USDA United States Department of Agriculture

Forest Service

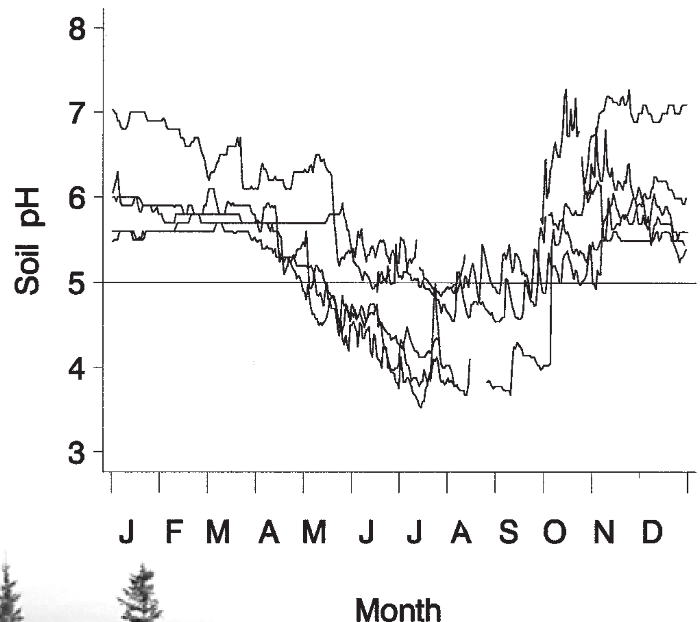
Rocky Mountain Research Station

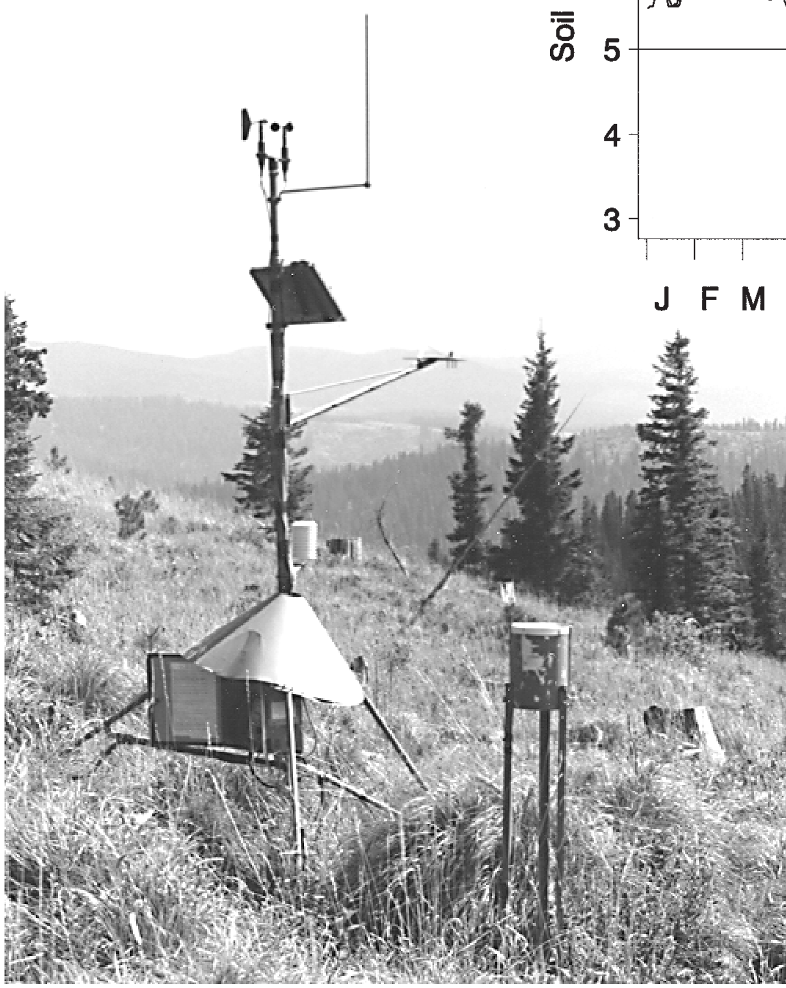
Research Paper RMRS-RP-24

May 2000

Environmental Characteristics of the Grand Fir Mosaic and Adjacent Habitat Types

Dennis E. Ferguson
John C. Byrne





Abstract

Ferguson, Dennis E.; Byrne, John C. 2000. Environmental characteristics of the Grand Fir Mosaic and adjacent habitat types. Research Paper RMRS-RP-24. Ft. Collins, CO: U.S. Department of Agriculture, Forest Service, Rocky Mountain Research Station. 20 p.

Grand Fir Mosaic habitats differ from adjacent forest habitats in their slow rate of secondary succession to woody vegetation. Remote monitoring stations were used to sample the environment at a Grand Fir Mosaic site and three adjacent habitat types. The Grand Fir Mosaic site has shorter growing seasons, cooler temperatures, and more soil moisture than the other sites. Soil pH at the Grand Fir Mosaic site cycled from 5.5 to 6.5 in winter months to 4.0 to 5.0 in summer months. These unique site and environmental characteristics are shown to cause highly acidic soils with high aluminum availability below pH 5.0.

Keywords: habitat types, forest succession, aluminum toxicity, allophanic soils, non-allophanic soils, soil pH, andisols, climate, weather data, environmental monitoring

Acknowledgments

We thank Dale O. (Duke) Coffen for his hard work installing the remote monitoring stations and for collecting as much data as possible. We also thank technical reviewers of an earlier draft of this paper: Paul A. McDaniel, Deborah S. Page-Dumroese, and David C. Powell.

The Authors

Dennis E. Ferguson is a research silviculturist with the Rocky Mountain Research Station in Moscow, Idaho.

John C. Byrne is a forester with the Rocky Mountain Research Station in Moscow, Idaho.

Contents

You may order additional copies of this publication by sending your mailing information in label form through one of the following media. Please specify the publication title and Research Paper number.

Fort Collins Service Center

Telephone (970) 498-1392

FAX (970) 498-1396

E-mail rschneider@fs.fed.us

Web site http://www.fs.fed.us/rm

Mailing Address Publications Distribution
Rocky Mountain Research Station
240 West Prospect Road
Fort Collins, CO 80526

Environmental Characteristics of the Grand Fir Mosaic and Adjacent Habitat Types

Dennis E. Ferguson
John C. Byrne

Introduction

Grand Fir Mosaic habitats are found in upland forests that form drainages of the Clearwater River in northern Idaho and in the Blue Mountains of northeastern Oregon. The Grand Fir Mosaic (GFM) is named for the dominant conifer, grand fir (*Abies grandis* (Dougl. ex D. Don) Lindl.), and the variety of sizes and shapes of natural openings in the forest canopy (Ferguson and Johnson 1996). Dominant species in natural openings are Sitka alder (*Alnus sinuata* (Regel) Rydb.), bracken fern (*Pteridium aquilinum* (L.) Kuhn), and fool's huckleberry (*Menziesia ferruginea* Smith).

The Grand Fir Mosaic is about 500,000 acres, occurring at elevations between 4,200 feet and 6,000 feet, with most occurrences between 4,500 and 5,500 feet. GFM forests can occupy all aspects and topographic positions within this elevation zone. The predominant habitat type is *Abies grandis/Asarum caudatum* (grand fir/wild ginger) in northern Idaho (as defined by Cooper and others 1991) and *Abies grandis/Clintonia uniflora* (grand fir/queencup beadlily) in northeastern Oregon (as defined by Johnson and Clausnitzer 1992). Other habitat types in the GFM are *Abies grandis/Senecio triangularis* (grand fir/arrowleaf groundsel), *Thuja plicata/Asarum caudatum* (western redcedar/wild ginger), *Tsuga mertensiana/Streptopus amplexifolius* (mountain hemlock/twisted stalk), and *Abies lasiocarpa/Streptopus amplexifolius* (subalpine fir/twisted stalk) (Ferguson and Johnson 1996).

The species composition of conifers in the GFM differs from non-Mosaic habitats (Ferguson and Johnson 1996). Grand fir is found most often, followed by Engelmann spruce (*Picea engelmannii* Parry ex Engelm.), subalpine fir (*Abies lasiocarpa* (Hook.) Nutt.), and Douglas-fir (*Pseudotsuga menziesii* var. *glauca* (Beissn.) Franco). Western white pine (*Pinus monticola* Dougl. ex D. Don) and western larch (*Larix occidentalis* Nutt.) are found infrequently in northern Idaho, although western larch is common in northeastern Oregon. Elevations in the GFM are generally too high for ponderosa pine (*Pinus ponderosa* Dougl. ex Laws. var. *ponderosa*). Western redcedar (*Thuja plicata* Donn. ex D. Don) and mountain hemlock (*Tsuga heterophylla* (Raf.) Sarg.) are only found in certain parts of the GFM in Idaho. Of special note is lodgepole pine (*Pinus contorta* Dougl. ex Loud.), which is found in higher and lower elevation forests adjacent to the GFM, but rarely in the GFM.

Investigations on this ecosystem were begun because of the slow rate of secondary succession to woody vegetation (conifers and shrubs) following disturbance, such as timber harvest. Initially, land managers were concerned about the lack of conifer regeneration, but over time, it became apparent that ecological processes in the GFM were unlike those of other habitats in the northern Rocky Mountains. More information was needed to properly manage GFM sites.

In the Grand Fir Mosaic, northern pocket gophers (*Thomomys talpoides*), bracken fern, and western coneflower (*Rudbeckia occidentalis* Nutt.) rapidly invade cutover forests. Several factors could account for the lack of succession to woody species. Competition for space, light, water, and nutrients is one of the first considerations, but more factors appeared to be involved. While competition could account for the lack of some shrubs and conifers, adjacent ecosystems at higher and lower elevations have a plentiful supply of shrubs and conifers. It seems unlikely that competition is the only factor.

This research is one of several studies on the GFM to determine probable causes for the slow rate of secondary succession to woody vegetation. Other studies have dealt with soil genesis (Johnson-Maynard 1995; Johnson-Maynard and others 1997, 1998; Sommer 1991), pocket gophers (Ferguson 1999), ecology (Ferguson and Johnson 1996), and allelopathy (Ferguson 1991; Ferguson and Boyd 1988).

The objective of this study was to compare environmental conditions in the GFM with adjacent non-Mosaic habitats to see if unique environmental characteristics of the GFM could account for the slow rate of secondary succession to woody species. We discuss results of monitoring the above- and belowground environment in the GFM and three adjacent habitat types.

Methods

Study Sites

Four study sites were chosen on the Nez Perce National Forest in Idaho to represent four different environments in and near the GFM. The study sites are located in the vicinity of Lookout Butte (fig. 1). Study sites were selected to be as physically similar as possible. All sites were located in clearcuts with south-to-southwest aspects, upper slope topographic position, and 10 to 20 percent slopes. The habitat types represented are *Abies grandis/Asarum caudatum* (two sites), *Thuja plicata/Asarum caudatum*, and *Abies lasiocarpa/Xerophyllum tenax*. Following is a description for each site. Abbreviations for non-Mosaic study sites are named for the climax conifer; for example, the THPL site is named for *THuja PLicata*.

