5	11.2	12.5	7.9
10E07S	Thumb Divide	7.2	11.4	14.3	17.2	15.1
10E19S	Two Ocean Plateau	12.9	18.2	22.4	25.3	27.6
11E07S	West Yellowstone	4.2	6.4	8.2	9.1	4.5
11E30S	Whiskey Creek	7.0	11.2	14.5	17.5	15.2
09D08S	White Mill	11.4	16.8	21.2	25.1	26.3
09F18S	Younts Peak	8.9	12.2	14.8	17.3	18.3
SNOW COURSE*						
10E08	Aster Creek, WY	12.0	18.8	23.8	28.9	NM
10D05	Crevice Mountain, MT	NM	6.3	8.2	9.9	NM
11E05	Hebgen Dam, MT	4.5	7.6	9.8	11.0	6.2
10E04	Lake Camp, WY	3.6	5.7	7.7	9.3	6.8
10E01	Lupine Creek, WY	4.0	6.5	8.4	9.6	6.2
10E19	Norris Basin, WY	4.7	7.5	9.3	10.8	7.0
10E18	Old Faithful, WY	6.0	10.2	12.9	13.9	9.4
11D21	Rock Creek Meadows, MT	NM	NM	15.8	20.0	22.0
11E06	Twenty-one Mile, MT	6.6	10.6	13.6	15.8	13.5
CLIMATOLOGICAL STATION						
MT1995	Cooke City, 2W	See Northeast Entrance Snow Pillow				
MT3378	Gardiner	Not Calculated - Normally near zero				
MT4038	Hebgen Dam	5.7	9.0	11.6	12.2	3.2
WY5345	Lake Yellowstone	3.7	5.7	7.2	8.2	4.9
WY5355	Lamar RS	1.5	2.4	3.0	1.8	0.1
WY6845	Old Faithful	5.3	8.1	10.0	10.4	4.8
WY8315	Snake River	See Snake River Station Snow Pillow				
WY9025	Tower Falls	2.2	3.6	4.3	2.8	0.2
WY9905	Yellowstone Park (Mammoth)	1.2	2.1	2.1	0.6	0.0

NM = Not regularly measured on this date.

* Adjusted to represent "true" SWE, 0.91 X Montana Sites and 0.94 X Wyoming Sites

Appendix 2. Summary of snow accumulation, growing degree-days and KBDI for sites in and adjacent to Yellowstone National Park, Wyoming, for sites having daily climatological data.

		1961-1990 Average Snow Accumulation				
Site No.	Site Name	Day Snow Starts	Max SWE (inches)	Day Max SWE	Day Snow Ends	Days with Snow Cover
09E10S	Beartooth Lake	10/04	27.6	5/02	6/26	267
11E35S	Black Bear	10/12	43.5	4/19	6/20	253
10E03S	Canyon	10/25	14.9	4/08	5/26	215
MT1995	Cooke City, 2W	See Northeast Entrance				
09E11S	Evening Star	10/08	32.7	5/09	6/27	264
09D06S	Fisher Creek	10/07	41.0	4/30	6/30	268
MT3378	Gardiner	Intermittent Snow Pack - Not Calculated				
11E15S	Grassy Lake	10/22	38.3	4/11	6/06	229
MT4038	Hebgen Dam	11/09	13.6	3/26	5/01	176
WY5345	Lake Yellowstone	11/04	8.9	4/06	5/14	196
WY5355	Lamar RS	11/21	3.3	3/17	4/13	154
10E09S	Lewis Lake Divide	10/27	37.9	4/17	6/11	229
11E31S	Madison Plateau	10/15	26.6	4/13	6/05	235
10D12S	Monument Peak	10/09	26.6	4/30	6/22	258
10D07S	Northeast Entrance	11/01	12.4	4/07	5/16	198
WY6845	Old Faithful	11/07	11.7	3/26	5/11	190
09E07S	Parker Peak	10/02	35.8	5/04	6/25	268
10D16S	Shower Falls	10/05	31.4	5/07	6/29	269
10E12S	Snake River Station	11/06	19.0	4/03	5/12	189
10E06S	Sylvan Lake	10/15	26.3	4/28	6/12	242
10E20S	Sylvan Road	10/23	13.2	4/11	5/16	207
10E07S	Thumb Divide	10/25	18.5	4/17	5/25	214
WY9025	Tower Falls	11/15	4.8	3/13	4/18	158
10E19S	Two Ocean Plateau	10/07	29.6	5/08	7/02	270
11E07S	West Yellowstone	10/31	9.9	4/01	5/10	193
11E30S	Whiskey Creek	10/23	18.7	4/09	5/24	215
09D08S	White Mill	10/13	28.1	4/23	6/27	259
WY9905	Yellowstone Park (Mammoth)	11/27	3.0	2/26	3/23	128
09F18S	Younts Peak	10/09	19.4	4/29	6/08	244

