Ecological effects of weather modificiation, Bridger Range area, Montana : relationships of soil, vegetation and microclimate
by Bruce Albert Buchanan

A thesis submitted to the Graduate Faculty in partial fulfillment of the requirements for the degree of DOCTOR OF PHILOSOPHY in Crop and Soil Science
Montana State University

Abstract:
Ecological effects of weather modification were studied for two years near Bozeman, Montana in a lodgepole pine zone characterized by open meadow, ecotone (transition), and forest. A program to study the effects of seeding winter orographic clouds on precipitation is being conducted by Montana State University in the Bridget Range area. The objective of this study was to determine effects of winter precipitation on factors that maintain the vegetational patterns. Data was collected along transects that extended across the vegetational types and a gradient of snow depth.

Factors correlated with snow depth in the meadow include: soil pH (-), soil phosphorus (+), frequency of Festuca, Lupinus, Achillea, Danthonia, Dodecatheon, and Myosotis (all -), and frequency of Viola, PhIeum, Stipa, Bromus, and native lodgepole pine seedlings (all +). Factors correlated with snow depth in the ecotone include: soil pH (-), soil phosphorus (+), frequency of Lupinus, Danthonia, Dodecatheon, and Myosotis (all -), frequency of Erythronium. Viola, Claytonia, Phleum, Stipa, and Bromus (all +), and ground level summer precipitation (-). Factors correlated with snow depth in the forest includes soil calcium (+), frequency of Arnica, and lodgepole pine greater than 2 m tall (both -), frequency of Achillea and Koeleria (both +), and ground level summer precipitation (+).

Soil profile descriptions, plant frequency, and microclimatic measurements indicated that the forest community is discrete and areas classified as ecotone are relic meadows. Trees are presently invading meadows. The rate of this enchroachment will likely increase with increases in winter precipitation, as suggested by the correlation between survival of planted lodgepole pine seedlings and maximum snow depth measured in the spring of 1970. Factors that maintain vegetation patterns and that could be affected by weather modification include growing season length and the availability of nutrients and soil moisture.

Available soil moisture was emphasized in this study and was measured with neutron scatter equipment periodically from September 1968 thru September 1970. High soil moisture stress occurred sooner in meadow than in ecotone or forest. Deep snow tended to delay the onset of high soil moisture stress. An important conclusion of this study was that late season soil moisture availability was positively correlated with snow depth. This relationship of snow depth with soil moisture explains, in part, the correlation between survival of planted lodgepole pine seedlings and snow depth.

ECOLOGICAL EFFECTS OF WEATHER MODIFICATION, BRIDGER RANGE AREA, MONTANA: RELATIONSHIPS OF SOIL, VEGETATION AND MICROCLIMATE

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ABSTRACT

Ecological effects of weather modification were studied for two years near Bozeman, Montana in a lodgepole pine zone characterized by open meadow, ecotone (transition), and forest. A program to study the effects of seeding winter orographic clouds on precipitation is being conducted by Montana State University in the Bridger Range area. The objective of this study was to determine effects of winter precipitation on factors that maintain the vegetational patterns. Data was collected along transects that extended across the vegetational types and a gradient of snow depth.

Factors correlated with snow depth in the meadow include: soil pH (-), soil phosphorus (+), frequency of *Festuca*, *Lupinus*, *Achillea*, *Danthonia*, *Dodecatheon*, and *Myosotis* (all -), and frequency of *Viola*, *Phleum*, *Stipa*, *Bromus*, and native lodgepole pine seedlings (all +). Factors correlated with snow depth in the ecotone include: soil pH (-), soil phosphorus (+), frequency of *Lupinus*, *Danthonia*, *Dodecatheon*, and *Myosotis* (all -), frequency of *Erythronium*, *Viola*, *Claytonia*, *Phleum*, *Stipa*, and *Bromus* (all +), and ground level summer precipitation (-). Factors correlated with snow depth in the forest includes soil calcium (+), frequency of *Arnica*, and lodgepole pine greater than 2 m tall (both -), frequency of *Achillea* and *Koeleria* (both +), and ground level summer precipitation (+).

Soil profile descriptions, plant frequency, and microclimatic measurements indicated that the forest community is discrete and areas classified as ecotone are relic meadows. Trees are presently invading meadows. The rate of this enchroachment will likely increase with increases in winter precipitation, as suggested by the correlation between survival of planted lodgepole pine seedlings and maximum snow depth measured in the spring of 1970. Factors that maintain vegetation patterns and that could be affected by weather modification include growing season length and the availability of nutrients and soil moisture.

Available soil moisture was emphasized in this study and was measured with neutron scatter equipment periodically from September 1968 thru September 1970. High soil moisture stress occurred sooner in meadow than in ecotone or forest. Deep snow tended to delay the onset of high soil moisture stress. An important conclusion of this study was that late season soil moisture availability was positively correlated with snow depth. This relationship of snow depth with soil moisture explains, in part, the correlation between survival of planted lodgepole pine seedlings and snow depth.

INTRODUCTION

Man, like any other organism, has a relationship with his environment; it can be one of balance or one of imbalance. The decision is unique to man most of the time, and imbalances are often the unforeseen consequences affecting environmental quality. These consequences are thought by Cooper (1970) to be a result of man's increasing technological ability to interfere constructively in natural ecological processes.

A technological ability that was recognized by man in the early thirties is artificial modification of weather (Fleagle 1969). Now, it is an accomplished fact that cloud seeding can produce an increase in rain and snow from orographic clouds (Dennis 1970). Because weather modification could be responsible for unforeseen consequences, this study was initiated. Effects of weather modification could influence: 1) law and legislation, 2) human behavior, 3) international affairs, and 4) biological processes. This last possibility was the subject of this study.

The objective was to determine effects of an increase in winter precipitation on factors that maintain plant communities in the target area. It was hypothesized that for weather modification to bring about community change, it must significantly affect the maintaining factors. Measurements of available soil moisture and their relationship with snow depth was emphasized.

Research began during July 1968 and continued through September 1970 and was in part supported by two National Science Foundation Grants, GB 7302 and GB 20960.

Plate 1. Krummholz communities in the Bangtail study area. Photograph by Lyn Taylor, Earth Science Dept., M.S.U., May 29, 1969. Direction of prevailing wind is from center right (west) to lower left (east). Approximate slope is 7%, aspect NE, and elevation 2400 m.

Snow drifts associated with the trees may persist until July 15, nearly two months longer than snow in the open meadow. These krummholz communities are considered beneficial for late water yield and as recreational sites. They also provide aesthetic diversity not provided by solid forest (background) or vast meadow. Tree invasion is apparent in several areas of the meadow.

STUDY AREA

The Bridger Range is the target area of a current weather modification study at Montana State University. The Bangtail Ridge, located in the Bridger area, was selected for this study because it may be affected by the modification of winter precipitation.

LOCATION - The approximate center of the ridge (Bangtail Ranger Station) is located 24 km (15 mi) northeast of Bozeman, Montana, and 11 km (7 mi) due east of the Bridger Range. It extends along a northwest axis for approximately 11 km (7 mi) and reaches a maximum elevation of 2434 m (7982 ft).

An aerial mosaic made from zerox copies of aerial photographs is presented in Fig. 1 to show the complex pattern of vegetation. Generally, the light colored areas are meadows and the dark areas, forest. The areas associated with the forest-meadow interface and those appearing as a forest-meadow complex are thought to be transitional areas. These areas are referred to throughout the paper as the ecotone.

The name for this community follows the concept of Odum (1959) who describes the ecotone as a tension belt narrower than the adjoining communities commonly containing organisms from each and some that are characteristic of and often restricted to the community.

Also included in Fig. 1 are study site locations, roads and trails, and the 2194 m (7200 ft) and 2316 m (7600 ft) contours.

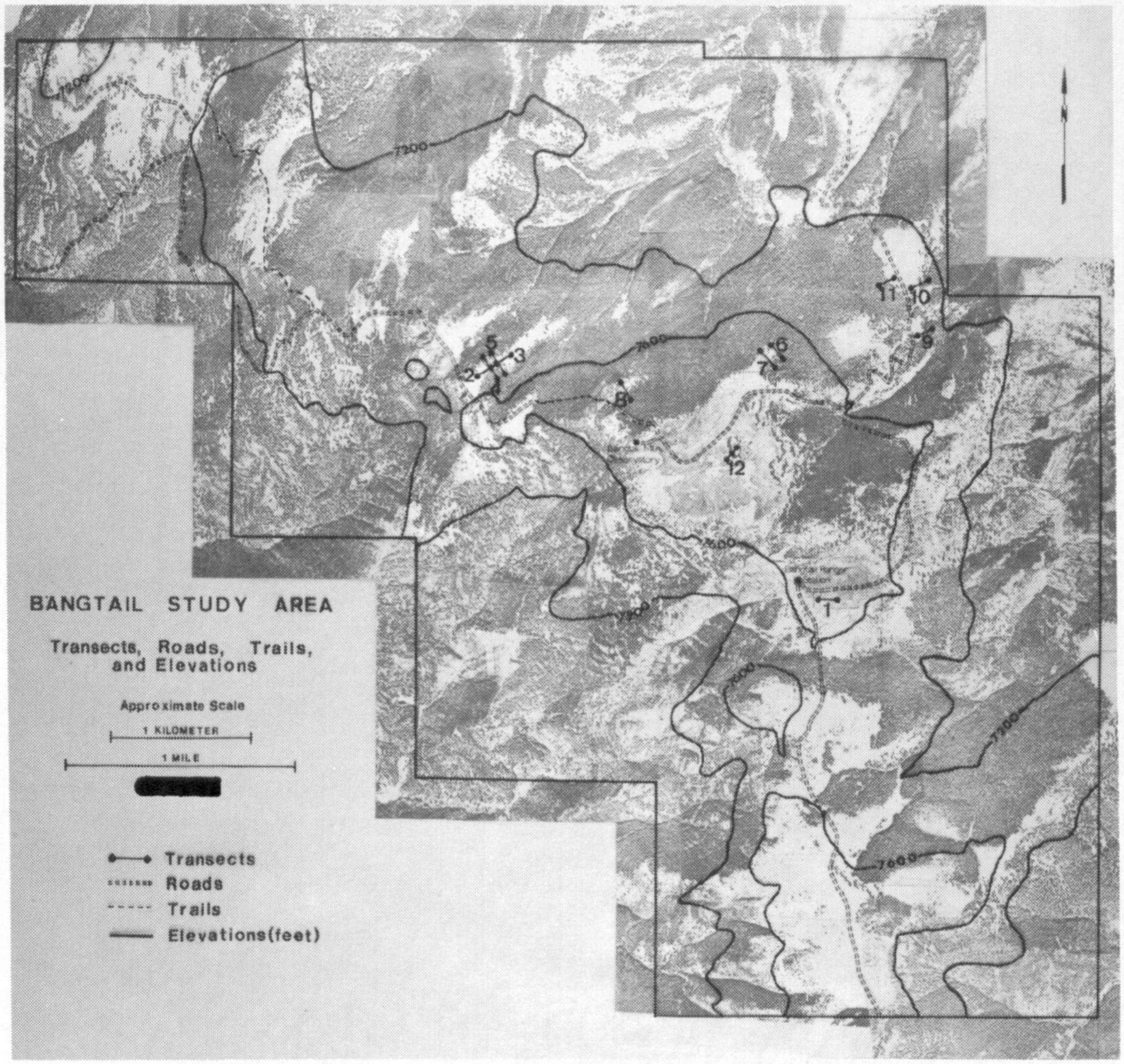

Fig. 1. Bangtail study area: transects, roads, trails, and elevations. Light areas are meadows, and dark areas, forest. Ecotones are associated with forest-meadow interfaces.