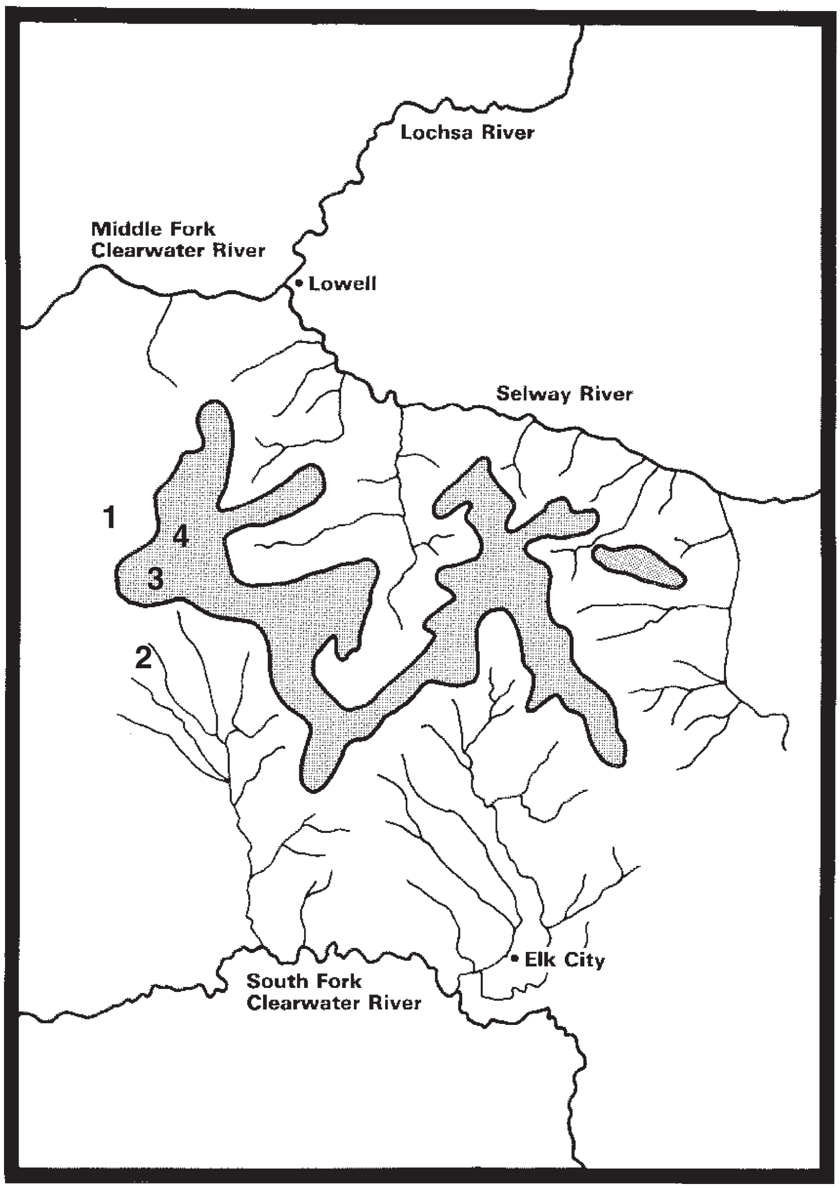


Figure 1—Location of remote monitoring stations near Lookout Butte on the Nez Perce National Forest. The shaded area is the Grand Fir Mosaic Ecosystem. 1 = THPL Station; *Thuja plicata/Asarum caudatum* habitat type, not in the Mosaic. 2 = ABGR Station; *Abies grandis/Asarum caudatum* habitat type, not in the Mosaic. 3 = Mosaic Station: *Abies grandis/Asarum caudatum* habitat type, in the Mosaic. 4 = ABLA Station; *Abies lasiocarpa/Xerophyllum tenax* habitat type at Lookout Butte above the elevation range of the Mosaic.

1. THPL site. This is the lowest elevation of the four sites, representing the *Thuja plicata/Asarum caudatum* habitat type at an elevation of 4,720 feet; T31N, R6E, S10; latitude 46° 2' 43.1079"N; longitude 115° 41' 43.7869"W. The clearcut has good representation of woody species such as snowberry (*Symphoricarpos albus* (L.) Blake), thimbleberry (*Rubus parviflorus* Nutt.), pachistima (*Pachistima myrsinites* (Pursh) Raf.), rose (*Rosa* spp.), huckleberry (*Vaccinium globulare* Rydb.), and serviceberry (*Amelanchier alnifolia* Nutt.). Regeneration of the following species is present at this site: planted ponderosa pine and Douglas-fir, and natural grand fir, western redcedar, and Pacific yew (*Taxus brevifolia* Nutt.). Bracken fern, western coneflower, and pocket gophers are infrequent.

2. ABGR site. This site is an *Abies grandis/Asarum caudatum* habitat type but is not in the Grand Fir Mosaic. Elevation is 4,850 feet; T30N, R6E, S3; latitude 45° 57' 44.5276"N; longitude 115° 41' 38.7602"W. The area was chosen for monitoring because it occurs at a lower elevation than the GFM but is the same habitat type as commonly found in the Mosaic. There are more shrubs (both number of species and percent coverage) than the Mosaic site described below. Woody vegetation includes snowberry, shinyleaf ceanothus (*Ceanothus velutinus* Dougl. ex Hook.), pachistima, elderberry (*Sambucus racemosa* L.), twinflower (*Linnaea borealis* L.), huckleberry, fool's huckleberry, thimbleberry, and serviceberry. Conifer regeneration in the clearcut includes natural grand fir and planted Douglas-fir, ponderosa pine, and Engelmann spruce. Also, beargrass (*Xerophyllum tenax* (Pursh) Nutt.) is common in the clearcut. This site also has little coverage by bracken fern and western coneflower, and there is some pocket gopher activity.

3. Mosaic site. This site represents an *Abies grandis/Asarum caudatum* habitat type in the GFM. Elevation is 5,700 feet; T31N, R6E, S23; latitude 46° 0' 25.7599"N; longitude 115° 40' 48.0855"W. Woody vegetation in the clearcut includes elderberry, thimbleberry, snowberry, and mountain ash (*Sorbus scopulina* Greene), but only in minor amounts. There are patches of fool's huckleberry and Sitka alder in the clearcut that were present before the stand was harvested. Western coneflower and bracken fern are abundant.

The Mosaic site has been planted several times. Only scattered Engelmann spruce have survived to provide stocking along with some natural Engelmann spruce regeneration. Pocket gopher activity is very high, which probably resulted in the plantation failures. This site was used by Ferguson (1999) to study the effects of pocket gophers and successional plant communities on survival and growth of conifers.

4. ABLA site. This site is southwest of the lookout tower at Lookout Butte and is at the highest elevation of the four stations (5,840 feet); T31N, R6E, S12; latitude 46° 2' 41.1209"N; longitude 115° 39' 40.8869"W. The top of Lookout Butte exceeds the higher elevation limits of the surrounding Grand Fir Mosaic. The habitat type is *Abies lasiocarpa/Xerophyllum tenax*. There are no lodgepole pine, Douglas-fir, or western larch in the vicinity. This site is warmer than a typical *Abies lasiocarpa/Xerophyllum tenax* habitat type as described by Cooper and others (1991). Indicators of this warmer environment include lack of grouse whortleberry (*Vaccinium scoparium* Leiberg), and the occasional occurrence of wild ginger (*Asarum caudatum* Lindl.) and evergreen synthyris (*Synthyris platycarpa* Gail and Pennell). Shrubs found in the vicinity are huckleberry, spiraea (*Spiraea betulifolia* (Doublas.) Hitchc.), snowberry, elderberry, Rocky Mountain maple (*Acer glabrum* Torr.), thimbleberry, currant (*Ribes* spp.), bittercherry (*Prunus emarginata* (Dougl.) Walpers), and ninebark (*Physocarpus malvaceus* (Greene) Kuntze). The clearcut has abundant beargrass. Ponderosa pine was planted in the clearcut, but it grows slowly at this elevation and stems are deformed by snow. Bracken fern, western coneflower, and pocket gophers are infrequent.

Remote Monitoring Stations

Electronic monitoring of the four sites was done with Omnidata™ remote monitoring stations installed in June 1988 and removed in June 1996. Replication was not possible because of limited funding. Sensors attached to computer hardware were programmed to record data at specified time intervals. Data were stored on site, then periodically removed and transported to the office where the data were transferred to computers.

Time was synchronized among the stations so that information from sensors was collected and recorded at the same time. Stations were installed in the same manner with sensors at the same height and position. For example, the solar radiation sensor was 6 feet above the base of the weather station in a level position on a platform that extended from the south side of the station, rain gauges were all located on the west side of the station, and so on.

Placement of soil sensors used techniques to minimize soil disturbance. Soil water potential and temperature sensors at 1 inch and 8 inches were placed in the same soil pit. The pH sensor was buried in a separate location because it was removed during the dry part of the summer. For the water potential and temperature sensors, a small pit was dug about 9 inches deep. Loose soil was cleaned from the uphill vertical face of the pit. Horizontal holes for the sensors were dug at 1 and 8 inches from the soil surface, then sensors were placed in these holes. Wires leading from the sensors to the computer hardware were positioned to run downhill from the sensor for 6 to 12 inches. This prevented water from running down the wires to sensors. The soil was then replaced.

Manufactured soil temperature sensors are covered with a black waterproof covering. Those sensors used to record soil surface temperature were painted white to lessen the effect of solar radiation heating the sensor. A white neoprene paint was used because of its flexibility and adhesion properties.

Table 1 shows the type of sensors along with specifics on data collection. Sensors were scanned every 15 minutes and reports were written to the data storage pack either at 2-hour or 6-hour intervals. Two-hour reports were used for variables that changed most rapidly and 6-hour reports were used for variables that changed slowly. Averages of the 15-minute scans were recorded for most sensors. The maximum and minimum soil surface temperatures found during the scans for 2-hour periods were also recorded. This makes it possible to determine the maximum and minimum daily surface temperature. Wind direction was read instantaneously at the end of each 2-hour period. Precipitation was recorded as the cumulative total during the 2-hour period, as recorded by a tipping-bucket rain gauge.

The pH sensors are model 613 pH transducers manufactured by IC Controls™ in Ontario, Canada. They operate well in moist environments and compensate for temperature changes, but they were removed when soils dried to about –10.0 bars. Each pH sensor was calibrated between pH 3.0 and pH 7.0 with known buffers before field use, whenever they were removed from the field during dry soil periods, or annually in the field.

Analysis

The remote monitoring stations generally provided reliable, accurate data, but data were often missing or not usable for a variety of reasons. Animals often chewed on wires, broke wires, or dug up sensors. Snowloads bent sensors out of proper position. Sometimes the electronic components of sensors quit working. Data on precipitation are not accurate during the winter months when snow buries the rain gauge. Even if the rain gauge is not buried by snow, the snow that does accumulate can blow away before it melts. Sometimes the air temperature and relative humidity sensors at 4.5 feet were also buried by snow. Occasionally, the soil froze at 1 inch during the winter, which gave a false reading for soil water potential. Another interesting source of bad data occurred when the wind direction sensor was frozen in place by a buildup of ice.

Because these sites are remote and not accessible during the winter months, there can be long periods of missing and bad data. Sensors that break go undetected until the next visit, then it may take several days to complete repairs. Data were carefully screened to eliminate bad data before analyses. Once the data were screened, we considered appropriate ways to deal with missing data. Other researchers have calculated values for missing data by using available data from other sites (Finklin 1983a, b). We chose not to calculate missing values because too many sites were missing the same data for some time periods, and we wanted to compare actual data rather than mask differences by mixing actual and predicted values. We also decided to analyze only data collected during the growing season because all sites are covered with

Table 1—Information collected at four remote monitoring stations on the Nez Perce National Forest. Each sensor was scanned at 15-minute intervals.

Sensor	Position	Unit of measurement	Report Interval	Report mode[a]
Wind speed	9 feet	mph	2 hours	Ave.
Wind direction	9 feet	azimuth	2 hours	Inst.
Precipitation	3 feet	inches	2 hours[b]	Cum.
Solar radiation	6 feet	Langleys	2 hours	Ave.
Relative humidity	4.5 feet	percent	2 hours	Ave.
Air temperature	4.5 feet	°F	2 hours	Ave.
Soil temperature	surface	°F	2 hours	Ave., min., max.
Soil temperature	1 inch	°F	2 hours	Ave.
Soil temperature	8 inches	°F	6 hours	Ave.
Soil water potential	1 inch	bars	6 hours	Ave.
Soil water potential	8 inches	bars	6 hours	Ave.
Soil pH	1 inch	pH	6 hours	Ave.