Appendix 2 (cont.)

1961-1990 Average accumulation of growing degree-days (above 41°F)
after snow is zero and after three conservative days with Tavg above 41°F.

Site No.	Site Name	Start Accum.	Day 750GDD	May 1	Jun 1	Jul 1	Aug 1	Sep 1	Sep 30
09E10S	Beartooth Lake	6/29	9/14	0	0	69	279	534	605
11E35S	Black Bear	6/25	9/01	0	0	104	464	856	1011
10E03S	Canyon	6/01	8/06	0	24	238	685	1077	1244
MT1995	Cooke City, 2W			See Northeast Entrance					
09E11S	Evening Star	6/30	9/10	0	0	86	309	605	707
09D06S	Fisher Creek	7/03	9/12	0	0	70	292	602	719
MT3378	Gardiner	4/05	6/16	140	496	1105	1962	2756	3219
11E15S	Grassy Lake	6/09	8/02	0	0	204	728	1183	1400
MT4038	Hebgen Dam	5/08	7/12	10	160	555	1181	1753	2042
WY5345	Lake Yellowstone	5/25	8/07	1	30	250	685	1068	1214
WY5355	Lamar RS	4/30	7/23	17	117	417	908	1331	1512
10E09S	Lewis Lake Divide	6/14	7/24	0	0	285	883	1417	1688
11E31S	Madison Plateau	6/09	8/24	0	0	168	594	993	1147
10D12S	Monument Peak	6/25	8/25	0	0	99	470	868	1022
10D07S	Northeast Entrance	5/25	8/15	1	35	240	634	967	1099
WY6845	Old Faithful	5/18	7/27	3	63	356	846	1256	1416
09E07S	Parker Peak	6/29	9/03	0	0	73	328	631	754
10D16S	Shower Falls	7/01	8/25	0	0	64	296	601	742
10E12S	Snake River Station	5/18	7/18	0	72	420	975	1462	1680
10E06S	Sylvan Lake	6/15	8/19	0	8	137	514	882	1022
10E20S	Sylvan Road	5/23	7/24	0	58	401	884	1315	1491
10E07S	Thumb Divide	5/28	8/01	0	0	272	752	1164	1345
WY9025	Tower Falls	5/01	7/17	11	148	485	1029	1517	1743
10E19S	Two Ocean Plateau	7/05	9/23	0	0	0	323	655	788
MT8859	West Yellowstone 9N	5/12	7/16	5	121	483	1071	1577	1791
11E30S	Whiskey Creek	6/07	8/13	0	27	227	640	997	1121
09D08S	White Mill	6/30	9/08	0	0	65	289	569	667
WY9905	Yellowstone Park (Mammoth)	4/17	7/02	51	274	741	1451	2098	2439
09F18S	Younts Peak	6/11	8/09	0	0	169	634	1043	1206

Appendix 2 (cont.)