The mosaic represents an approximate area of 3,271 hectares and includes the following sections:

R.7 E., T.1 N.	Sec. 25, 26, 27, 35, 36
R.8 E., T.1 N.	Sec. 30, 31, 32
R.7 E., T.1 S.	Sec. 1
R.8 E., T.1 S.	Sec. 5, 6, 7, 8

The study site locations were restricted to the zone above 2194 m, an estimated area of 1755 hectares and classified as upper montane or as the lodgepole pine zone described by Moir (1969). Within the study zone the estimated area of forest is 580 hectares, of meadow 355 hectares, and that called ecotone 840 hectares.

SOIL - An intensive soil survey of the area was not available, but a National Atlas map of the principal soils of the United States shows that the general region is dominated by cool, moist Cryoboralfs (USDI G.S. 1967).

A reconnaissance soil survey of the study area was conducted during the fall of 1968 under the leadership of Mr. Dick Elvis, USDA Forest Service. The major objective was to prepare a map, Fig. 2, of the general soil resources of the study area. Nine soil units and associated vegetation types were distinguished. Characteristics of each unit are summarized in Tables 1a and 1b from the original report. A discussion of soil classification will follow in a later section.

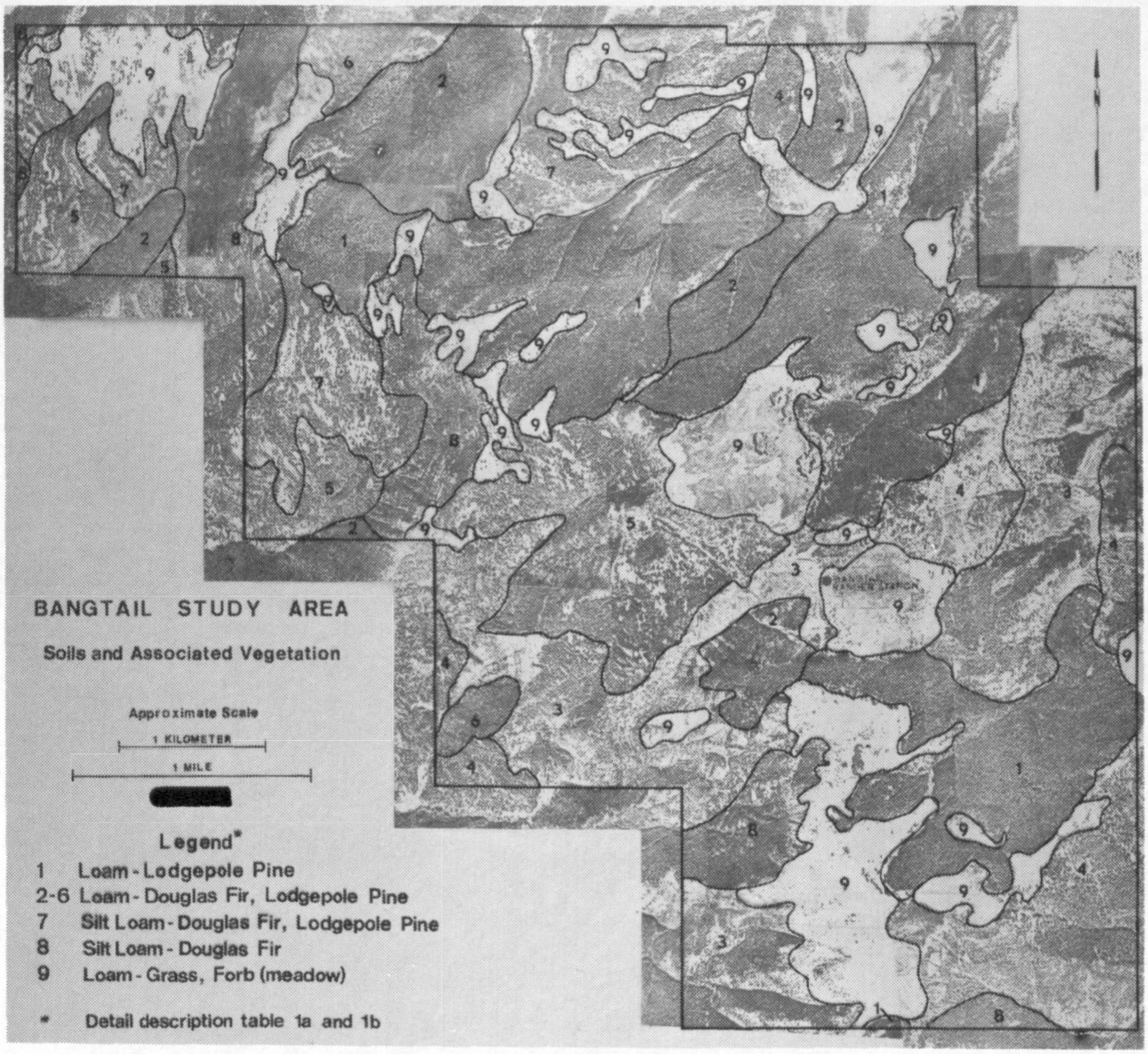

Fig. 2. Bangtail study area: soils and associated vegetation. Transects are located in Map Units 1 and 9.

Table 1a

Detailed Legend of the Soil Reconnaissance Map

Map Unit[1]	Surface A- Horizon						Subsoil B - Horizon				
	Texture	Structure	Consistence	Color	pH	Thickness[2]	Texture	Structure	Consistence	Color	pH
1-100	loam	weak granular	slightly sticky slightly plastic	dark brown	4.5	3-8	loam	weak subangular	slightly sticky slightly plastic	brown	4.5
2-100	"	weak subangular	"	dark grayish brown	"	10-16	clay loam	"	slightly sticky plastic	dark grayish brown	5.0
3-100	"	moderate granular	"	"	5.0	6-14	"	moderate blocky	sticky plastic	"	"
4- 55	"	"	"	very dark brown	"	6-16	"	"	slightly sticky plastic	dark brown	"
4- 25	"	"	"	"	"	"	"	"	"	"	"
4- 20	"	"	"	"	"	0-6	"	"	"	"	"
5- 35	"	"	"	"	"	6-16	"	"	"	"	"
5- 40	"	"	"	"	"	"	"	"	"	"	"
5- 25	"	"	"	"	"	0-6	"	"	"	"	"
6-100	"	weak granular	"	very dark grayish brown	5.5	8-14	loam	weak subangular	sticky plastic	brown	5.5
7-100	silt loam	"	"	dark brown	"	4-8	silty clay loam	strong blocky	"	"	5.0
8- 75	"	"	"	"	"	"	"	"	"	"	"
8- 25	"	"	"	"	"	"	clay loam	moderate blocky	"	"	"
9-100	loam	"	"	"	"	3-10	loam	moderate subangular	slightly sticky slightly plastic	"	5.5

[1]First number corresponds to mapping unit; the second to approximate area of unit as described.

[2]Thickness of A - horizon (inches).

Table 1b

Detailed Legend of the Soil Reconnaissance Map

Map Unit[1]	Bed Rock[2]	Vegetation[3]	Aspect	Clay Films	Drainage Features	Special Features
1-100	40-80	lp,f	north	faint films on ped and rock	undissected	occur on smooth dip slopes
2-100	30-60	df,lp,pg,f	"	discontinuous films on peds	slightly dissected	irregular slope
3-100	20-40	"	south	"	well dissected	occur on strike face and benches
4- 55	30-100	df,lp,pg,f,s,o	"	faint films on ped and rock	moderate dissected	occur on lower microstrike and colluvial
4- 25	6-30	"	"	"	"	occur on upper microstrike and microdip faces
4- 20	0-6	"	"	"	scabland	microdip scabland
5- 35	30-100	"	"	"	moderate dissected	lower strike and dip slopes
5- 40	6-30	"	"	"	"	dip slope and upper strike face
5- 25	0-6	"	"	"	scabland	dip slope scabland
6-100	50-100	df,lp,pg,f,o	north	indistinct	slightly dissected	strike faces
7-100	50-80	"	"	continuous films on peds	undissected	dip slope and strike slope
8- 75	30-80	df,lp,pg,f	"	"	"	strike faces
8- 25	6-30	"	"	"	"	"
9-100	50-100	o	"	faint films on ped and rock	slightly dissected "blowouts"[4]	dip slopes

1/First number corresponds to mapping unit; the second to approximate area of unit as described.

2/Depth to bedrock (inches).

3/Key: lp = lodgepole pine, df = douglas fir, pg = pinegrass, f = forbs, s = shrubs, o = open areas with grasses and forbs

4/"Blowouts" - These are thought to more likely be formed during periods of rapid snow melt where subsurface drainage reaches the surface in areas shallow to bedrock.

CLIMATE - Climatically, the area is typical of mountain regions having cool summers, and frost may occur in any month. The nearest weather station is located at an elevation of 1813 m (5950 ft) in Bridger Canyon, 19 km (12 mi) NE of Bozeman at the Forsythe Ranch and about 9 km (5.6 mi) northwest of the Bangtail Ranger Station. Data from the weather station (Bozeman 12 NE) can only be applied to the study area for general purposes but does provide a means of showing the relationship of 1969 and 1970 (years of data collection) climatic records to the average. Mean temperature and precipitation for the past 18 years of record at the nearby weather station and also the records for 1969 and 1970 (USWB) were reported as follows:

Observation		Station Bozeman 12 NE		
Temperature (C^o)		1953-1970	1969	1970
May	max.	14.2	16.7	13.9
	min.	-.6	-1.1	-1.7
June	max.	18.7	16.7	20.5
	min.	3.1	1.3	3.2
July	max.	24.6	23.5	24.2
	min.	4.9	3.6	4.2
August	max.	24.0	26.0	25.8
	min.	4.0	2.7	3.2

Observation	Station Bozeman 12 NE		
Precipitation (cm)	1953-1970	1969	1970
January	7.26	13.08	14.55
February	5.99	2.16	6.55
March	6.62	2.21	7.98
April	7.74	5.64	10.39
May	10.57	9.55	13.44
June	12.50	16.20	9.50
July	4.76	3.25	9.42
August	5.70	2.64	2.87
September	7.66	4.77	11.81
October	3.41	8.18	11.18
November	6.93	6.91	10.08
December	6.58	8.76	7.82
Total	85.72	83.35	115.59

None of the monthly means for 1969 and 1970 were significantly different from the 18-year average when tested at the 5% probability level. However, the snow pack for 1970 was recorded as a maximum for the years of record in the Bozeman area and was not considered a result of weather modification; areas not affected by seeding were also recorded as a maximum.[1]

The climatic record for 1969-1970 indicates temperatures were slightly cooler but very near the 18-year average. Precipitation for the two growing seasons (June, July, August) was nearly the same; average: 22.96 cm; 1969:22.09cm; 1970:21.76 cm. However, the August precipitation was lower both years than the 18-year average. In general, summer climate was very near average and winter precipitation was higher than average during 1969 and 1970. In Appendix Fig. 10, climatic data for two weather stations have been presented graphically to show that similar changes were recorded at another station in the Bozeman area.

PARENT MATERIAL - Geologically, the study area is relatively uniform and is underlayed by a common parent material of andesitic sandstone. The sediments are included in the Fort Union formation of Paleocene age and estimated to be 65 million years old.[2] Samples of bedrock were taken from various locations in the study area and verified by Gerry Dent and Jim Goolsby of the Earth Science Department, Montana State University. Because of the bedrock uniformity, the type of parent material has been excluded as a factor contributing to local vegetational differences.

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[1] P. E. Farnes, Snow Survey Supervisor, Snow Survey and Water Supply Forecast Unit, Soil Conservation Service, Bozeman.

[2] Dr. William McMannis, Professor of Geology, Earth Science Department, Montana State University, personal communication.