[a]Ave. = average. Cum. = cumulative. Inst. = instantaneous (one reading).
[b]Report interval was 6 hours prior to June 1991.

snow during the winter. Learning how to best maintain the weather stations to assure accurate measurements took 1 to 2 years; 1988 and 1989 often had large data gaps as methods were established and appropriate sensors selected.

Data used for analyses are as follows:

1. Data recorded from April 1 through October 31 of each year.
2. Years of monitoring from 1990 through 1996.
3. There must be at least $^3/_4$ of the reports per day in order to calculate daily averages (nine of the 12 2-hour reports or three of the four 6-hour reports).
4. There must be at least 20 days with valid data in order to calculate an average for a month.
5. There must be at least 4 of the 7 years of monthly data that is common to all four stations in order to calculate monthly averages. However, this means that different monthly averages can have different years used in the computations.

Standard statistical analyses for comparing data between sites were not possible because there was no replication of experimental units. Since the GFM site was the focus of research, we summarized the data in different ways for comparing the other sites to the Mosaic site. We carried out two major types of summarization to compare sites. First, for those months with sufficient data (based on the criteria previously described), we calculated summary statistics for each sensor by site including mean, standard deviation, minimum, and maximum. Second, differences between non-Mosaic sites and the Mosaic site were calculated at the 2-hour or 6-hour time frame and then summarized to obtain mean monthly differences along with standard deviations. To visually detect differences between the Mosaic and other sites, bar charts showing mean monthly differences ±2 standard deviations were graphed for each month against a zero difference line. Lack of overlap of these bar graphs with the zero difference line suggests where true differences between a site and the Mosaic site exist. Summary statistics were only calculated where sufficient data existed for all four sites, whereas the comparison graphs use means and standard deviations where sufficient data existed between just the individual site of interest and the Mosaic site. Additional data summaries were also done for some sensors and are discussed where appropriate in the results section.

Results

Wind Speed and Direction

Winter conditions (heavy snows and freezing/refreezing) caused problems with the wind speed sensors and it was often not until the summer months that sensors could be put back into working condition. Therefore, summary statistics were only calculated for the months of July, August, and September, which had 4 of 6 years of data available for every site.

Average wind speeds increased with increasing elevation, and standard deviations roughly followed the same pattern (table 2). The THPL site had the lowest average wind speed (1.7 mph) followed by the ABGR site (2.7 mph), the Mosaic site (3.1 mph), and the ABLA site (3.7 mph).

The comparison graphs in figure 2 generally follow the trend shown in table 2. For all months from June to October, except July, wind speed was less at the THPL site than at the Mosaic site. Wind speed at the ABGR site was less than the Mosaic site in the spring months (April to June) and also in October. The wind speed was greater at the ABLA site than the Mosaic site only in the month of October.

The wind direction sensor at the ABGR site rarely functioned properly, so we based our assessment of wind direction only on the other three sites where data were fairly reliable (only May had insufficient data; the other months mostly had 5 of 6 years available). Figure 3 shows star charts for these sites. The star charts show the percent of observations of wind direction that occur in each of eight 45-degree segments. The three sites are similar in that the predominant wind direction is from the west, with the next prevalent winds from the east. Winds at the

Table 2—Summary statistics for wind speed (miles per hour).

Site	Number of observations	Mean	Standard deviation	Minimum	Maximum
THPL	4394	1.7	1.5	0.0	15.0
ABGR	4284	2.7	2.3	0.0	13.0
Mosaic	4290	3.1	2.2	0.0	15.0
ABLA	4399	3.7	2.9	0.0	23.0

Note: Data for July, August, and September only.

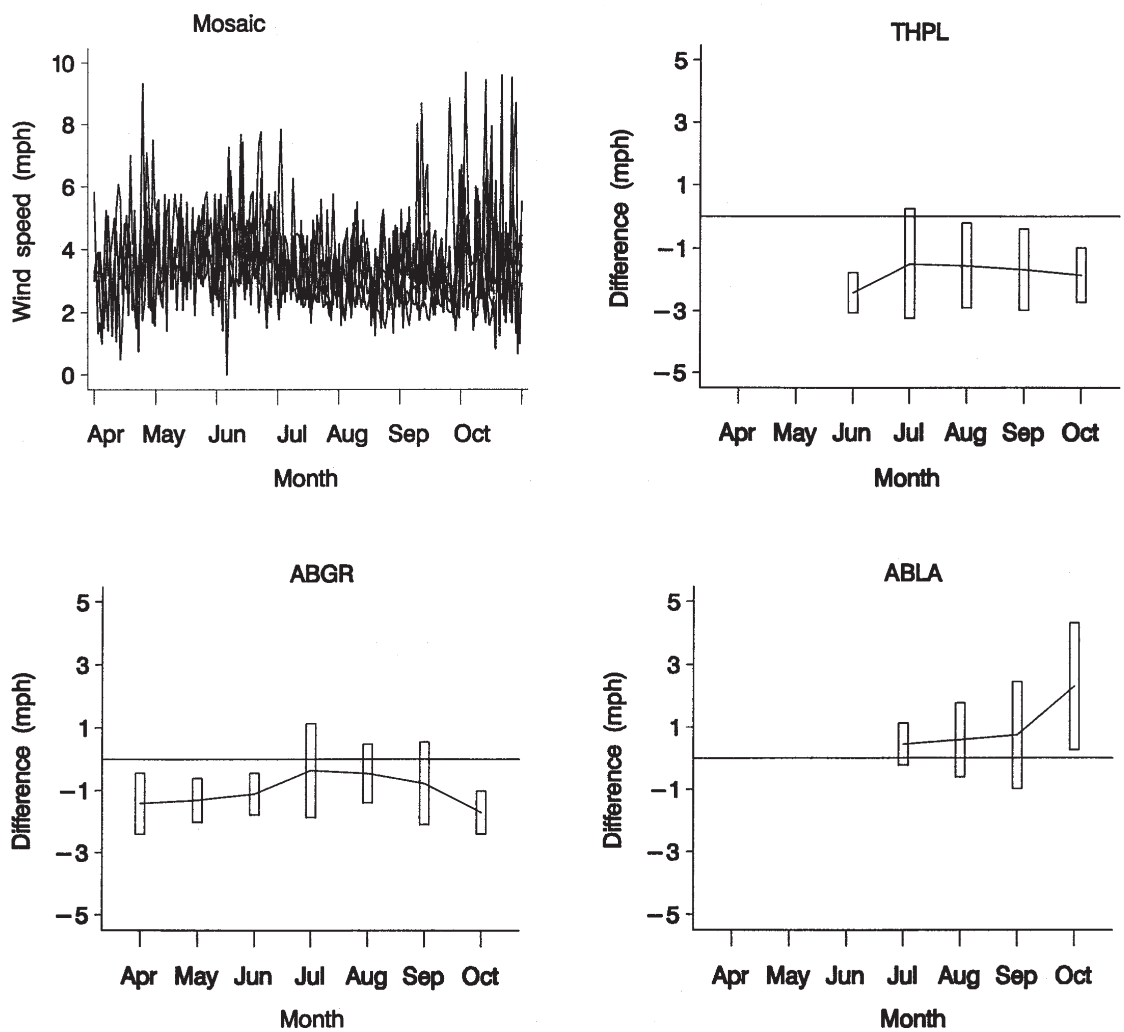


Figure 2—Average wind speed (mph) at the Mosaic site, and differences in average wind speed from the Mosaic site for the THPL, ABGR, and ABLA sites.

ABLA site more often come from the northwest than the west.

Rainfall

Rainfall sensors were quite reliable. Data were available to calculate monthly averages using 4 years of data for May, 5 years of data for April and October, and 6 years of data for the remaining months of the growing season.

Average daily rainfall did not follow an elevational pattern. Rainfall was highest at the Mosaic (0.12 inches) and THPL (0.11 inches) sites, and lowest at the ABGR (0.09 inches) and ABLA (0.08 inches) sites (table 3). Standard deviations for rainfall were ranked similar to the averages. Maximum rainfall per day varied between 2.32 inches at the ABGR site to 2.48 inches at the THPL site. Maximums are ranked similar to the averages.

Patterns of rainfall over the growing season were not different between the THPL and Mosaic sites except in April when the THPL site had more rain (fig. 4). The higher rainfall at the THPL site may be due to warmer spring temperatures. Rainfall at the ABGR and ABLA sites was consistently less than the Mosaic site, but all averages were within two standard deviations of the mean.

Solar Radiation

Solar radiation was measured in Langleys per minute (1 Langley/minute = 1 calorie per square meter per minute). Pyranometers are reliable sensors that record solar radiation in the wavelength range of 400 to 1100 nanometers. Summer and fall months had very complete data (July through September had 6 of 6 years of data, October had 5 of 6 years). However, spring months were less dependable because of damage to

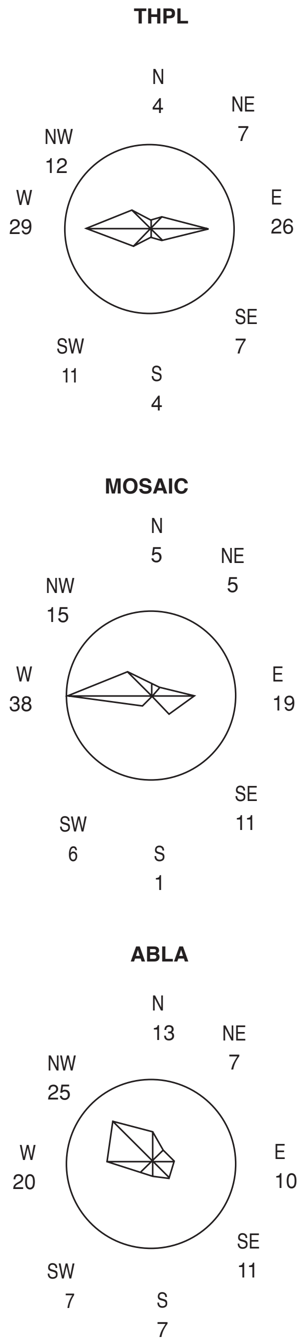


Figure 3—Star charts of wind direction at the THPL (top), Mosaic (middle), and ABLA (bottom) sites. Each chart shows the percent of observations by 45-degree segments.

sensors during the winter, with May having insufficient data for summarization, while April had 4 of 7 years of data and June had 5 of 7 years of data. Solar radiation data from the ABLA site were not used because the sensor gave readings about 20 percent low, which was not detected until the data were analyzed.

An index of solar radiation was developed in order to compare the three sites (THPL, ABGR, and Mosaic). Each of the 2-hour averages was expanded to the 2-hour period, then summed for the day. This calculated the total number of Langleys/day at each site. The average number of Langleys/day was essentially the same for the THPL (204,000) and ABGR (206,000) sites (table 4). There was an increase at the Mosaic site to 215,000 Langleys/day. This increased solar radiation at the Mosaic site is likely related to the elevational difference between the Mosaic site and the ABGR and THPL sites (850 feet higher than ABGR and 980 feet higher than THPL).

Comparison graphs in figure 5 show that the THPL site has lower solar radiation averaging about 12,000 Langleys/day from April through July (excluding May). The ABGR is lower by about 10,000 Langleys/day in July and August. These reductions are similar to those seen in the overall averages in table 4.

Relative Humidity

Adequate data for relative humidity are available for the months of July, August, and September. Those three months had 4 years of data. Data for April, May, and June were lacking because relative humidity sensors had to be replaced each spring and access to sites was not possible until after snowmelt.

Average relative humidity was calculated for July, August, and September to see if humidity differences could cause differences in evapotranspiration rates. The ABGR site averaged the highest humidity at 58.8 percent and the highest standard deviation (table 5). Next highest in humidity was the Mosaic site, averaging 54.1 percent. The THPL and ABLA sites had similar humidities at 52.8 percent for the THPL site and 52.5 percent for the ABLA site. Only the ABGR site showed any difference from the Mosaic

Table 3—Summary statistics for average daily rainfall (inches).