1961-1990 Average daily, Keetch-Byram drought index
Maximum for Month

Site No.	Site Name	Apr	May	Jun	Jul	Aug	Sep	Avg 0-750 GDD	Max 0-750 GDD	Max Season
09E10S	Beartooth Lake	0	1	14	69	94	91	50	95	104
11E35S	Black Bear	0	2	91	255	357	369	199	350	385
10E03S	Canyon	2	19	82	195	270	238	96	211	282
MT1995	Cooke City, 2W				See Northeast Entrance					
09E11S	Evening Star	0	1	27	92	146	155	72	147	163
09D06S	Fisher Creek	0	0	38	114	179	177	91	163	197
MT3378	Gardiner	197	206	209	266	326	315	178	228	345
11E15S	Grassy Lake	0	14	130	377	478	435	172	380	483
MT4038	Hebgen Dam	12	44	98	222	299	275	43	149	318
WY5345	Lake Yellowstone	1	14	45	107	139	108	41	116	150
WY5355	Lamar RS	12	34	62	126	168	155	37	115	181
10E09S	Lewis Lake Divide	0	13	122	333	445	409	167	357	486
11E31S	Madison Plateau	0	19	63	213	301	311	129	252	326
10D12S	Monument Peak	0	0	37	125	188	190	83	154	208
10D07S	Northeast Entrance	8	19	51	110	136	105	41	118	149
WY6845	Old Faithful	8	28	75	176	238	247	61	172	263
09E07S	Parker Peak	0	0	17	72	101	97	45	101	118
10D16S	Shower Falls	0	0	37	164	223	240	127	228	264
10E12S	Snake River Station	2	29	111	258	333	316	87	232	352
10E06S	Sylvan Lake	0	9	63	188	242	260	122	236	280
10E20S	Sylvan Road	0	29	87	211	318	337	88	211	344
10E07S	Thumb Divide	0	14	83	224	298	280	108	257	339
WY9025	Tower Falls	10	32	67	145	200	196	31	111	222
10E19S	Two Ocean Plateau	0	0	18	125	189	169	97	208	217
MT8859	West Yellowstone 9N	3	30	84	186	248	232	42	142	267
11E30S	Whiskey Creek	0	20	95	216	304	316	115	269	329
09D08S	White Mill	0	0	37	137	223	241	128	220	245
WY9905	Yellowstone Park (Mammoth)	14	34	73	162	212	204	20	80	230
09F18S	Younts Peak	0	1	54	160	211	184	80	193	221

Appendix 3. Index of winter severity (IWS) values for Yellowstone National Park and adjacent winter ranges, 1950-1999, for winter seasons ending on April 1.