METHODS

TRANSECT - Permanent sampling sites were established across areas of naturally varying snow depth in the three main vegetation types (i.e., forest, ecotone, and meadow) to determine what environmental factors were related to the change in snow depth. The sampling sites were located every 10 m along variable length transects that are shown in Fig. 2. Four of the transects extended from forest to meadow, four from forest to ecotone, two from meadow to ecotone, and one across a meadow. A twelfth transect was located through a krummholz community.

The main criteria in selecting the location of a transect were: 1) that the ends should represent a "homogeneous" area of 100 m^2, and 2) there was no apparent evidence of slope or aspect change along the transect. The second criterion allowed the exclusion of slope and aspect as being factors affecting the change of vegetation along a transect.

The three vegetational classifications that are discussed throughout this paper were distinguished on the basis of tree density. Forest areas were defined as having more than 20 trees per 100 m^2. This included those trees of the first two size classes, i.e., 1) trees taller than 2 m, and 2) trees 0.5-2 m tall. A site was also considered forest if there was more than 10 trees per 100 m^2 of size class 1. Ecotone areas were defined as having a density of trees from 1-20 per 100 m^2 of size class 1) and 2), and from 1-10 trees per 100 m^2 of size class 1. Meadows were defined as having an absence of trees in size class 1) and 2). A total of 122 sampling sites were classified along the first 11 transects, 33-forest, 53-ecotone, and 36-meadow. Sample size was reduced for some analyses. Results from transect #12 (krummholz) are discussed separately in Appendix II.

SOIL - Soil profiles were examined at each transect end during July 1969 and pits were opened to the depth of bedrock. Only one pit was examined at the transect extending across the meadow and three pits were examined in the krummholz community. At each of the 24 soil profile sites, the following field data was recorded:

1. Principle horizons designated:
    a. Structure: grade, size, type
    b. Texture: clay and sand (% estimated)
    c. Color: moist and dry
    d. Pores: size and number
    e. Roots: size and number
    f. Coarse fragments (% estimated by volume)
    g. Bulk density: sample of known volume. Oven-dry weight determined later.

From each horizon, 2 kg of soil was sampled for laboratory analysis. Saturated pastes were made from undried subsamples to determine pH potentiometrically. Samples were then dried in a forced draft oven at 105° C and later sieved, separating the rock by a 2 mm round hole sieve. The samples were not ground, but peds were broken by lightly passing a rolling pin over them. The following methods of analysis were used for all samples:

	Method
Texture - sand, silt, clay, %	(Hydrometer)
Organic matter, %	(Sims & Haby 1971)
Available P, ppm	(Bray #1, Smith, et. al. 1957)
Available K, ppm	(Neutral normal NH_4OAC extractable)
Exchangeable Ca, ppm	"
Exchangeable Mg, ppm	"
Exchangeable Na, ppm	"
pH	(Saturated paste) potentiometric

The following analysis was made on selected samples:

Saturation %	(Saturated paste)
1/3 bar water holding capacity	(Pressure membrane)
15 bar water holding capacity	(Pressure membrane)
% rock weight	(Calculation from sieved samples)
Bulk density, rocks	(Paraffin method)
Bulk density, soil	"

VEGETATION - Tree density was determined for each species, for three size classes at each of the 122 sites. The three classes were: 1) trees taller than 2 m, 2) trees 2-0.5 m tall, and 3) trees less than 0.5 m tall. The last class is considered to designate the seedlings, realizing, however, that some of these trees may have been 10-25 years old or older. The quarter method (Greig-Smith 1964) was used to estimate seedling density. Density of the first two classes of trees was determined by counting individuals having more than half their basal area in a square quadrat that was 10 m on a side and centered on the sampling site. Tree density of these two size classes was used to distinguish the vegetation type as forest, ecotone, or meadow.

Presence of the identifiable plant species was recorded in each of four adjacent 1/4 m^2 quadrats located at each of the 122 sample sites. Samples representative of the first 11 transects were observed during the last two weeks of June and the last two weeks of July 1970. Species frequency was determined by measuring the number of occurrences in the four quadrats at each site.

MICROCLIMATE - The microclimatic data was recorded at both ends of every transect except the meadow transect where only one station was established. Three stations were operated at transect 12. An attempt was made to record data each Monday beginning in June and continuing through September of 1970. On occasion the area became inaccessible; therefore, data collections vary from 5-10 day periods and because of limited funds not all stations were fully equipped. The following kinds of data were collected, and sample size for each vegetation type is given:

Measurement		Sample Size Meadow	Ecotone	Forest
Precipitation	20 cm funnel gauge 30 cm above soil surface	7	6	8
50 cm soil temperature	Thermistor	7	6	8
50 cm soil temperature maximum and minimum	Taylor indoor-outdoor	6	5	5
50 cm air temperature maximum and minimum	Taylor	7	3	6
Pan evaporation	#1 wash tub (Sims & Jackson 1971)	4	3	3

Mean annual soil temperature was determined by averaging the soil temperature measurement at 50 cm for the 15th of March, June, September, and December (Smith, et. al. 1964). Average soil temperature at 50 cm for the growing season was determined as the average of measurements at 50 cm for the 15th of June, July, and August.

LODGEPOLE PINE - During the last week of June and the first week of July 1969, lodgepole pine, Pinus contorta, seedlings were planted 6 to a site 1 m apart at 89 of the 122 sampling sites. The trees were 2-0 stock donated by the USDA IFRES at Bozeman. Initial heights of the trees were measured the week following planting. Survival and tree height was recorded later as a measure of tree response to the environment. These measurements were taken the first week of August 1970 and again during the first week of July 1971. Survival for both years was calculated from the original number of trees planted, and growth as the difference of tree height from the previous year.

SOIL MOISTURE - Soil moisture was recorded at 25 sites, each transect end and the three sites along transect 12 beginning in October 1968 and continuing through September 1970. Moisture was measured using a Troxler model 1257 moisture meter and a model 1651 scaler-ratemeter. Aluminum access tubes were installed at each transect in holes opened by a King tube to a depth of 150 cm or bedrock. Access tubes extended 30 cm above the soil surface. The extension should have no effect on changing soil temperatures or moisture locally (Dickey, Ferguson, and Brown 1964; Hanks and Bowers 1960).

Readings were initially taken at 15 cm (6 in) intervals. In the fall of 1969, readings were taken to depths equivalent to the center of the major soil horizons. The position of the probe during a reading corresponded to the recommendation of Shultz[3/] (1967). This involved setting the center of the detector at the desired depth. Data for each date of collection was converted to water volume and graphed. From the moisture curve, data were extrapolated for each 20 cm depth and also for depths of 25 and 50 cm. Available water was calculated for each of these depths and for the total rooting profile depth.

[3/] Dr. J. Shultz, University of Alberta, was consulted about using the neutron probe. He suggested readings from 0-6 inches are unreliable and he is currently studying the influence of organic matter on neutron readings.

Soil moisture data were collected at irregular times between 1968 and 1970. Dates of collection are given with the plotted data in the Appendix, Fig. 11. Beginning in August of 1969, all 25 tubes had been installed and complete sets of data became available. Missing datum was primarily a result of difficulty in finding the access tube under the snow, although 2 m extensions had been attached to some tubes in the fall. Twice the neutron equipment needed repair; once during the summer of 1969 and then again during the winter of 1970; thus, readings were not obtained during those periods.

CALIBRATION AND INFILTRATION - The instrument was calibrated by determining soil moisture at five sites during late August 1970. To insure a broad range of moisture contents, water was added at two sites. This also provided data for estimating infiltration rates and the _in situ_ water retention at "field capacity." Water was added to a 10 cm diameter pipe nested inside a 20 cm diameter pipe until a constant rate of infiltration was established. Initially, 80-100 liters of water was added in one hours time, then an additional 100 liters of water was added. After two days, assuming that the soil was near field capacity, access tubes were installed and count ratios determined every 5 cm to the depth of bedrock.

The soil profile was then excavated and 4 liters of soil were sampled from each major horizon. The sample was weighed in the field and sieved through a 1/4 inch screen. The rock fragments were weighed and bagged.

The material passing through the sieve was subsampled, placed in sealed moisture cans and weighed in the laboratory. Both fractions were then dried at 105° C and percent water by weight was calculated. The average bulk density of material passing the sieve was estimated from the bulk density of the same horizon at nearby sites measured during earlier soil profile studies. The volume of water for the soil (rock and matrix) was estimated and correlated to the count ratio.

AVAILABLE MOISTURE - Plant "available" water was determined by subtracting the 15-bar water holding capacity from the measured value for that soil depth. Gravitational water in the profile was thought to exist for only a few days after local snow melt in the early spring. Since spring measurements were made a few weeks after snow melt, they should not include a measure of gravitational water. The lower limit of available water was chosen at the 15-bar water retention percentage with the realization that some plants, including lodgepole pine, may extract water at higher tensions. Moisture readings below the estimated 15-bar percentage and readings of zero have been termed a critical level of soil moisture. Water at these levels may limit the growth and survival of vegetation.

Available water use was calculated as follows: available water use = S-F+P.

Where:

S = available spring soil moisture

F = available fall soil moisture

P = growing season precipitation (June 14 - August 31, 1970)

Available water use is the reduction in that quantity of soil moisture hold by a tension of less than 15 atmospheres, plus rainfall. This method was similarly applied by Brown and Thompson (1965).

Multiple regression analysis was used to predict 15-bar and 1/3-bar water retention for each soil horizon from measurements for selected samples. These estimations also included several rock samples which were imbeded in sieved soil on the pressure membrane plate.

SNOW - Snow depth and snow water equivalent was measured on March 23 and 24, 1970, at what was considered to be the maximum snow pack at 131 sampling sites. Measurements were made with a federal snow sampler. These data include the 89 lodgepole pine planting sites, part of the 122 sampling sites, and nine sites in the krummholz.

POCKET GOPHER - A measure of pocket gopher (Thomomys talpoides) activity was recorded on July 4, 1971. At the first 122 sampling sites, bare ground (%), area covered by winter gopher cast (%), area covered by spring mounds (%), and number of casts and mounds was recorded in two adjacent 1/4 m^2 quadrats. Data from the two quadrats were averaged and then treated as a single observation.

To predict the weight of soil brought to the surface from surface area measurements of mound and cast workings, nine cast samples and six mound samples of estimated area and volume were collected, then air-dried at room temperature for five days and weighed.

CORRELATION ANALYSIS - The data were interpreted with the aid of regression analysis but mainly through the technique of correlation. Correlation coefficients are shown to express the mutual relationship of two variables emphasizing snow depth with characteristics of soil, vegetation, and microclimate.

The correlations and regressions were generated using a multiple regression program[4/] developed for the Sigma 7 computer at Montana State University.

The data were divided into two groups; 1) those relating to the study of lodgepole pine survival and 2) those associated with the 122 study sites along the 11 transects.

The 89 and 122 study sites allowed the possibility of showing relationships of vegetation with snow depth. Other soil and microclimatic measurements were collected at transect ends which represented 17 of 89 lodgepole pine sites and 22 of the 122 study sites. The sample size for relationships of vegetation, soil, microclimate, and snow depth was,

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[4/]This program was developed by Dr. R. E. Lund, Associate Professor of Statistics, Mathematics Department, Montana State University. Dr. Lund also helped with many of the techniques used to analyze the data.

therefore, increased to improve statistical reliability. This was done by extrapolating data from the transect end to "nearby" study site locations. In this case, nearby meant:

1. It was within 50 cm of the transect end.
2. It was of the same vegetational classification, e.g., forest, ecotone, or meadow.
3. The depth of solum and snow was statistically the same.

ANALYSIS OF MEANS - The t-distribution was used to test the null hypothesis that the mean difference was equal to zero. Variance was pooled for two samples, e.g., one from meadow data and one from ecotone data, and the t-value compared to a students t-distribution table (Snedecor and Cochran 1967). A comparison of means for meadow data with forest data or ecotone data with forest data involved calculating a new pooled variance. Means are compared horizontally in the tables and were never compared vertically.