Site	Number of observations	Mean	Standard deviation	Minimum	Maximum
THPL	823	0.11	0.27	0.00	2.48
ABGR	818	0.09	0.22	0.00	2.32
Mosaic	825	0.12	0.26	0.00	2.42
ABLA	838	0.08	0.20	0.00	2.33

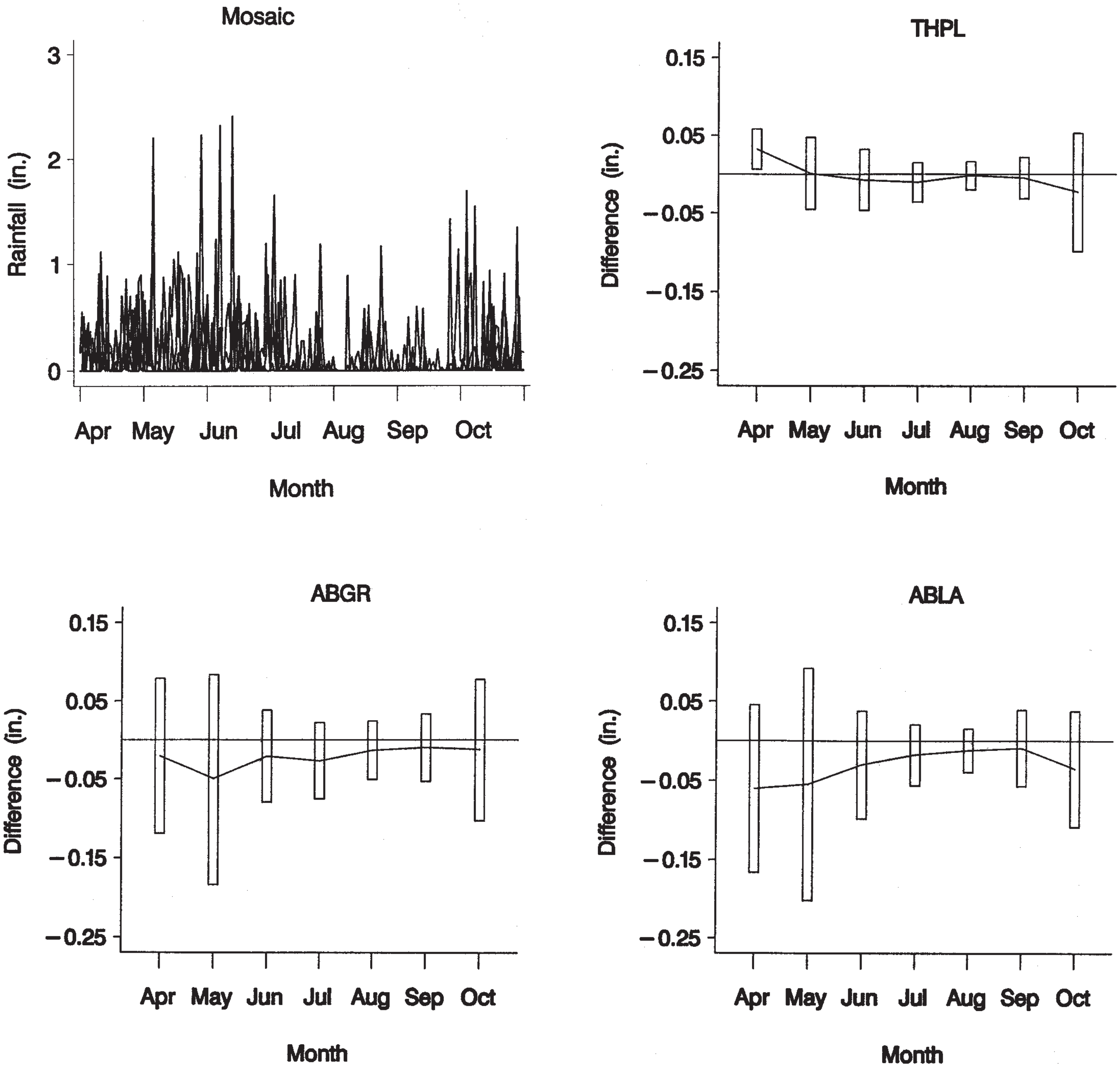


Figure 4—Average rainfall (inches) at the Mosaic site, and differences in average rainfall from the Mosaic site for the THPL, ABGR, and ABLA sites.

Table 4—Summary statistics for average daily solar radiation (Langleys per day to the nearest thousand).

Site	Number of observations	Mean	Standard deviation	Minimum	Maximum
THPL	932	204	95	4	359
ABGR	936	206	89	8	358
Mosaic	945	215	99	10	376
ABLA	0				

Note: Pyranometer measures solar radiation in the wavelength range of 400-1100 nanometers. Not enough data were obtained for May, so it was not used in calculations.

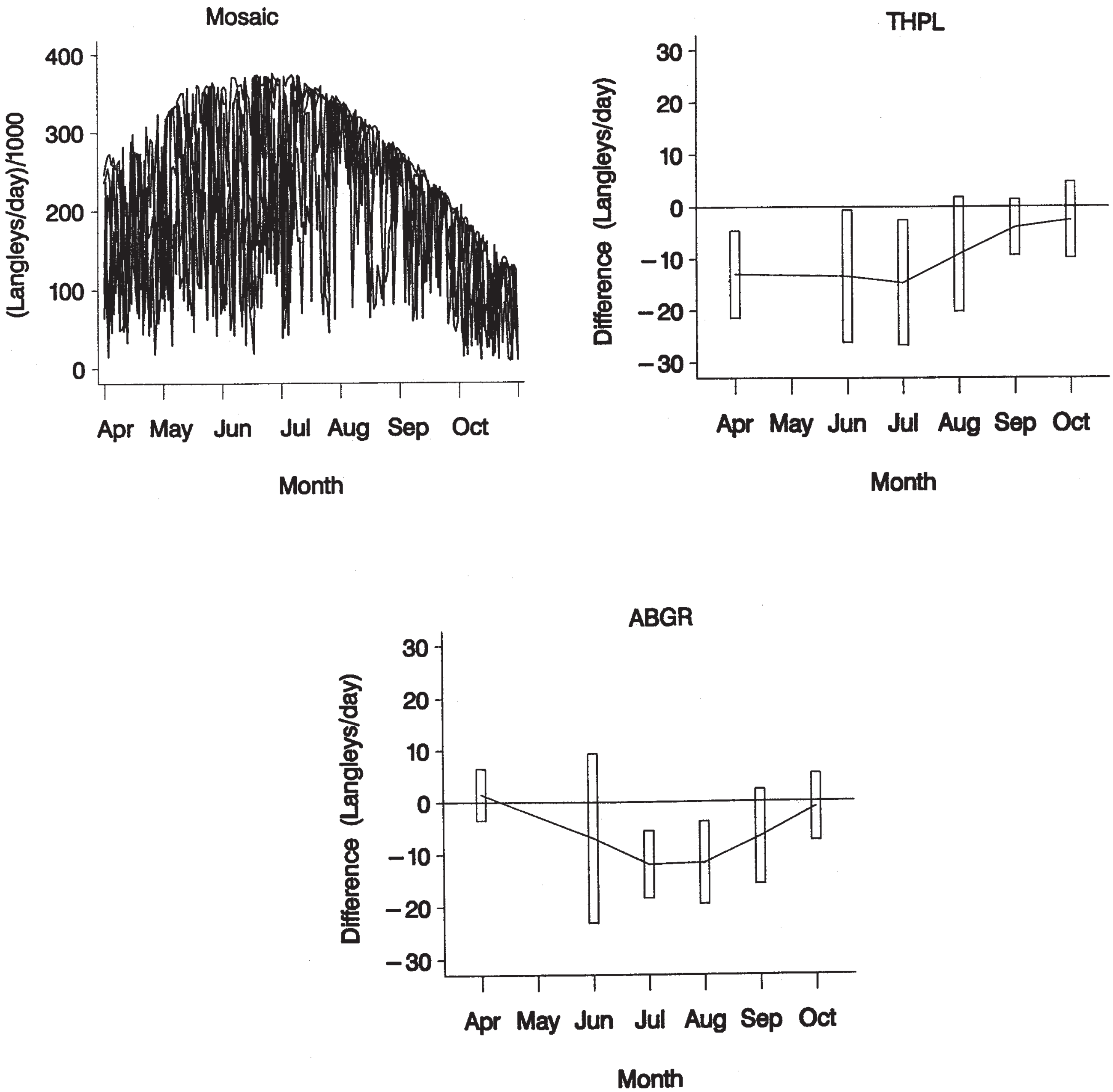


Figure 5—Solar radiation (Langleys/day) at the Mosaic site, and differences in solar radiation from the Mosaic site for the THPL, and ABGR sites.

Table 5—Summary statistics for relative humidity (percent) at 4.5 feet above ground.

Site	Number of observations	Mean	Standard deviation	Minimum	Maximum
THPL	4158	52.8	19.8	13.1	93.8
ABGR	4071	58.8	20.6	9.8	100.0
Mosaic	4077	54.1	17.3	16.2	93.7
ABLA	4379	52.5	16.4	14.3	87.4

Note: Data for July, August, and September only.

site (fig. 6) and then only in September, where it showed about a 6 percent increase over the Mosaic site. The bar graphs of the other sites all crossed the zero difference line.

Air Temperature at 4.5 Feet

Air temperature sensors had 4 years of data for April, May, and October. For the remaining months of the growing season, there were 5 years of data available for analysis.

The Mosaic site was the coolest of the four sites, averaging 49.6 °F at 4.5 feet above the ground for April through October (table 6). However, the average temperature at the Mosaic site was only slightly cooler than the ABGR (50.3 °F) and ABLA (50.4 °F) sites. The ABGR site was warmer than the Mosaic site in April, May, and June, but the sites were not different in July through October (fig. 7). The ABLA site was slightly warmer than the Mosaic site, but none of the months are different from the Mosaic site. Air temperature at the THPL site was the highest of the four