	Northern Range Montana	Lower Northern Range in YNP		Lower Northern Range		Upper Northern Range (Lamar)		Madison - Firehole		Upper Gallatin	Pelican-Hayden
Winter	Elk	Elk	Bison	Prong-horn	Mule Deer	Elk	Bison	Elk	Bison	Elk	Bison
49-50						2.6	2.5			1.0	-1.5
50-51						1.5	1.6			1.2	-0.1
51-52						-1.6	-1.8			-2.4	-0.9
52-53						0.9	-0.1			1.5	2.1
53-54						0.0	-1.9			0.5	-1.7
54-55						0.2	2.1			0.2	2.3
55-56						-2.8	-3.4			-2.6	-2.2
56-57						-1.7	-0.6			-2.9	-0.7
57-58	3.5	3.4	3.6	2.9	3.5	2.6	2.2			2.4	0.4
58-59	1.0	1.8	1.6	0.1	1.1	0.9	-0.2			2.0	1.7
59-60	0.9	1.2	3.0	0.2	1.2	1.0	2.8			0.7	2.7
60-61	2.8	2.3	2.2	2.2	2.8	1.6	1.7			-0.5	1.0
61-62	-3.5	-3.5	-3.5	-3.5	-3.4	-3.5	-3.4			-2.7	-2.7
62-63	0.7	1.3	3.2	2.8	1.1	0.3	1.3			1.4	3.1
63-64	0.6	0.7	0.7	-0.8	0.5	-0.7	-1.1			-0.9	0.4
64-65	-1.6	-2.6	-2.2	-2.9	-1.5	-3.0	-3.2			-2.9	-2.8
65-66	2.8	2.4	3.2	1.1	2.9	2.5	2.1			2.3	1.5
66-67	-1.0	-0.6	-3.0	-0.6	-1.2	-0.5	-2.7			-0.6	-2.8
67-68	-1.6	-0.4	-1.9	-2.1	-1.8	-0.3	-0.4			1.3	2.3
68-69	-0.6	-0.3	-1.6	-1.9	-0.7	-0.2	-1.2			-0.9	-2.2
69-70	1.1	0.5	0.9	1.3	1.1	0.6	-0.3			0.3	1.4
70-71	-0.9	-0.4	-1.9	-0.9	-1.0	-0.5	-1.3			-2.0	-2.4
71-72	-2.0	-0.6	-3.1	-2.3	-2.0	-0.4	-1.4			0.6	-2.0
72-73	-0.3	0.8	1.3	1.1	0.1	0.7	2.2			0.4	1.8
73-74	-0.3	-0.6	-0.9	2.4	-0.3	2.1	1.7			-1.0	-2.0
74-75	-0.2	-1.3	-0.6	-0.3	-0.2	-1.7	-1.4			-1.6	-0.4
75-76	-1.5	-0.2	-2.8	-1.0	-1.5	-1.4	-1.2			-1.3	-1.1
76-77	1.3	2.2	1.5	0.0	1.4	2.3	2.2			0.9	1.6
77-78	-1.0	-0.1	-1.7	0.2	-1.2	-0.1	-1.7			0.5	-1.4
78-79	-2.7	-3.1	-1.6	-3.2	-2.6	-2.5	-1.6			-2.3	-0.3
79-80	0.5	-0.4	0.3	0.6	0.7	-0.6	-0.8	-1.1	-1.0	0.4	-0.6
80-81	2.2	3.6	1.9	2.7	2.3	3.3	3.0	3.2	2.9	3.5	3.5
81-82	-2.5	-0.4	-2.0	-0.7	-2.4	-0.2	-1.1	-0.8	-2.0	0.0	-2.1
82-83	2.5	2.3	2.3	2.2	2.5	2.4	2.3	0.5	-0.2	0.0	1.5
83-84	-0.1	-0.1	2.1	1.5	0.2	0.5	2.7	1.2	2.6	0.5	2.3
84-85	-0.5	-0.9	0.2	-1.0	-0.2	-0.7	1.0	-2.0	-0.9	-0.7	1.4
85-86	1.4	0.8	1.6	1.9	1.5	0.5	0.1	0.0	-1.8	0.8	-0.7
86-87	3.1	1.2	3.3	3.0	3.2	0.5	2.0	1.6	2.5	1.4	3.2
87-88	1.6	1.6	1.8	1.3	1.7	1.8	2.9	1.3	2.3	2.3	3.2
88-89	-2.3	-2.2	-2.0	-1.5	-2.1	-1.5	-1.2	-1.8	-2.9	-1.6	-3.1
89-90	-0.4	0.6	-0.7	1.3	-0.4	0.3	-0.1	1.7	1.5	2.1	0.5
90-91	-1.2	-0.1	1.0	1.6	-0.9	0.1	1.0	-0.1	1.1	0.5	1.4
91-92	0.9	0.5	0.0	1.1	0.9	-0.7	-1.1	1.1	1.1	0.6	0.9
92-93	-0.9	0.4	-0.6	-2.0	-0.7	0.7	2.1	-0.2	0.9	-0.4	1.1
93-94	0.2	2.1	0.3	0.2	0.2	2.1	2.1	3.0	3.0	3.3	2.4
94-95	1.5	0.3	0.4	2.1	1.5	-0.1	0.3	-0.2	-1.0	-0.2	-0.7
95-96	-0.8	0.1	0.9	1.6	-0.7	-1.2	-0.9	-1.4	-0.7	0.0	-1.9
96-97	-0.7	-2.8	-1.9	1.4	-0.8	-2.7	-3.8	-2.6	-3.8	-2.1	-2.8
97-98	1.4	2.5	1.3	1.7	1.4	2.5	2.4	2.2	1.9	2.7	1.9
98-99	0.1	-0.1	-1.4	1.0	0.1	0.5	-0.7	-0.3	-1.4	0.3	-2.3