RESULTS

SOIL - The soils described under forest, ecotone, and meadow are similar, especially in characteristics of the B and C horizons. They are classified in the coarse loamy family of Typic Cryoborolls. A typical pedon from a meadow (transect 2) is described below:

A_1 0-10 cm, dark brown (10YR 4/3) dry; sandy loam; very dark brown (10YR 2.2) moist; moderate very fine granular; slightly hard, very friable, slightly sticky, slightly plastic; clear smooth lower boundary; less than 1% coarse fragments; pH 5.2.

B_2 10-44 cm, dark brown (10YR 4/3) dry; loam; very dark grayish brown (10YR 3/2) moist; moderate coarse subangular blocky to weak prismatic; slightly hard, friable, slightly sticky, slightly plastic; gradual smooth lower boundary; 5% coarse fragments; pH 5.0.

C_1 44-62 cm, brown (10YR 5/3) dry; loam; very dark grayish brown (10YR 3/2) moist; moderate fine granular to weak medium subangular blocky; slightly hard, very friable, slightly sticky, slightly plastic; gradual smooth lower boundary; 5% coarse fragments; pH 5.0.

C_2 62-110 cm, brown (10YR 5/3) dry; loam; dark brown (10YR 3/3) moist; moderate fine granular; slightly hard, very friable, slightly sticky, slightly plastic; clear smooth lower boundary; 80% coarse fragments; pH 4.3.

R 110 cm, yellowish brown (10YR 5/4) dry; sandy loam between flaggy fragments of andesitic sandstone.

Means of soil characteristics, Table 2, represent data from 21 soil profiles (8-forest, 6-ecotone, 7-meadow), and horizons were selected on the basis of maximum expression. The major differences between soils under the different vegetation types appear in characteristics of the A_1 horizon. The distribution of phosphorous and the pH were exceptions being different in all three horizons. Most characteristics of the ecotone soils appear intermediate between forest and meadow, especially the distribution of nutrients. With the exception of the fine root measurement, the A_1 horizon of the ecotone is either like meadow or forest but never different from both. The ecotone soils are more often similar to meadow soils; thus, the steepest gradient of change appears between forest and ecotone rather than from meadow and ecotone. The horizons recognized in each soil profile and the depth of rooting are given in Appendix Table 20 for the three vegetation types.

Other characteristics measured but not given in Table 2 are the presence of charcoal and crotovinas (animal burrows filled with soil). Charcoal was found in every forest soil within the top 50 cm and on occasion, to depths of 80 cm. It was less common in ecotone soils and rarely found in the meadow soils. Crotovinas were observed in every meadow soil and were never seen in the forest. They are less common to the ecotones but were seen on occasion.

Table 2. Mean characteristics of A, B, and C horizons determined in field and laboratory for soils under meadow, ecotone, and forest[1/]

	Horizon*	Field Data**		
		Meadow	Ecotone	Forest
Upper boundary (cm)	A	0	0	0.7
	B	20ab	11b	24a
	C	53a	34b	53a
Thickness (cm)	A	12a	15ab	19b
	B	33	29	26
	C	44a	27b	32ab
Sand, field (%)	A	49	47	47
	B	41	40	44
	C	42	37	48
Clay, field (%)	A	18a	18a	23b
	B	24	24	27
	C	29	27	25
Rock, volume (%)	A	1	2	5
	B	35a	15ab	8b
	C	50	45	44
Roots-size Very fine/inch^2	A	12ab	14a	9b
	B	8	9	7
	C	5	8	4
Fine/inch^2	A	7a	14b	9a
	B	5	9	8
	C	<1a	8b	5b
Medium/foot^2	A	2a	2a	8b
	B	2a	3ab	7b
	C	0a	1b	2ab
Coarse/yard^2	A	<1a	1a	6b
	B	<1	1	2
	C	0	0	1

Table 2. Continued

	Horizon*	Field Data** Meadow	Ecotone	Forest
Pores-size	A	5ab	1a	8b
Very fine/inch^2	B	9	14	13
	C	7	11	10
Fine/inch^2	A	0	0	0
	B	2	0	2
	C	1	0	3
Structure				
Grade	A	2.0	1.8	2.0
1 = weak	B	1.9	2.0	2.0
2 = moderate	C	1.3	2.0	1.7
3 = strong				
Size				
1 = very fine	A	1.3a	1.5ab	2.6b
2 = fine	B	3.4	3.7	3.7
3 = medium	C	2.0a	3.8b	3.1ab
4 = coarse				
Type				
0 = structureless	A	1.0a	1.2ab	1.5b
1 = granular	B	2.3	2.0	2.0
2 = subangular	C	.8	1.5	1.4
3 = prismatic				
Color 10YR	A	4.1/2.7a	4.8/3.3b	4.9/3.2b
Dry	B	4.4/3.0	5.0/4.0	5.0/3.9
Value/chroma	C	6.0/4.2	5.5/4.0	5.5/3.9
Moist	A	2.7/1.9	2.8/2.2	2.2/2.1
Value/chroma	B	2.9/2.3	3.0/2.7	3.0/3.0
	C	4.0/3.5	3.5/3.7	3.6/3.1
Elevation (m)	all	2280	2310	2290
Bedrock depth (cm)	all	97	73	117
Rooting depth (cm)	all	110a	91b	110a

Table 2. Continued

	Horizon	Field Data** Meadow	Ecotone	Forest
Sand (%)	A	68ab	69a	64b
	B	62	59	63
	C	61	63	64
Clay (%)	A	6a	8a	11b
	B	10	11	12
	C	10	11	11
Bulk density (g/cm)	A	1.06	1.14	1.14
	B	1.29	1.25	1.25
	C	1.46	1.34	1.38
Saturation (%) wt:basis	A	50a	47a	40b
	B	41	38	36
	C	33	35	33
1/3 bar H_2O (%) wt:basis	A	25a	23ab	22b
	B	23	22	20
	C	20	20	18
15 bar H_2O (%) wt:basis	A	16a	15a	13b
	B	14	13	12
	C	12	12	12
pH sat:paste	A	5.6a	5.2b	5.1b
	B	5.4a	5.0ab	5.0b
	C	5.4a	5.0ab	4.8b
Organic matter (%)	A	5.4a	5.2a	3.9b
	B	3.9	3.4	3.0
	C	2.3	2.7	2.7

Table 2. Concluded

	Horizon*	Laboratory Data**		
		Meadow	Ecotone	Forest
Phosphorus (ppm)	A	36a	42a	110b
	B	32a	57b	100c
	C	31a	37a	84b
Potassium (ppm)	A	520	460	550
	B	250a	300ab	400b
	C	200	240	310
Calcium (ppm)	A	3240	2750	2280
	B	3190	2090	1970
	C	4310a	3830ab	2750b
Magnesium (ppm)	A	580	530	500
	B	650	520	500
	C	720	640	600
Sodium (ppm)	A	130	125	130
	B	150	180	130
	C	160	130	150

* Data characterize the A_1, B_2, and C_1 horizons, not transitional horizons.

**Means of the same horizon were tested by t-test and those followed by the same letter or no letter are not significantly different at P = .05.

1/Sample size for each vegetation type and horizon.

Horizon	Sample Size		
	Meadow	Ecotone	Forest
A	7	6	8
B	7	4	7
C	6	6	8

VEGETATION - Alpine fir (Abies lasiocarpa) tends to be more common in what was defined as forest, Table 3, and lodgepole pine (Pinus contorta) more common in the ecotone areas. Although the means are not significantly different, "younger" (2-0.5 m tall) lodgepole pine seem to be more common to the ecotone than the "older" (taller than 2 m) lodgepole pine. Means are significantly different for alpine fir where the "younger" trees are more common to the forest type than the ecotone. In these forest communities fir is expected to replace pine and become the climax species; whereas lodgepole pine will be the more common species to invade the meadow (Patten 1963). The density of lodgepole pine seedlings, Table 3, was less than alpine fir seedlings (size class 3) in the ecotone and meadow. However, when density for a vegetation type is converted to a relative percentage for all types of vegetation, lodgepole pine seedlings were more common to the ecotone and meadow than alpine fir (relative percentage is shown in Fig. 3).

Mean frequency of the identifiable species[5] is given in Table 4 for the three vegetation types. The steepest gradient of vegetational change appears to be from forest to ecotone; whereas the ecotone and meadow vegetation was similar in many respects as were the ecotone and meadow soils.

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[5] Representative samples of each species counted were identified by Dr. W. E. Booth, Professor of Botany, Department of Botany and Microbiology, Montana State University. Nomenclature follows Booth and Wright (1959) and Booth (1950).

Table 3. Mean density of tree species for three size classes at 122 sampling sites (transects 1-11) in meadow, ecotone, and forest

Trees and Size Class[1/]	Density (trees per hectare) Meadow	Ecotone	Forest
	n=36	n=53	n=33
Lodgepole pine 1	0a	230b	690c
Lodgepole pine 2	0a	370b	300b
Lodgepole pine 3	7a	310b	190b
Alpine fir 1	0a	38b	650c
Alpine fir 2	0a	150b	1210c
Alpine fir 3	13a	510b	4600c
Total trees 1	0a	268b	1350c
Total trees 2	0a	520b	1510c
Total trees 3	20a	820b	4790c

[1/] Size class

1. Taller than 2 m
2. 2 m-0.5 m tall
3. Shorter than 0.5 m ("seedlings")

* Means were tested by t-test and those followed by the same letter are not significantly different at P = .05.

Table 4. Mean frequency of identifiable plant species at 122 sampling sites (transects 1-11) in meadow, ecotone, and forest

Plant Species	Frequency* (%)/½m²		
	Meadow	Ecotone	Forest
	n=36	n=53	n=33
GRASSES & SEDGES			
Agropyron subsecundum[1/]	53a	10b	4b
Agrostis scabra	7	13	4
Bromus marginatus	68a	30b	0c
Carex geyeri[1/]	29a	74b	99c
Carex spp.[1/]	36a	19b	0c
Danthonia intermedia	37a	40a	7b
Festuca idahoensis	59a	75b	14c
Koeleria cristata[1/]	16a	15a	4b
Melica spectabilis	26a	12b	0c
Phleum alpinum	21a	21a	4b
Poa pratensis[1/]	12a	5ab	0b
Stipa columbiana[1/]	58a	39b	6c
FORBS			
Achillea millefolium	92a	90a	37b
Agoseris glauca	30a	22a	0b
Antennaria rosea	23a	15ab	5b
Arabis nolboellii[2/]	8	3	3
Arenaria congesta	34a	37a	3b
Arnica cordifolia	3a	10a	43b
Besseya wyomingensis[2/]	3ab	11a	0b
bryophytes	4a	13ab	24b
Campanula rotundifolia	49a	45a	17b
Cerastium arvense	54a	10b	0c
Claytonia lanceolata	70a	79a	9b
Collinsia parviflora[2/]	21a	1b	0b
Collomia linearis	24a	17a	0b
Delphinium bicolor	33a	31a	0b
Delphinium occidentale[2/]	4a	1b	0b
Dodecatheon conjugens	18a	12a	0b
Erigeron speciosus[2/]	8	5	0
Eriogonum umbellatum[2/]	14a	6ab	1b
Erythronium grandiflorum	11a	66b	48b
Galium boreale	28a	30a	8b

Table 4. Concluded

Plant Species	Frequency* (%)/½m² Meadow	Ecotone	Forest
	n=36	n=53	n=33
FORBS cont.			
Geranium viscossissimum	30a	23a	4b
Geum triflorum[2/]	3	10	4
Hackelia floribunda[2/]	5a	1b	0b
Lithophragma pariflora	26a	0b	0b
Lomatium cous[2/]	15a	0b	0b
Lupinus argenteus	38a	45a	9b
Myosotis sylvatica	49a	26b	1c
Polygonum bistortoides	10ab	14a	3b
Polygonum douglasii	53a	28b	1c
Potentilla gracilis	25	20	10
Saxaifraga rhomboidea[2/]	0	1	0
Senecio integremus	5a	15b	0c
Silene parryi[2/]	8a	1b	0b
Spergula arvensis	25a	15a	0b
Taraxacum officinale	21a	12ab	5b
Thalictrum occidentale[1/]	1a	4a	28b
Thlaspi arvensis	34a	25a	3b
Vaccinium scoparium	0a	4a	43b
Viola praemorsa	40a	45a	10b

[1/]Represents the dominant member of a group of 2 or more species that were not separately identified in the field. Probably species within the group are identified in the species list, Appendix Table 21.