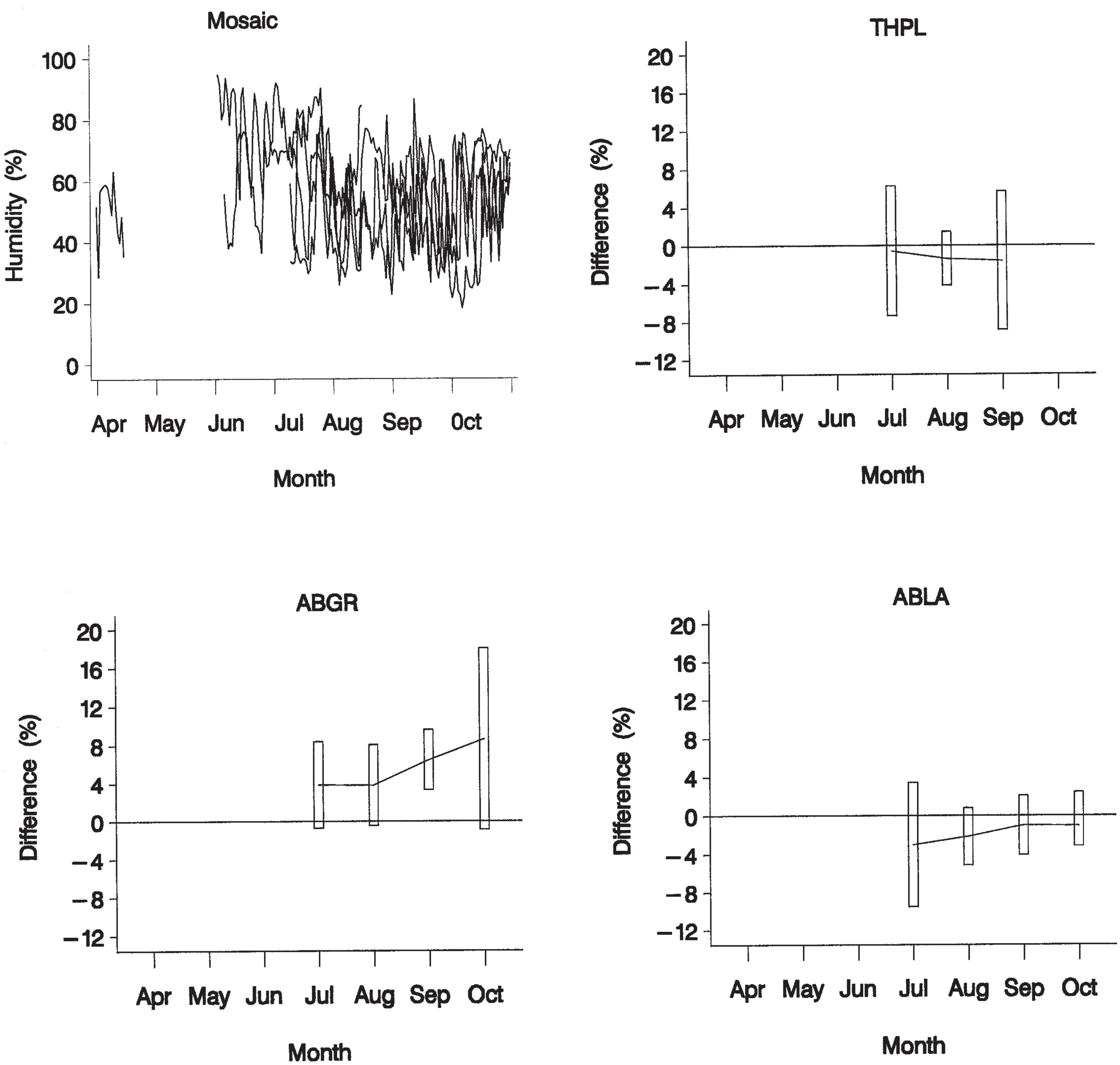


Figure 6—Average relative humidity (percent) at the Mosaic site, and differences in average relative humidity from the Mosaic site for the THPL, ABGR, and ABLA sites.

Table 6—Summary statistics for average air temperature (°F) at 4.5 feet above ground.

Site	Number of observations	Mean	Standard deviation	Minimum	Maximum
THPL	11522	53.8	13.2	19.6	93.7
ABGR	11449	50.3	13.5	17.4	92.3
Mosaic	11578	49.6	12.8	16.0	86.0
ABLA	11686	50.4	12.7	17.4	87.4

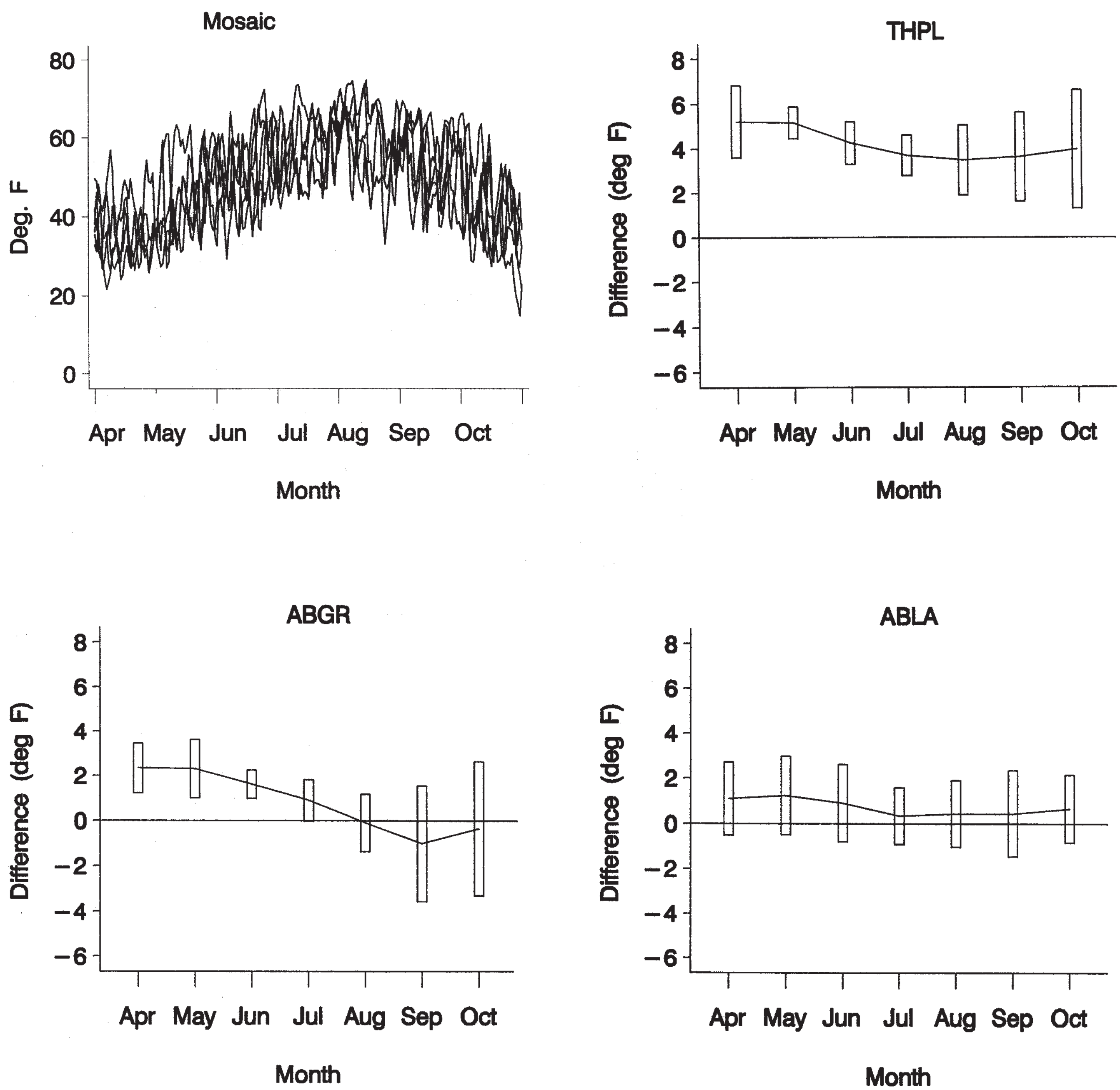


Figure 7—Average air temperature at 4.5 feet (°F) at the Mosaic site, and differences in average air temperature from the Mosaic site for the THPL, ABGR, and ABLA sites.

sites, averaging 4.2 °F higher than at the Mosaic site. This higher temperature was consistent for all months during the growing season (fig. 7).

Soil Surface Temperature

Soil surface temperature sensors were very reliable. The surface sensors among the sites had 4 years of data for May and June, 5 years of data for April and October, and 6 years of data for the remaining months.

The surface temperature sensors were installed to sample conditions that would be experienced by germinating seeds. The sensors were also used to determine the day snowpack melted in the spring. Presence of a snowpack was obvious because a temperature sensor covered by snow has a constant temperature slightly above freezing. Once the snowpack melts, surface temperatures begin to fluctuate.

The average date that the snowpack melted varied by site. Average snowmelt date for the THPL site was March 18, with a range from February 21 to April 11, which averages 52 days earlier than the Mosaic site. Average snowmelt date at the ABGR site was April 6, 24 days before the Mosaic site, with a range from March 8 to April 24. The ABLA site was April 30, 9 days earlier than the Mosaic site, with a range from March 31 to May 16. The latest date of snowpack melt was the Mosaic site, averaging May 9, with a range from April 14 to May 27.

Surface temperatures were lowest at the Mosaic site where they averaged 52.0 °F (table 7). The THPL site was warmest at 57.7 °F, and this warmer temperature was consistent during the growing season (fig. 8). The warmer average April temperature is due to earlier snowmelt at the THPL site. The warmer May temperature at the THPL site also reflects earlier snowmelt, but the higher standard deviation reflects the yearly variability of snowmelt at the Mosaic site in May.

The ABLA site had nearly the same average surface temperature (52.1 °F) as the Mosaic site, and there were no differences by months during the growing season (fig. 8). Average surface temperature at the ABGR site was 54.5 °F, an increase of 2.5 °F over the Mosaic site. Most of this difference can be attributed to the months of April and May (fig. 8) where there was earlier snowmelt at the ABGR site.

Since high surface temperatures can kill newly germinated seedlings and thus affect secondary succession, the data were analyzed for maximum daily temperatures. We chose 120 °F as a threshold temperature to compare sites since this is the approximate temperature that results in heat girdling of conifer seedlings (Haig and others 1941).

During the growing season, the THPL site averaged 21.2 days when surface temperature was ≥120 °F, an increase of 13.6 days over the Mosaic site. The ABGR site averaged 5.2 days ≥120 °F, 2.3 days less than the Mosaic site. Surprisingly, the ABLA site averaged 30.3 days ≥120 °F, an increase of 22.8 days over the Mosaic site. The warmer maximum temperatures are also evident in figure 9. The THPL site is warmer in April, June, and July, while the ABGR site is warmer only in April because of earlier snowmelt.

Minimum surface temperatures are similar at the Mosaic, ABGR, and ABLA sites (fig. 10). Only the minimum temperatures at the THPL site were warmer than the Mosaic site, from May through September.

The diurnal fluctuations for temperature sensors were greatest at the soil surface, so surface temperatures were analyzed to see which sites might be experiencing the greatest changes. The difference between the maximum and minimum daily surface temperatures was lowest at the Mosaic site, averaging 36.4 °F. At the ABGR site, diurnal fluctuations averaged 40.6 °F. The ABLA and THPL sites had the highest diurnal fluctuations, averaging 42.8 °F (ABLA) and 43.2 °F (THPL).

Soil Temperature at 1 and 8 Inches

Soil temperature was monitored at 1-inch and 8-inch depths. The 1-inch depth was chosen as an indicator of the rooting environment for newly germinated seeds. The 8-inch depth was chosen as an indicator of the environment for larger plants. Soil temperature sensors were among the most reliable sensors used at the monitoring stations. For most of the growing season months, data were available for at least 5 of the 7 possible years, with the exception of May where we have data for 4 of the 7 years.

Average soil temperatures at both depths (tables 8 and 9) had an inverse relationship with elevation

Table 7—Summary statistics for average soil surface temperature (°F).

Site	Number of observations	Mean	Standard deviation	Minimum	Maximum
THPL	13290	57.7	23.2	19.8	144.0
ABGR	13217	54.5	21.0	14.9	129.2
Mosaic	13183	52.0	22.0	17.2	137.3
ABLA	13493	52.1	24.1	17.8	143.8

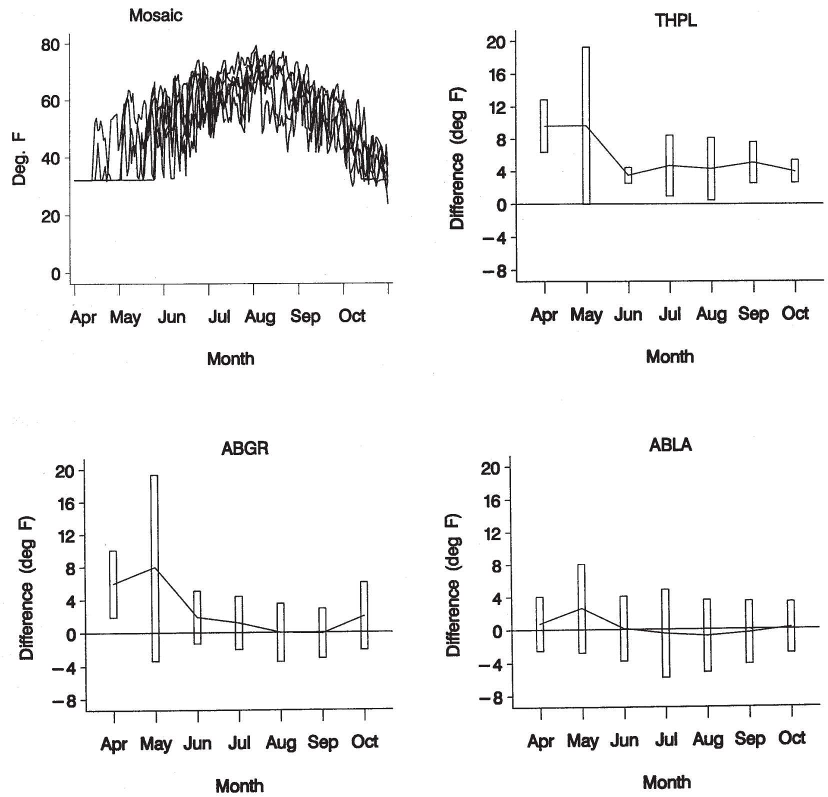


Figure 8—Average soil surface temperature (°F) at the Mosaic site, and differences in surface temperature from the Mosaic site for the THPL, ABGR, and ABLA sites.