[2/]These species have not been used in the correlation or regression analysis because their frequency is thought to represent an inadequate sample for those analysis. Species were eliminated that had a constancy x frequency less than 100.

*Means were tested by t-test and those followed by the same letter or no letter are not significantly different at P = .05.

Each species has been ranked by calculating its relative frequency in each vegetation type. Those that were thought to represent an adequate sample have been positioned in a triangle, Fig. 3, similar to a soil texture triangle. A species that was found exclusively in meadow, ecotone, or forest would appear at that apex of the triangle. A species excluded from the forest and equally distributed in meadow and ecotone is located along the triangle perimeter equal distance from the meadow and ecotone apex. Those equally distributed in all vegetation types would appear in the triangle center. Note, however, that there are no species completely ubiquitous, but a number of species appear equally distributed in both meadow and ecotone. These species might be considered as being more adaptable to different environments; thus, they express a wide ecological amplitude. The most restricted species are those close to an apex and are probably less adapted to environmental change.

The forest is dominated by species of Vaccinium, Thalictrum, Arnica, and trees. The meadow is characterized by Lithophragma, Cerastium, and Agropyron. Ecotone areas are less definable because they share species from both meadow and forest and none seem to be restricted to the area. This same difficulty arises in the field where one has little trouble distinguishing a meadow or a forest, but the limits of an ecotone (the transition area) become very arbitary.

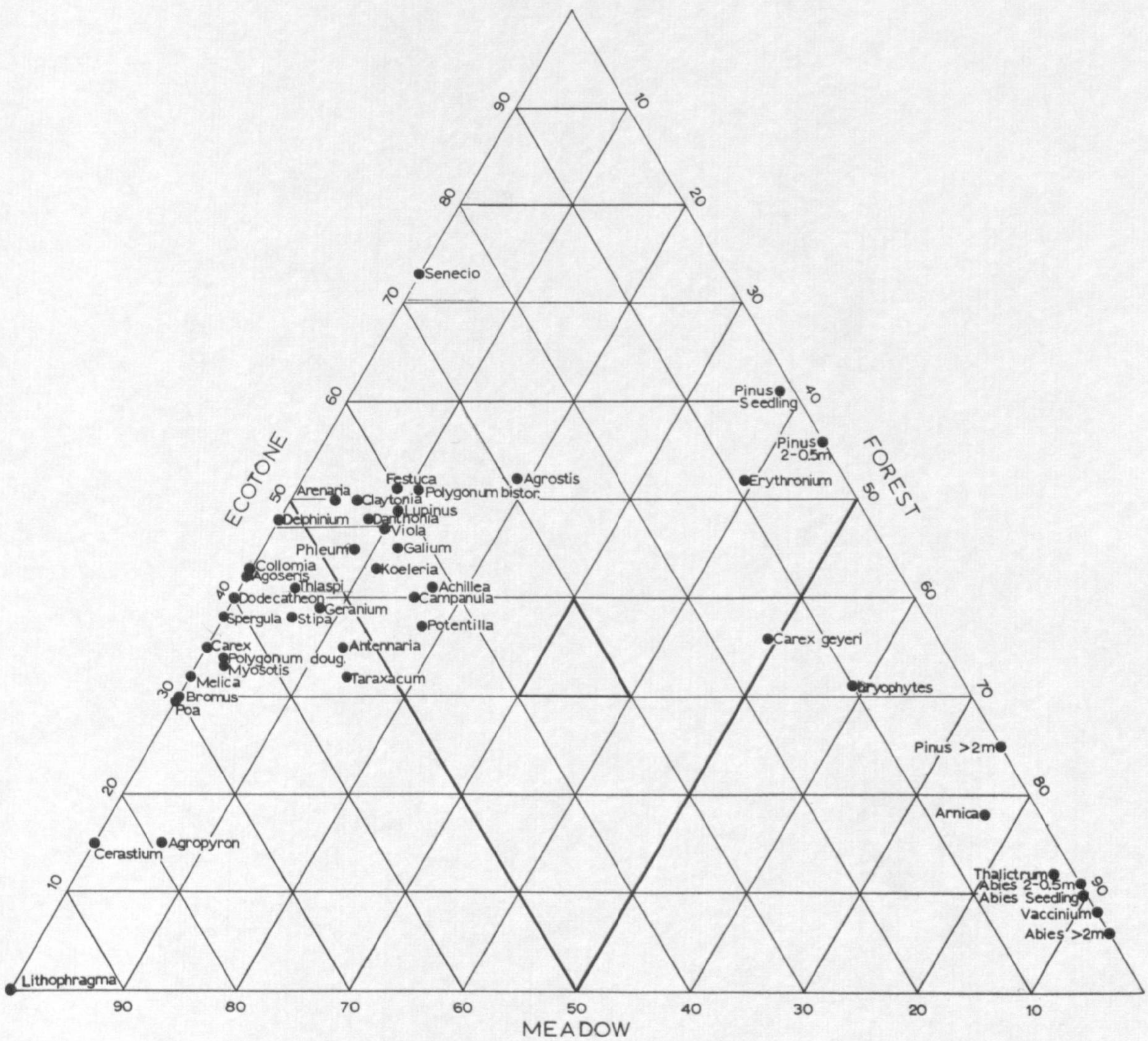

Fig. 3. Relative frequency distribution of plant species in forest, ecotone, and meadow. Species near an apex have a narrower ecological amplitude than species between apexes.

A species was considered to be associated with one of the vegetational classes if its relative frequency was greater than 50% in that class. Those not associated with meadow or forest by this criteria were than assigned to the ecotone.

Once the species had been ranked, they were listed in a correlation matrix beginning with species dominant in the forest and ending with species dominant in the meadow. The first matrix, Appendix Table 22, shows the correlation coefficients (r-value) that were significantly different from zero at the 5% level and positive. This same matrix is shown in Fig. 4 except the r-values have been replaced by dots that increase in size relative to the r-value.

Listed below are the first and last species associated with the three vegetation types which distinguish one type from another. The first species listed has the highest relative frequency and the last the lowest for that type.

Forest	Ecotone	Meadow
Abies >2 m	Carex geyeri	Delphinium
Bryophytes	Phleum	Lithophragma

In Fig. 4, the three types are distinguished by a wide line to be found between the above groups of species. Strong relationships between species appear in several areas of the matrix, and are indicated by the large dots.

Theorically, the matrix would appear as a diagonal of dots (corner

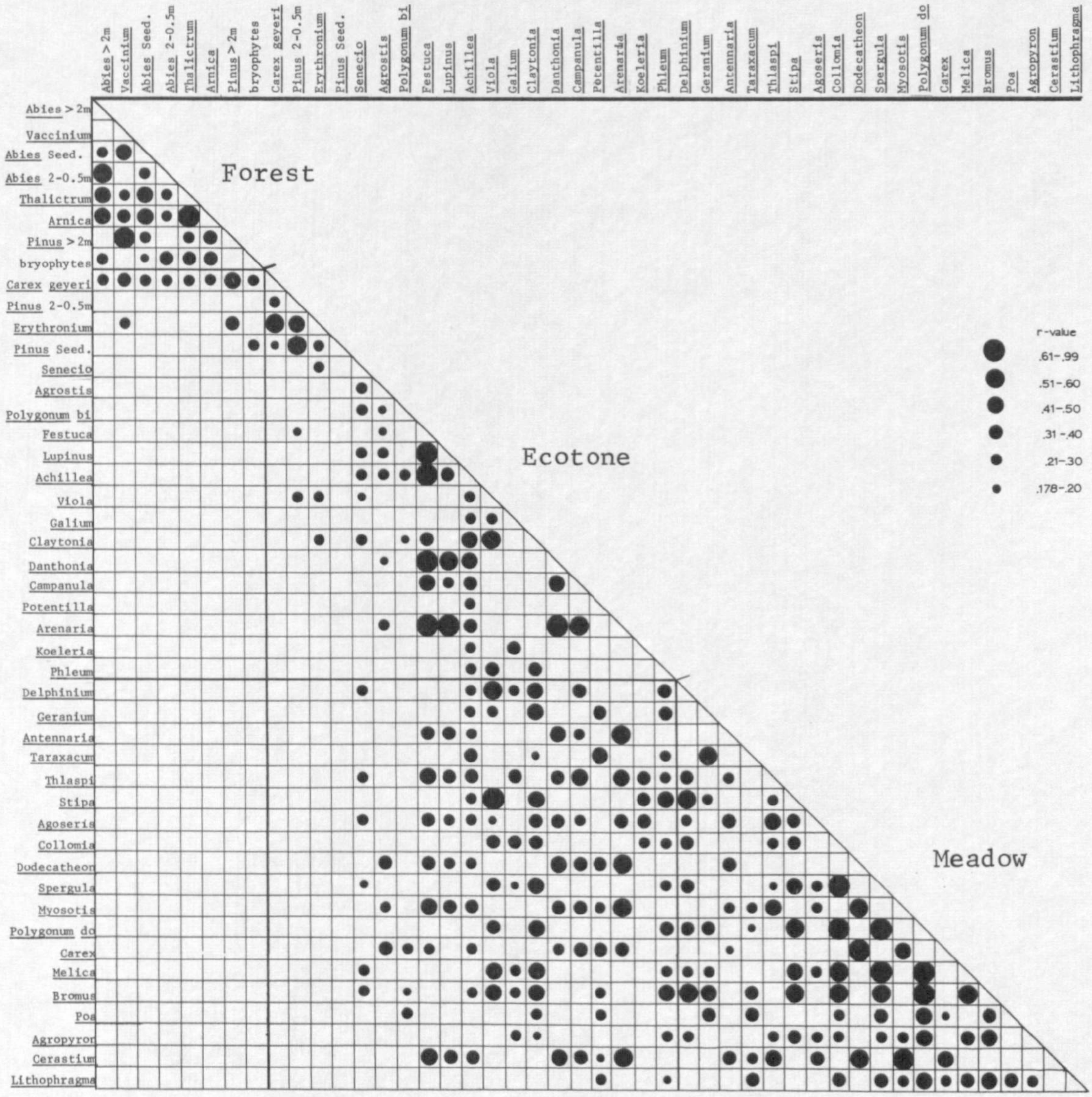

Fig. 4. Correlation matrix of plant species frequency ordered from those most common in the forest to those most common in the meadow. Degree of association increases with dot size. Only positive correlations significant at the 5% level are shown.

to corner) if those species having similar relative frequency were the only species correlated or related. Related here means found together or sharing the same environment. If a dot were to appear in the bottom left corner, it would indicate a relationship between a forest species and a meadow species. However, the forest species appear to be distantly related to the meadow species, meaning one would not expect to find forest species sharing the same local environment as meadow species.

When two or three species are closely related (sharing the same environment) they have been called species associations, e.g., the *Festuca* - *Agropyron* association of Daubenmire (1942) or the *Festuca* - *Agropyron* - *Antennaria* associations of Mueggler and Harris (1969). A few examples of associations for the Bangtail species are pointed out below.

Forest type

Vaccinium - *Thalictrum* - *Arnica*
Abies - *Pinus* (these are distantly related)

Ecotone type

Erythronium - *Pinus* (all sizes)
Festuca - *Lupinus* - *Achillea*

Meadow type

Spergula - *Polygonum* - *Melica* - *Bromus*
Myosotis - *Cerastium*

The distribution of dots and their sizes, Fig. 4, gives the general impression that most forest species are positively related only to other forest species, indicating a discrete community. Several species in the ecotone and meadow types, Fig. 4, are positively related to one another; but, only two species from meadow and ecotone are related to the forest species, Carex geyeri and Erythronium. Actually, Carex geyeri was combined with Calamogrostis rubescens in the field identification and therefore relationships cannot be considered as the true expression of only Carex geyeri.

The dispersion of dots away from the theorical diagonal in the ecotone and meadow type suggest the gradient of change between these types is less abrupt than the change between ecotone and forest. This supports the results for the soil studies.

MICROCLIMATE - The microclimatic measurements are summarized as means in Table 5. These values should be taken as indexes rather than the true mean of the climatic measurement since the data were collected at irregular intervals 4-5 times a month. Thus, the data are not true monthly means. However, as indexes, the data are comparable from site to site and give a general characterization of the different environments. The forest climate was less variable than the meadow and tended to be slightly cooler in summer (note 50 cm soil temperature). The forest climate was also less severe than the open meadow climate in terms of temperature extremes and water loss. Note the four-fold difference in pan evaporation from forest to meadow in August. Stations measuring precipitation were thought to be close enought so that differences between vegetation types represent interception by trees rather than

Table 5. Mean monthly climatic index values and mean annual soil temperatures for meadow, ecotone, and forest, 1970*

		Meadow	Ecotone	Forest
June	Temperature (^{o}C)			
	Air maximum	23	22	17
	Air minimum	-3	-3	-2
	Soil maximum, 5 cm	16	15	8
	Soil minimum, 5 cm	5	5	2
	Soil, 50 cm	7.3	6.0	3.2
	Precipitation (cm)	6.4	5.8	4.1
July	Temperature (^{o}C)			
	Air maximum	29	28	25
	Air minimum	3	2	3
	Soil maximum, 5 cm	22	21	12
	Soil minimum, 5 cm	9	9	8
	Soil, 50 cm	11.8	10.5	8.0
	Precipitation (cm)	8.7	9.1	6.4
August	Temperature (^{o}C)			
	Air maximum	30	30	26
	Air minimum	2	2	4
	Soil maximum, 5 cm	22	21	12
	Soil minimum, 5 cm	12	11	9
	Soil, 50 cm	13.0	11.5	8.8
	Precipitation (cm)	1.7	1.6	1.2
	Evaporation (cm/day)	0.51	0.46	0.13
September	Temperature (^{o}C)			
	Air maximum	22	21	18
	Air minimum	-6	-6	-4
	Soil maximum, 5 cm	17	15	10
	Soil minimum, 5 cm	6	6	6
	Soil, 50 cm	12.6	8.3	6.3
	Precipitation (cm)	6.8	6.2	5.7
	Evaporation (cm/day)	0.35	0.28	0.10
	Mean annual soil (^{o}C)	3.0	2.6	1.8

*Means were not compared statistically.

differences in rainfall. Although means were not compared statistically, the ecotone climate tends to be more like meadow than forest. This suggests that the steepest gradient of difference is between ecotone and forest.

LODGEPOLE PINE - A total of 534 trees were planted, 6 per site, at 26 forest, 28 ecotone, and 35 meadow locations. Survival, Table 6, was lowest in the meadow during both 1970 and 1971 and the same in the forest and ecotone areas. The average initial height was 19 cm for trees planted in each vegetation type and root length, although not measured, varied from approximately 20-50 cm. Trees in the meadow and ecotone had similar "growth" the first year, but the ecotone was more like the forest the second year. The best growth of the surviving trees was in the meadow. Mean height of the surviving trees was less than the initial height, thus growth appears to be negative. One reason the negative appears is because trees were considered living if they had green leaves, not new growth. Therefore, many trees that had been broken, eaten, or had lost the previous year's growth were considered as surviving although some may not continue living.

SOIL MOISTURE - Soil moisture profiles for each individual site on dates of collection are given in the Appendix, Fig. 11. These graphs (Fig. 11) for the individual sites were used to extrapolate soil moisture measurements for the same depth at all sites. Similar graphs are

Table 6. Mean survival and growth of planted lodgepole pine with other site factors measured at 89 planting sites in meadow, ecotone, and forest*

Lodgepole Pine 6/Site	Meadow	Ecotone	Forest
	n=35	n=28	n=26
Survival (% of original) 1970	25a	66b	66b
Survival (% of original) 1971	15a	48b	52b
Growth (cm - from previous yr.) 1970	-2.8a	-3.0a	-6.8b
Growth (cm - from previous yr.) 1971	-0.5a	-2.1b	-1.7b
Site Factors			
Trees taller than 2 m (#/ha)	0a	240b	1340c
Trees 2-0.5 tall (#/ha)	0a	480b	1680c
Lodgepole "seedings" (#/ha)	5a	130b	170b
Alpine fir "seedlings" (#/ha)	13a	780b	5660c
Solum depth (cm) (A and B horizons)	50a	49a	56a
Snow depth (cm) (March 23, 1970)	140a	180b	170ab

*Means were tested by t-test and those followed by the same letter are not significantly different at P = .05.

shown in Fig. 5 which represent the mean available soil moisture to a depth of 100 cm for the three vegetation types. They show that soil moisture throughout the soil profile was generally evenly distributed in the spring and similar for soils under each vegetation type. Moisture loss is best expressed by the graphs representing the August 1970 data, with forest soils having the most available moisture, the ecotone soils intermediate, and meadow soils the least in late August.

Mean available soil moisture for 25 cm, 50 cm, and to the depth of rooting is given in Table 7. Depth of rooting was used because it was thought to represent a meaningful zone estimating total water available to the vegetation. The 50 cm measurement was determined because it represents the approximate depth of solum (A and B horizon) and the approximate lower depth of maximum root expression (see Table 2). The 25 cm depth was thought to represent the depth to which first or second year tree seedlings would obtain most of their water.

An important point that should be seen in Table 7 is that available soil moisture to the depth of rooting was the same each spring in forest, ecotone, and meadow. The dates 6-21-69 and 6-14-70 represent this period and measurements are in centimeters of available water in the rooting profile. The ecotone appears to have slightly less total available water than forest or meadow, but this is partly a result of the ecotone having a shallower root zone (see Table 2). Available moisture near the end of the growing season, however, was distributed differently

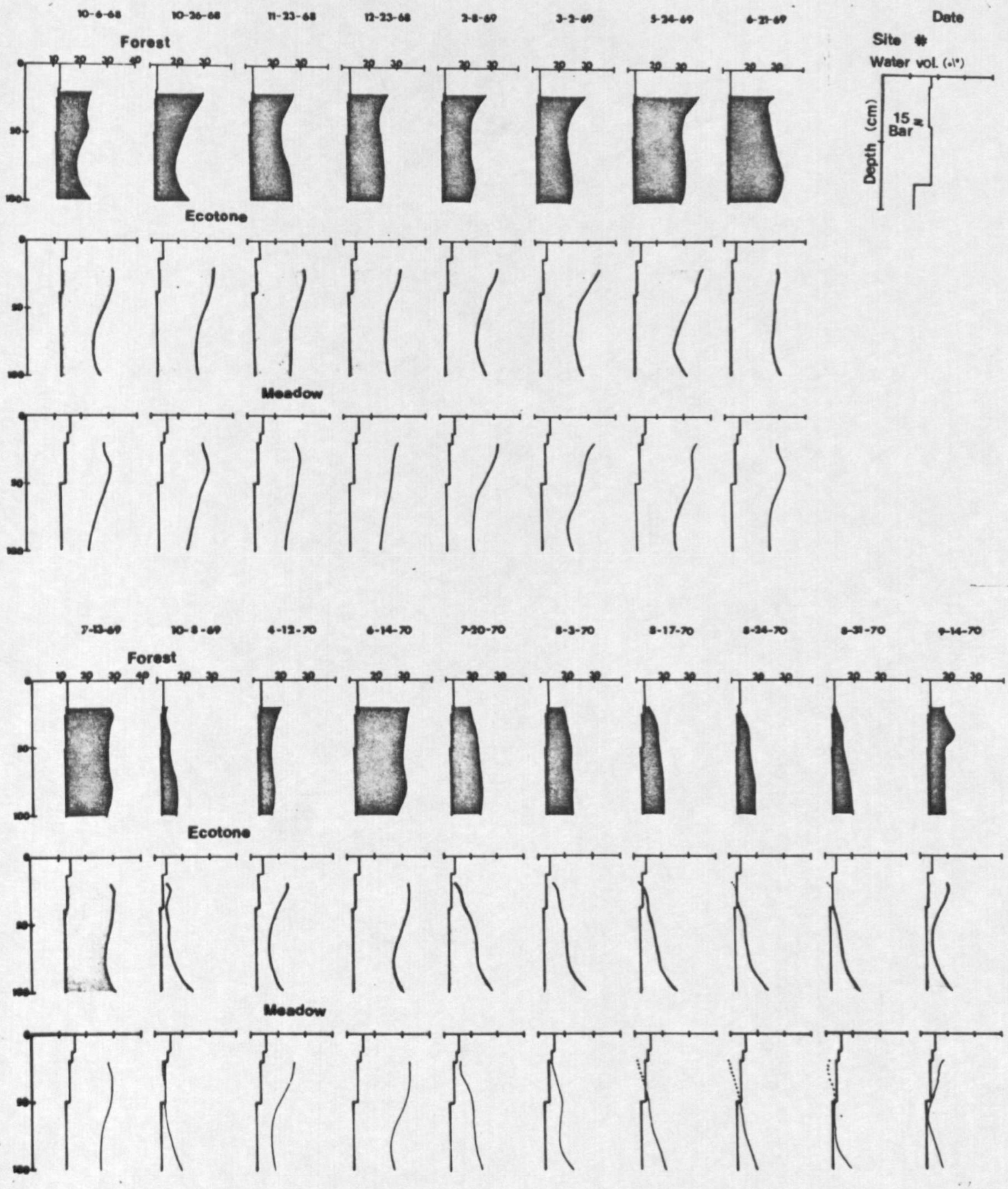

Fig. 5. Soil moisture distribution from 20-100 cm depths for dates of collection in forest, ecotone, and meadow. Curves show distribution of soil moisture by volume. Available soil moisture is represented by the area between curve and 15-bar retention line.

Table 7. Mean available soil moisture (volume basis) at 25 and 50 cm and depth of rooting for dates of collection in meadow, ecotone, and forest. Sample size for each mean can be determined from Fig. 11.