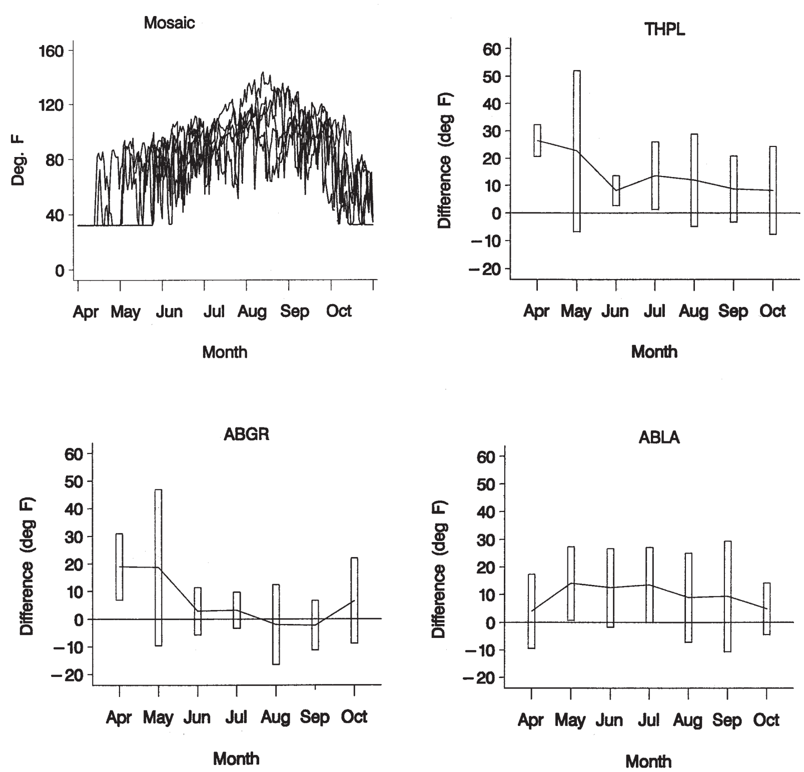


Figure 9—Average daily maximum soil surface temperature (°F) at the Mosaic site, and differences in maximum surface temperature from the Mosaic site for the THPL, ABGR, and ABLA sites.

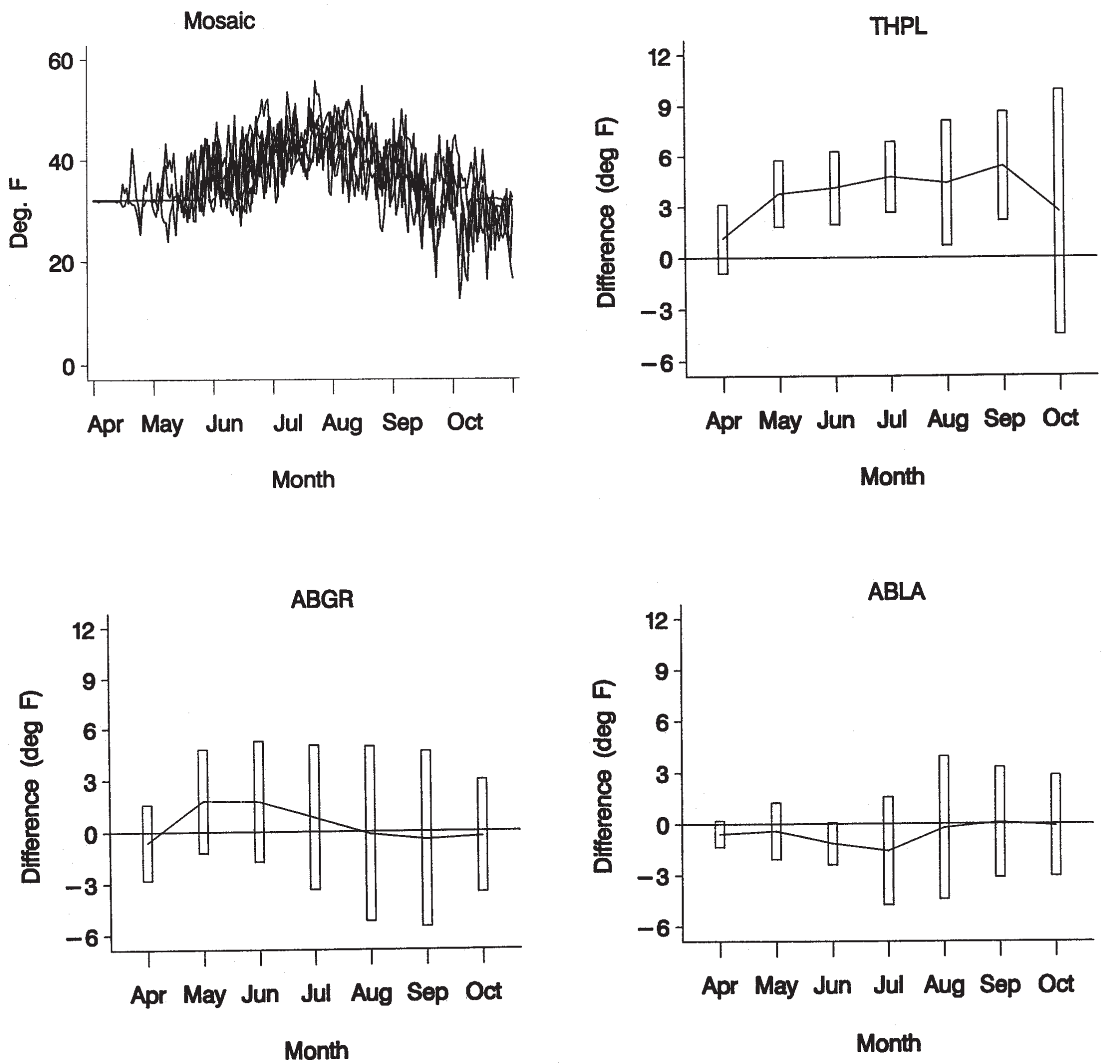


Figure 10—Average daily minimum soil surface temperatures (°F) at the Mosaic site, and differences in minimum surface temperature from the Mosaic site for the THPL, ABGR, and ABLA sites.

Table 8—Summary statistics for average soil temperature (°F) at 1 inch.

Site	Number of observations	Mean	Standard deviation	Minimum	Maximum
THPL	14033	56.7	12.0	32.9	98.1
ABGR	13960	56.0	15.1	32.2	113.9
Mosaic	13924	51.7	13.5	32.0	107.6
ABLA	14223	50.9	12.1	31.4	86.9

Table 9—Summary statistics for average soil temperature (°F) at 8 inches.

Site	Number of observations	Mean	Standard deviation	Minimum	Maximum
THPL	4670	54.9	8.2	33.8	72.5
ABGR	4643	53.4	7.9	33.3	68.4
Mosaic	4631	50.0	9.9	32.4	69.8
ABLA	4740	48.9	8.3	32.1	65.8

of the sites, with the lowest elevation site (THPL) having the highest temperatures, progressing to the highest elevation site (ABLA) having the lowest temperatures. Average temperatures were always cooler at the 8-inch depth, compared to the 1-inch depth, by about 2 °F for all sites. Standard deviations were always higher at the 1-inch depth than the 8-inch depth, reflecting the greater insulating effect of the soil at a greater depth. Warm surface temperatures take a longer time to change soil temperature at 8 inches than at 1 inch (fig. 11).

The minimum temperatures indicate that soil rarely freezes at the 1-inch depth (only the ABLA site dropped below freezing) and never freezes at the 8-inch depth during the growing season. Soil freezing at the ABLA site occurred after the insulating snow cover had left in the early spring but before the chance of below-freezing temperatures passed. Soils at all four sites rarely froze during the winter months because of the insulating effect of deep snowpack.

Comparing the graphs of differences between the three non-Mosaic sites and the Mosaic site (fig. 12 and 13), the THPL site is consistently warmer for all months than the Mosaic site by about 4 to 5 °F at both the 1-inch and 8-inch depths. The THPL site is about 8 to 9 °F warmer in April and May, reflecting earlier snowmelt on the THPL site. Also, the variability of differences in soil temperatures in May is greater than the other months for all sites due to the timing of snowmelt, as discussed previously for surface temperature. Soil temperatures at the ABGR site are higher than the Mosaic site in spring (April through

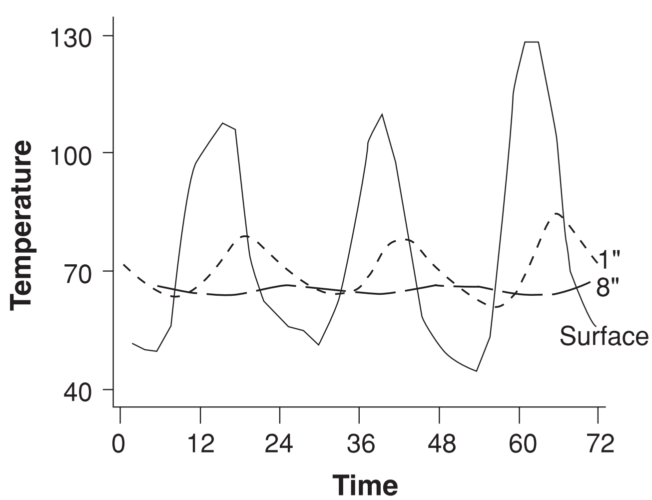


Figure 11—Soil temperatures (°F) over a 72-hour period (July 29-31, 1994) at the Mosaic site, showing differences among the surface, 1-inch, and 8-inch temperatures. The amount of heat transferred from the soil surface to lower depths diminished with distance from the surface, and there is a definite time lag. This figure is for a dry soil; moist soils had a similar pattern.

June) and fall (September and October) at both depths. Warmer spring temperatures are consistent with the air and surface temperature trends on the ABGR site but warmer fall temperatures are not consistent with the air and surface temperatures. The ABLA site is 2 to 3 °F cooler than the Mosaic site from June to August at the 1-inch depth and from June to September at the 8-inch depth.

Soil Water Potential at 1 and 8 Inches

Soil water potential sensors were very reliable, with 6 years of data for the 1-inch depth from June to September and 5 years of data for April and October. The 8-inch depth had 1 less year of data for all months than the 1-inch depth. Insufficient data were available for the 8-inch depth in May, so no May statistics are reported for either the 8-inch or 1-inch depths.

Tables 10 and 11 show average soil water potential at 1 and 8 inches in bars. The ABLA site has the lowest average soil water potential at –4.2 bars at 1 inch and –5.0 bars at 8 inches. The THPL site is the second lowest at –4.1 bars at 1 inch and –3.9 bars at 8 inches. Third lowest is the ABGR site at –4.0 and –3.4 bars. The Mosaic site is the least dry during the growing season. Average soil water potential is –3.3 bars at 1 inch and –3.0 bars at 8 inches.