Date	Depth	Meadow	Ecotone	Forest	Date	Depth	Meadow	Ecotone	Forest
10-6-68	25	14.2a	18.4b	11.4ab	10-8-69	25	1.2a	3.0b	1.0ab
	50	16.3	16.3	11.2		50	.4	3.1	3.1
	root	13.6	12.9	12.0		root	2.4	2.7	4.0
10-26-68	25	14.9a	19.5b	17.1ab	4-12-70	25	11.3a	10.2a	6.5b
	50	15.9	17.5	11.2		50	7.4	5.6	4.4
	root	13.8	13.8	13.2		root	7.3	5.5	5.6
11-23-68	25	14.0	17.7	14.4	6-14-70	25	18.9	20.7	18.6
	50	15.0	15.7	11.1		50	18.3	18.9	17.5
	root	13.4	12.5	11.9		root	16.7	14.2	17.2
12-23-68	25	14.5	17.2	12.9	7-20-70	25	2.0ab	3.2b	7.4a
	50	14.0	14.8	12.1		50	7.2	8.8	9.7
	root	13.4	12.4	11.9		root	6.8	6.1	11.1
2-8-69	25	17.6	18.3	13.8	8-3-70	25	1.5	4.3	6.8
	50	13.2	14.1	10.4		50	5.8	8.3	9.1
	root	12.8	11.7	11.1		root	5.6	5.9	10.1
3-2-69	25	16.3ab	20.2b	15.3a	8-17-70	25	-2.5a	.7b	3.6b
	50	14.6	13.5	10.7		50	2.0a	4.6ab	6.3b
	root	13.7	12.3	12.8		root	2.8	3.9	6.8
5-24-69	25	20.4	23.0	22.4	8-24-70	25	-3.8a	-.5b	1.6b
	50	19.2	18.9	17.9		50	.7a	3.3b	4.7b
	root	17.0	15.4	19.2		root	1.5	2.3	5.3
6-21-69	25	15.4	16.2	14.4	8-31-70	25	-3.3a	-.7ab	1.7b
	50	17.3	16.0	16.3		50	.2a	2.3ab	4.0b
	root	15.4	12.9	17.2		root	1.4	1.6	5.1
7-13-69	25	14.6	17.4	16.7	9-14-70	25	3.0a	7.7ab	6.1b
	50	15.9	17.2	15.5		50	.7a	3.3ab	6.2b
	root	14.1	13.5	15.8		root	2.9	4.1	7.5

25 = available soil moisture (%) at 25 cm depth
50 = available soil moisture (%) at 50 cm depth
root = available soil moisture (cm) in profile to depth of rooting

*Means for the same date and depth followed by the same letter or no letter are not significantly different at P = .05.

being highest in the forest. Late season moisture data are best represented by the date 8-31-70 when forest was significantly different from both meadow and ecotone at the 10% probability level.

Water use, Table 8, was lowest in the forest soils, intermediate in the ecotone soils, and highest in the meadow soils for the period mid June to late August, the approximate growing season. It is also important to note, Table 7, that the meadow type reached what has been termed a critical moisture level before the end of the growing season. This is seen for the 1970 data at 25 and 50 cm depths. Forest and ecotone either reach this level later or not at all. Negative values represent the amount of water extracted at tensions greater than 15-bar, the "wilting point."

Data in Table 7 for forest and meadow are shown graphically in Fig. 6 and 7. The spring "maxima" show similarities between types and between years and the "minima" the differences in the fall. The frequency of observations was inadequate to define the "true" maximum and minimum.

The available soil moisture at 25 cm, Fig. 6, appears to increase during the period of December 1968 to March 1969 (over-winter), whereas soil moisture decreased at 50 cm. This phenomenon is explained by the concept that water moves toward a freezing front described for a similar situation by Ferguson, Brown, and Dickey (1964).

In the rooting profile, Fig. 7, there was very little water

Table 8. Mean water depletion in meadow, ecotone, and forest*

Water	Vegetation Type		
	Meadow	Ecotone	Forest
	n=8	n=6	n=8
Available spring soil moisture (cm) 6-14-70 (Table 7)	16.7 a-I	14.2 a-I	17.2 a-I
Available fall soil moisture (cm) 8-31-70 (Table 7)	1.4 a-I	1.6 a-I	5.1 a-II
Precipitation (cm) 6-14 thru 8-31, 1970 (Table 6)	16.8 a-I	16.5 a-I	11.7 b-II
Water use (cm)	32.1 a-I	29.1 a-I	23.8 b-II

*Means across types significantly not different at the 5% level are followed by the same letter; those at the 10% level by the same Roman numeral.

Note: Precipitation at the forest floor was 5.1 cm lower than meadow, largely representing interception. If this is added to forest water use the total use becomes 28.9 cm.

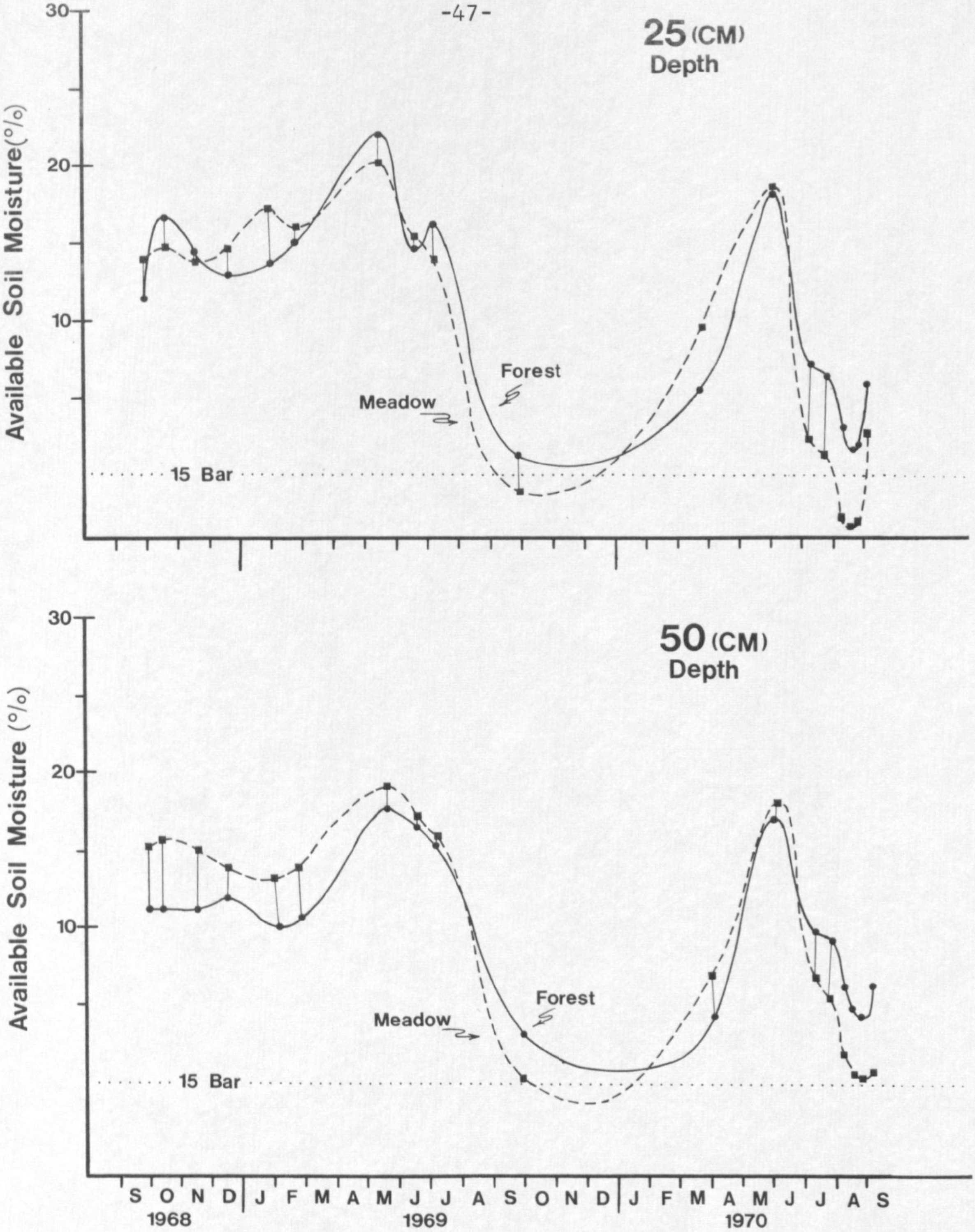

Fig. 6. Mean available soil moisture (vol. basis) at depths of 25 and 50cm for the period of Sept. 1968-70 in forest and meadow. Points connected by a vertical line are not significantly different at the 5% level.

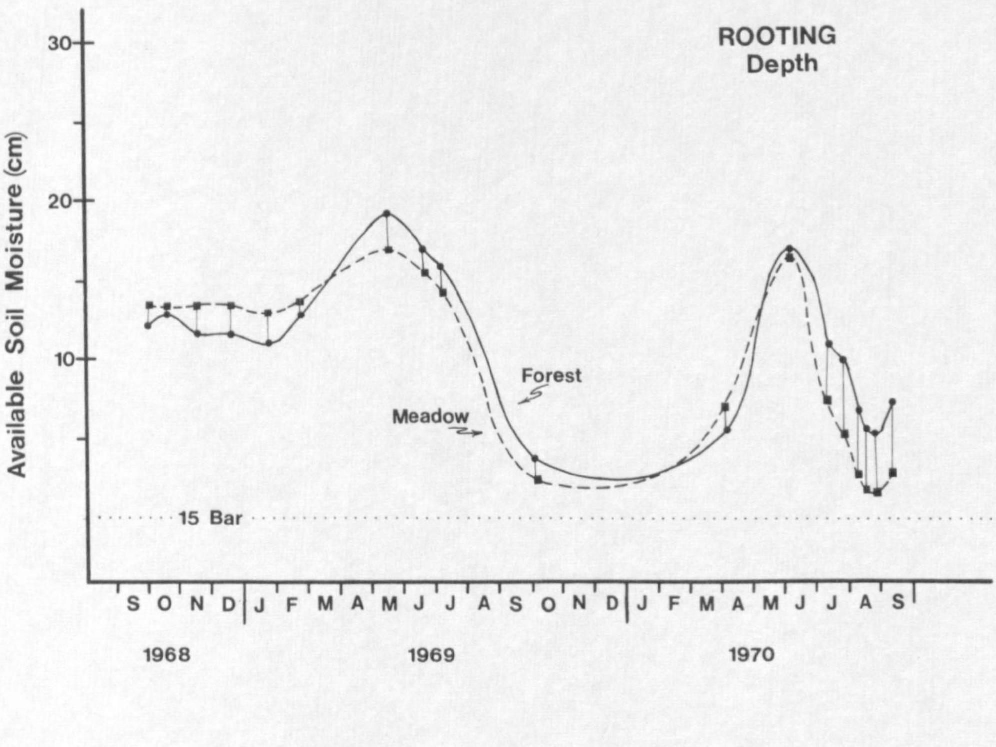

Fig. 7. Mean available soil moisture (volume basis) to the depth of rooting for the period of September 1968 - September 1970 in forest and meadow. Points connected by a vertical line are not significantly different at the 5% level.

movement for this over-winter period. Fig. 7 shows more available water to the depth of rooting during the winter of 1968-69 as compared to 1969-70. The difference is thought to be a result of prewinter precipitation. Precipitation records at Bozeman 12 NE (nearest weather station) for August, September, and October 1968 and 1969 were 39.3 cm (15.5 in) and 15.6 cm (6.1 in), respectively. Therefore, the soils were recharged with more water prior to winter in 1968 than in 1969.

Mean available soil moisture, Table 9, for forest, ecotone, and meadow is represented as centimeters of water per 20 cm of soil. Means have not been compared statistically but show trends similar to those in Table 7. These data are used later for the correlations of snow depth and soil moisture.

CALIBRATION AND INFILTRATION - Equation (1) below represents the curve to convert the neutron count ratio (measured count:standard count) to volume of soil moisture.