Another way to consider differences in soil water potential is to look at the number of years soil water potential equals or is less than –15.0 bars (permanent wilting point for plants). Soils at the ABLA site dried to –15.0 bars in 6 of 6 years at 1 inch from 1990 to 1995, averaging 30.5 days per growing season ≤–15.0 bars. Soils at the ABGR site also dried to –15.0 bars in 6 of 6 years, also averaging 30.5 days ≤–15.0 bars. The THPL site dried 4 of 5 years at 1 inch, averaging 35.0 days. The Mosaic site dried to –15.0 bars in only 3 of 6 years at 1 inch, averaging 26.0 days.

Soils were moister at 8 inches, compared to 1 inch, but the patterns among the stations were similar. The ABLA site dried to ≤–15.0 at 8 inches in 5 of 5 years, averaging 37.8 days per growing season. The ABGR site dried in to ≤–15.0 bars in 4 of 6 years, averaging 20.5 days. The THPL site dried to ≤–15.0 in 4 of 5 years, averaging 32.2 days. The Mosaic site was the least dry, drying to ≤–15.0 in only 2 of 6 years at 8 inches, averaging 18.5 days per growing season.

Soil pH

Soil pH sensors performed well in the field, but there are many periods of missing data. Sensors were removed when the soil began to dry in the summer (< about –10.0 bars), as recommended by the manufacturer. Animals disturbed some pH sensors by pulling on the wires, which broke the direct contact between the sensor and the soil. Sensors sometimes

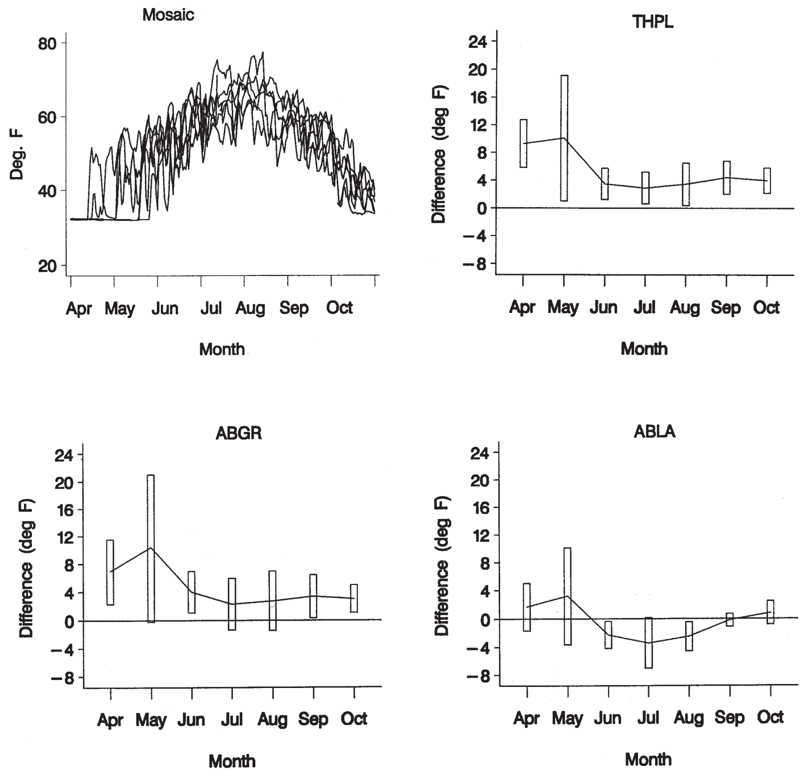


Figure 12—Average soil temperature (°F) at 1 inch at the Mosaic site, and differences in average soil temperature for the THPL, ABGR, and ABLA sites.

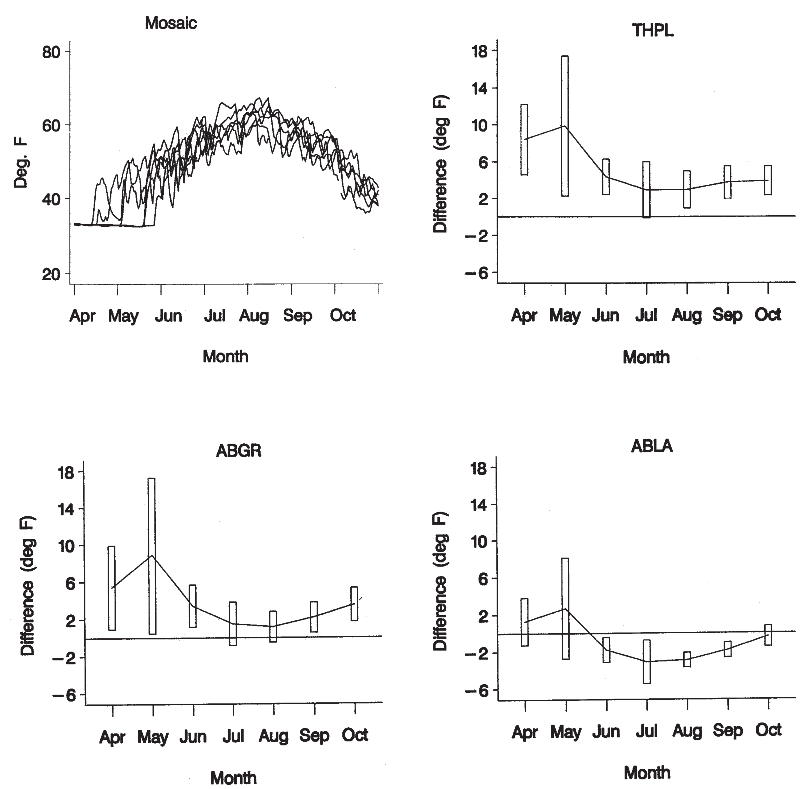


Figure 13—Average soil temperature (°F) at 8 inches at the Mosaic site, and differences in average soil temperature for the THPL, ABGR, and ABLA sites.

Table 10—Summary statistics for average soil water potential (bars) at 1 inch.

Site	Number of observations	Mean	Standard deviation	Minimum	Maximum
THPL	10713	–4.1	5.7	–15.0	–0.2
ABGR	10676	–4.0	5.7	–15.0	–0.4
Mosaic	10779	–3.3	5.2	–15.0	–0.4
ABLA	10898	–4.2	5.8	–15.0	–0.3

Note: Since only 3 years of data were available for all stations in the month of May for soil water potential at 8 inches, May data were not included in the statistics so the 1 inch and 8 inch data could be compared.

Table 11—Summary statistics for average soil water potential (bars) at 8 inches.

Site	Number of observations	Mean	Standard deviation	Minimum	Maximum
THPL	9142	–3.9	5.6	–15.0	–0.4
ABGR	9107	–3.4	5.4	–15.0	–0.3
Mosaic	9223	–3.0	5.2	–15.0	–0.3
ABLA	8867	–5.0	6.1	–15.0	–0.3

Note: Since only 3 years of data were available for all stations in the month of May, May data were not included in the statistics.

became uncalibrated. Because of the lack of continuous pH data, there were not enough data to calculate meaningful monthly averages as described in the analysis section. Instead, we graphed available pH data as a way to look at variation among the stations throughout the year.

Soil pH provided interesting insights into unique processes in the GFM. The Mosaic site had a definite yearly fluctuation in pH (fig. 14). Soil pH in the spring was between 5.5 and 6.5, but began dropping in April through July. In August and September, pH began rising again. In most years, pH was below 5.0, and often was below 4.0. A pH of <5.0 is the value where aluminum saturation becomes high enough to cause aluminum toxicity in plants (Shoji and others 1993). Because pH 5.0 is a critical value for aluminum toxicity, a reference line has been placed on graphs in figure 14.

Soil pH at the ABLA site is rather erratic and somewhat cyclic (fig. 14). pH drops below 5.0 during the summer, but seldom goes below 4.5. Soil pH at the THPL and ABGR sites stays between 5.5 and 7.0, and does not drop below 5.0.

We considered the possibility that the pH fluctuations at the Mosaic site were due to soils drying in the spring and then wetting in the fall. Perhaps decreased moisture would increase the concentration of acids in the soil. Circumstances in 1993 and 1994 allowed us to address this question. The summer of 1993 was wet, and soil water potential at the Mosaic site did not exceed –5.0 bars (even the THPL site did not reach –15.0 bars in 1993). Conversely, 1994 was dry. Soil water potential at the Mosaic site reached –15.0 bars by early August and remained there until the middle of October. Even though the two years had much different moisture patterns, pHs were very similar (fig. 15).

Regression analysis was used to predict 1993 and 1994 Mosaic soil pH at 1 inch from Julian date, soil temperature at 1 inch, and soil water potential at 1 inch. Soil water potential alone accounted for 3.9 percent of the variation in 1993 and 4.6 percent of the variation in 1994. Soil temperature alone accounted for 76.2 percent of the variation in 1993 and 60.0 percent in 1994. The best regression, using all three variables, accounted for 85.8 percent of the variation in 1993 and 93.7 percent in 1994. The conclusion drawn from this analysis is that soil water potential is not a good predictor of soil pH.

Discussion

In this section we draw conclusions based on the results of this study, show how these results fit with other research on the GFM, and link these findings to research on the genesis and properties of volcanic ash soils.

The GFM has a shorter growing season than the other sites, even though it is not at the highest elevation. Compared to the Mosaic site, the ABLA site is

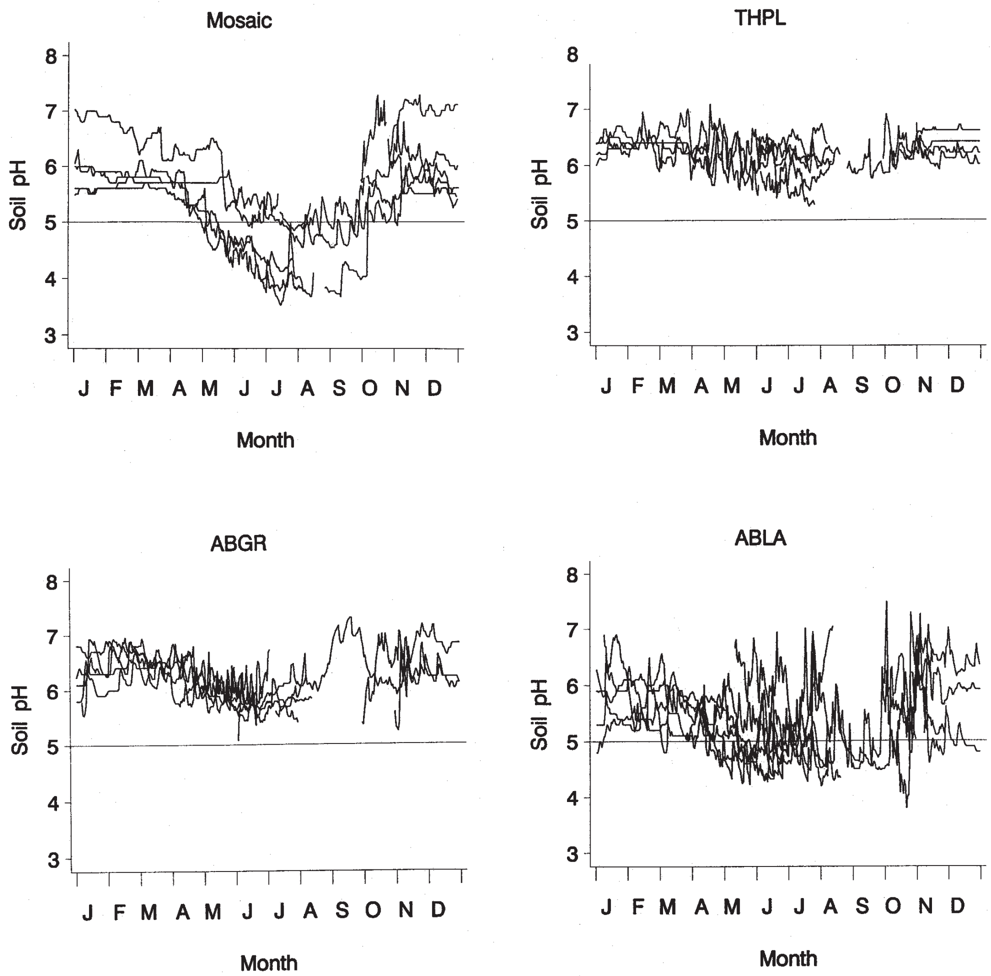


Figure 14—Average daily soil pH at 1 inch for the Mosaic, THPL, ABGR, and ABLA sites. Available data are shown for 1989 through 1995.

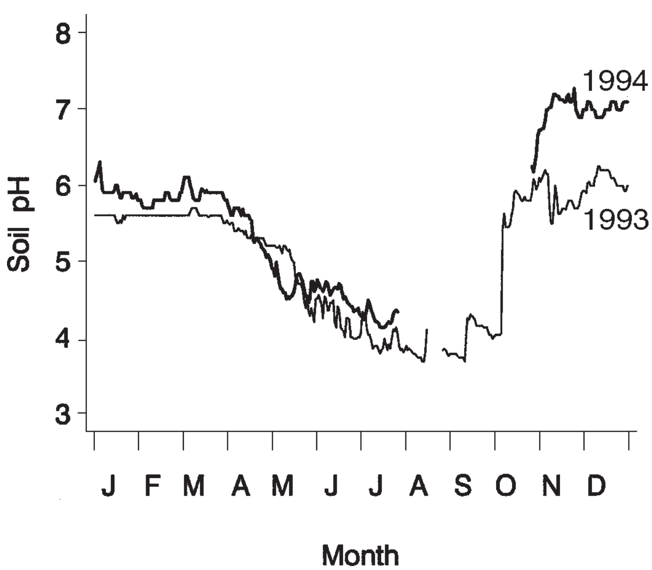


Figure 15—Average daily soil pH at 1 inch for the Mosaic site in 1993 (wet year) and 1994 (dry year).

free of snow 9 days earlier, the ABGR site 24 days earlier, and the THPL site 52 days earlier. The Mosaic site ranked the coolest for temperatures at 4.5 feet above the ground and on the soil surface, and ranked second for soil temperatures at 1 and 8 inches.

Soil water potential was lowest at the Mosaic site during the growing season. Soil water potential at 8 inches dried to –15.0 bars in only 2 of 6 years for the Mosaic site, while that threshold was reached 4 of 6 years at the ABGR site, 4 of 5 years at the THPL site, and 5 of 5 years at the ABLA site. Moist conditions at the GFM site should favor establishment of conifers and shrubs, especially since this moisture is accompanied by cooler temperatures. However, the GFM site has very little woody vegetation. Other environmental characteristics help explain this apparent contradiction.

Soil pH at 1 inch was very strongly acidic at the GFM site. From May through September, soil acidity typically dropped below pH 5.0, and often was below pH 4.0. Soil acidity during the winter at the Mosaic was typically between pH 5.5 and 6.5.

Forest soils of northern Idaho and adjacent states are heavily influenced by volcanic ash (Nimlos and Zuuring 1982), mostly from the eruption of Mount Mazama (Crater Lake, Oregon) about 6,850 years ago (Bacon 1983). Mount Mazama volcanic ash is rich in silicon and aluminum, with an average composition of 73.0 percent SiO_2 and 14.4 percent Al_2O_3 by weight (Johnson-Maynard 1995).

Typically, silicon and aluminum contained in volcanic ash weather to form various combinations of allophane and imogolite, which are noncrystalline hydrous aluminosilicates (Shoji and others 1993). Soils dominated by allophane and imogolite in the clay-size fraction are referred to as allophanic soils. They are characterized by moderately-to-slightly acid pH and low aluminum availability. As a result, aluminum phytotoxicity is rare in allophanic soils.

Under certain conditions, such as non-forested openings in the GFM, aluminum-humus complexes are preferentially formed instead of allophane and imogolite. This process gives rise to non-allophanic soils. Non-allophanic ash soils are strongly acidic, and aluminum toxicity is common to many crops below about pH 5.0 (Shoji and others 1993). Soils of the GFM have non-allophanic characteristics reflected in low seasonal pH, high water availability in most years, high organic matter inputs from forb communities dominated by bracken fern and western coneflower (Johnson-Maynard and others 1997), and a source of aluminum from the weathered volcanic ash.

Research has demonstrated that allophanic and non-allophanic soils exist side by side in the GFM (Johnson-Maynard 1995). Although allophanic soil characteristics develop under forest canopies, canopy openings can result in the formation of non-allophanic soils in just a few years. This rapid change in soil properties appears to be tied to the disruption of organic matter cycling that accompanies the establishment of successional forb communities (Johnson-Maynard and others 1997).

The development of non-allophanic soil characteristics in forest openings is only one factor limiting establishment of woody species in GFM habitats. The allelopathic potential of bracken fern and western coneflower has been demonstrated (Stewart 1975; Gliessman 1976; Ferguson 1991). Allelopathy, which is an additional factor beyond competition, can prevent germination of seed, delay germination, reduce growth, or reduce the plant's ability to survive.

Pocket gophers are also a factor limiting shrubs and trees. Although woody vegetation is not a preferred food source, it is eaten at certain times of the year, especially in winter when preferred food sources are absent (Teipner and others 1983; Marsh and Steele 1992; Ferguson 1999). Many GFM clearcuts have been planted several times without success because of seedling mortality or damage caused by pocket gophers.

The recognition that four factors cause the slow rate of secondary succession to woody vegetation is essential to successful management of GFM sites. First is competition for space, light, water, and nutrients. Second is allelopathy caused by species such as bracken fern and western coneflower. Third is the effect of pocket gophers. And fourth is non-allophanic soils.

Management of GFM sites that is based on recognition of all factors can be successful, but ignoring any one of the four factors could lead to regeneration failures. The order of limiting factors is also important. For example, the most limiting factor for plantation success is pocket gophers. If pocket gophers are controlled or gopher populations are low, then increments in survival and growth are possible from controlling bracken fern and western coneflower. Additional gains could be made by planting species that are adapted to acidic soils and by controlling other vegetation. In order to meet management objectives, planning must be matched to the unique combination of ecosystem processes in the GFM.

References

Bacon, C. R. 1983. Eruptive history of Mount Mazama and Crater Lake caldera, Cascade Range, USA. Journal of Volcanology and Geothermal Research. 18:57-155.

Cooper, S. V.; Neiman, K. E.; Roberts, D. W. 1991. Forest habitat types of northern Idaho: a second approximation. Gen. Tech. Rep. INT-236. Ogden, UT: U.S. Department of Agriculture, Forest Service, Intermountain Research Station. 143 p.

Ferguson, D. E. 1991. Allelopathic potential of western coneflower (*Rudbeckia occidentalis*). Canadian Journal of Botany. 69:2806-2808.

Ferguson, D. E. 1999. Effects of pocket gophers, bracken fern, and western coneflower on planted conifers in northern Idaho—an update and two more species. New Forests. 18:199-217.

Ferguson, D. E.; Boyd, R. J. 1988. Bracken fern inhibition of conifer regeneration in northern Idaho. Res. Pap. INT-388. Ogden, UT: U.S. Department of Agriculture, Forest Service, Intermountain Research Station. 11 p.

Ferguson, D. E.; Johnson, F. D. 1996. Classification of Grand Fir Mosaic habitats. Gen. Tech. Rep. INT-337. Ogden, UT: U.S. Department of Agriculture, Forest Service, Intermountain Research Station. 16 p.

Finklin, A. I. 1983a. Summarizing weather and climatic data—a guideline for wildland managers. Gen. Tech. Rep. INT-148. Ogden, UT: U.S. Department of Agriculture, Forest Service, Intermountain Forest and Range Experiment Station. 43 p.

Finklin, A. I. 1983b. Climate of Priest River Experimental Forest, northern Idaho. Gen. Tech. Rep. INT-159. Ogden, UT: U.S. Department of Agriculture, Forest Service, Intermountain Forest and Range Experiment Station. 53 p.

Gliessman, S. R. 1976. Allelopathy in a broad spectrum of environments as illustrated by bracken. Linnean Society Botanical Journal. 73:95-104.

Haig, I. T.; Davis, K. P.; Weidman, R. H. 1941. Natural regeneration in the western white pine type. Tech. Bull. 676. Washington, DC: U.S. Department of Agriculture, Forest Service. 99 p.

Johnson, C. G., Jr.; Clausnitzer, R. R. 1992. Plant associations of the Blue and Ochoco Mountains. R6-ERW-TP-036-92. U.S. Department of Agriculture, Forest Service, Wallowa-Whitman National Forest. 207 p.

Johnson-Maynard, J. 1995. Alteration of andisols in the Grand Fir Mosaic Ecosystem following invasion by bracken fern successional plant communities. University of Idaho. Moscow. M.S. thesis. 91 p.

Johnson-Maynard, J. L.; McDaniel, P. A.; Ferguson, D. E.; Falen, A. L. 1997. Chemical and mineralogical conversion of andisols following invasion by bracken fern. Soil Science Society of America Journal. 61:549-555.

Johnson-Maynard, J. L.; McDaniel, P. A.; Ferguson, D. E.; Falen, A. L. 1998. Changes in soil solution chemistry of andisols following invasion by bracken fern. Soil Science. 163:814-821.

Marsh, R. E.; Steele, R. W. 1992. Chapter 10—Pocket gophers. In: Black, H. C. (tech. ed.). Silvicultural approaches to animal damage management in Pacific Northwest forests. Gen. Tech. Rep. PNW-287. Portland, OR: U.S. Department of Agriculture, Forest Service, Pacific Northwest Research Station: 205-230.

Nimlos, T. J.; Zuuring, H. 1982. The distribution and thickness of volcanic ash in Montana. Northwest Science. 56:190-198.

Shoji, S.; Nanzyo, M.; Dahlgren, R. A. 1993. Volcanic ash soils: genesis, properties, and utilization. Elsevier Science Publishers. Amsterdam, The Netherlands. 288 p.

Sommer, M. R. 1991. Soils of the Grand Fir Mosaic. University of Idaho. Moscow. M. S. thesis. 97 p.

Stewart, R. E. 1975. Allelopathic potential of western bracken. Journal of Chemical Ecology. 1:161-169.

Teipner, C. L.; Garton. E. O.; Nelson, L., Jr. 1983. Pocket gophers in forest ecosystems. Gen. Tech. Rep. INT-154. Ogden, UT: U.S. Department of Agriculture, Forest Service, Intermountain Forest and Range Experiment Station. 53 p.

RMRS
ROCKY MOUNTAIN RESEARCH STATION

The Rocky Mountain Research Station develops scientific information and technology to improve management, protection, and use of the forests and rangelands. Research is designed to meet the needs of National Forest managers, Federal and State agencies, public and private organizations, academic institutions, industry, and individuals.

Studies accelerate solutions to problems involving ecosystems, range, forests, water, recreation, fire, resource inventory, land reclamation, community sustainability, forest engineering technology, multiple use economics, wildlife and fish habitat, and forest insects and diseases. Studies are conducted cooperatively, and applications may be found worldwide.

Research Locations

Flagstaff, Arizona
Fort Collins, Colorado*
Boise, Idaho
Moscow, Idaho
Bozeman, Montana
Missoula, Montana
Lincoln, Nebraska
Reno, Nevada
Albuquerque, New Mexico
Rapid City, South Dakota
Logan, Utah
Ogden, Utah
Provo, Utah
Laramie, Wyoming

*Station Headquarters, Natural Resources Research Center, 2150 Centre Avenue, Building A, Fort Collins, CO 80526