(1) $Y = A + B_1X_1 + B_2X_2$

where:

Y = soil moisture by volume
A = intercept = -3.975
B_1 = 48.50 (t-value = 21.18)
B_2 = 0.0696 (t-value = -5.57)
X_1 = count ratio
X_2 = rock weight (%) for that depth

and

$R^2 = .955$
$s_{y \cdot x} = 1.7$
$x = 24$

Table 9. Mean available soil moisture (volume basis) at five 20 cm depths for dates of collection in meadow, ecotone, and forest

		cm H_2O/20 cm Soil					cm H_2O/20 cm Soil		
Date	Depth	Meadow	Ecotone	Forest	Date	Depth	Meadow	Ecotone	Forest
10-6-68	10-30	2.7	3.6	2.4	10-8-69	10-30	-.3	.4	.3
	30-50	3.3	3.6	2.2		30-50	-.1	.5	.6
	50-70	3.1	2.7	1.9		50-70	.4	.5	.7
	70-90	2.4	2.4	1.5		70-90	.8	1.0	1.1
	90-110	2.0	2.9	2.5		90-110	1.6	2.2	1.0
10-26-68	10-30	2.8	3.9	3.4	4-12-70	10-30	2.2	2.0	1.5
	30-50	3.3	3.7	2.5		30-50	1.8	1.4	.9
	50-70	3.0	3.0	1.9		50-70	1.1	.9	.9
	70-90	2.5	2.8	1.5		70-90	1.0	1.0	1.1
	90-110	2.1	2.9	2.5		90-110	1.3	1.9	.9
11-23-68	10-30	2.6	3.4	2.9	6-14-70	10-30	3.7	3.9	3.7
	30-50	3.0	3.4	2.2		30-50	3.7	3.9	3.5
	50-70	2.9	2.8	2.3		50-70	3.4	3.4	3.5
	70-90	2.5	2.7	2.8		70-90	2.8	2.9	3.7
	90-110	2.3	2.6	3.0		90-110	3.0	3.7	3.0
12-23-68	10-30	3.0	3.5	2.8	7-20-70	10-30	.2	.3	1.2
	30-50	2.8	3.2	2.3		30-50	1.0	1.2	1.8
	50-70	2.7	2.7	2.5		50-70	1.6	1.9	2.1
	70-90	2.4	2.7	2.6		70-90	1.8	2.1	2.3
	90-110	2.3	2.9	2.4		90-110	2.3	3.2	2.2
2-8-69	10-30	3.5	3.6	3.1	8-3-70	10-30	.1	.5	1.1
	30-50	3.0	3.1	2.1		30-50	.7	1.3	1.7
	50-70	2.3	2.5	2.1		50-70	1.3	1.7	1.9
	70-90	2.0	2.4	2.4		70-90	1.5	1.8	2.0
	90-110	2.1	3.0	2.0		90-110	2.1	3.1	2.0
3-2-69	10-30	3.6	4.2	3.4	8-17-70	10-30	-.7	-.2	.4
	30-50	2.9	3.2	2.2		30-50	-.0	.6	1.2
	50-70	2.8	2.6	2.3		50-70	.6	1.0	1.4
	70-90	2.0	2.5	2.5		70-90	1.1	1.4	1.6
	90-110	3.0	3.1	2.2		90-110	1.7	2.7	1.6
5-24-69	10-30	4.0	4.8	4.7	8-24-70	10-30	-1.0	-.5	-.0
	30-50	3.8	4.4	3.6		30-50	-.3	.3	.9
	50-70	3.5	3.4	3.7		50-70	.4	.7	1.1
	70-90	2.7	2.8	3.9		70-90	.8	1.1	1.3
	90-110	3.4	3.7	3.4		90-110	1.5	2.4	1.4
6-21-69	10-30	2.9	3.2	3.2	8-31-70	10-30	-.7	-.5	.8
	30-50	3.6	3.2	3.1		30-50	-.3	.2	.7
	50-70	3.2	3.0	3.5		50-70	.1	.6	1.0
	70-90	2.7	2.9	4.1		70-90	.8	.9	1.3
	90-110	2.8	3.6	3.4		90-110	1.3	2.0	1.4
7-13-69	10-30	2.7	3.2	3.3	9-14-70	10-30	.8	1.4	1.1
	30-50	3.1	3.5	3.1		30-50	.3	1.1	2.0
	50-70	3.0	3.2	3.1		50-70	.1	.5	1.3
	70-90	2.6	3.0	3.2		70-90	.6	.7	1.3
	90-110	2.6	3.8	3.0		90-110	1.1	1.9	1.3

The curve was based on 24 soil samples collected from the 5 calibration sites. Soil moisture is the independent variable and represents percent water by volume for soil (fine earth and coarse fragments).

The standard calibration curve provided by the Troxler Company is shown below but was not used for this study. This curve is a calibration for a silt loam and does not account for the influence of coarse fragments.

$$Y = A + B_1X_1$$

where:

Y = soil moisture by volume
A = intercept = -5.09
B_1 = 63.33
X_1 = count ratio

Results from the infiltration study are shown in Fig. 8 for one site located near the profile described earlier (transect 2). The graph shows that water enters these soils very rapidly. Initial rate of infiltration (first 5 min) was measured to be 4 cm/min, 1 hour later at 2.7 cm/min, and an average rate of 0.8 cm/min after 2 hours. This last rate represents 19 in/hour.

AVAILABLE MOISTURE - The two equations developed to predict 1/3-bar and 15-bar water holding capacity are significant at the 5% level and are the result of fitting the best of some 15 "independent" variables. The dependent variable (water retention) was determined using the pressure membrane. The equations are considered functional for the soils in this study and may not apply to other soil types.

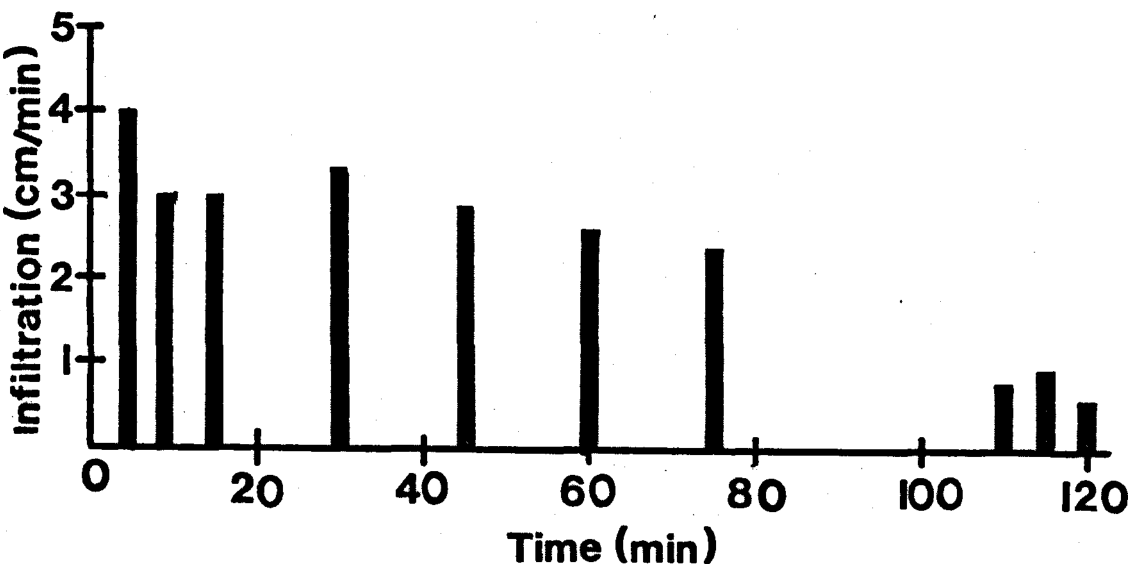

Fig. 8. Infiltration rate of a meadow soil located along transect 2, Bangtail study area. Profile description for this soil is given on the first page of the results section.

Equation (2) predicts 1/3-bar percentage

(2) $Y = A + B_1X_1 + B_2X_2$

where:

Y = 1/3-bar, % (weight basis)
A = 10.10
B_1 = 2.2
B_2 = 0.305
X_1 = (% organic matter)
X_2 = (% clay)

$s_{y \cdot x} = 2.56$
$R^2 = 0.566$
$F = 10.44$
$n = 19$

Equation (3) predicts 15-bar percentage

(3) $Y = A + B_1X_1 + B_2X_2 + B_3X_3$

where:

Y = 15-bar, % (weight basis)
A = 8.89
B_1 = 0.174
B_2 = -.156
B_3 = 0.348
X_1 = % silt
X_2 = % organic matter
X_3 = (% organic matter)^2

$s_{y \cdot x} = 1.12$
$R^2 = 0.778$
$F = 28.01$
$n = 28$

Two field capacity measurements are compared to the estimated 1/3-bar water retention in Table 10. Water retention at 1/3-bar generally was lower than either field measurement but similar to the gravimetric determination. The field gravimetric measurement was similar to the

Table 10. Field capacity of two soils by two methods and compared to the estimated 1/3-bar water retention

Location Transect #	Horizon	% Water by Volume: 1/3-Bar Retention Estimated	% Water by Volume: "Field Capacity" Gravimetric*	% Water by Volume: "Field Capacity" Neutron Scatter*
2m	A_1	27.8	27.3	
"	B_2	29.3	30.7	34.7
"	C_1	27.2	30.9	33.5
"	C_2	28.9	27.9	22.6
10m	A_1	26.3	41.7	
"	B_2	30.3	35.0	24.2
"	C_1	27.0	28.3	36.5

*Gravimetric measurements were based on samples analyzed for the two sites used to calibrate the neutron scatter equipment. Neutron scatter measurements were based on the soil moisture measured on June 14, 1970.

neutron scatter measurement but tends to be lower. It would appear from these few samples of soil moisture at "field capacity," 1/3-bar retention is lower than the estimate of field capacity (upper limit of available water) and further studies are needed to resolve the field capacity of these soils. Available soil moisture in this study was defined as the difference between the field measurement (neutron scatter method) and 15-bar water retention. Reliability of the 15-bar estimation can be inferred from Equation (3) and from the estimated available soil moisture in late August 1970 (Tables 7 and 9).

Combining data (Table 2) from all three vegetation types, the available water holding capacity (1/3 bar-15 bar) was an estimated 9% by weight or about 12% by volume; this is equivalent to 13 cm of water per 110 cm of soil (rooting profile). Spring measurements of available water holding capacity on the dates 6-21-69 and 6-14-70 were 16.0 and 17.0 cm of water in the 110 cm rooting profile. Snow pack measured in 1970 averaged a little more than 50 cm of water (Table 11), which exceeds the available water holding capacity of these soils by more than three times.

Rock is ordinarily not considered to be a source of water for vegetation. However, dense root mats were consistently observed on the upper surface of flat sandstone fragments in the soil profile. Therefore, effects of coarse fragments were considered in determining all 15-bar water retentions. The bulk density of the rock was 2.10. Its

1/3-bar and 15-bar water holding capacities were 8.0% (range 7.5-8.6). and 5.0% (range 4.8-5.5) respectively. Therefore, the "available water" was by weight 3.0% and by volume 6.3%. These rock samples were collected from A, B, and C soil horizons. Bedrock was excluded. Some rock samples were ground and passed through a 2 mm round hole sieve, and the average 1/3-bar and 15-bar water holding capacities by weight were 19.7% and 10.3%, respectively. Available water in the ground rock is very near that estimated for the soil matrix (Table 2).

SNOW DEPTH - The greatest accumulation of snow was measured in the ecotone (Table 11). Snow depths measured in the forest and meadow were similar. Deeper snow depths in the ecotone may be a result of snow drifting from the meadow and accumulating at the forest edge. Snow depth varies from year to year, however, a site will usually have the same relative difference when compared to other sites in the area[6/].
Therefore, the data are a relative indication of variation from site to site.

POCKET GOPHERS - Mean percentage of pocket gopher winter casts and summer mounds is given in Table 11. Also included in this table are the means of % bare ground, numbers of grass and sedge species, and numbers of forb species.

[6/] P. E. Farmes, personal communication.

Table 11. Mean snow depth, pocket gopher activity, % bare ground, and species measured at 122 sampling sites in meadow, ecotone, and forest

	Meadow	Ecotone	Forest
	n=36	n=53	n=33
Snow depth[1/] (cm)	145a	185b	171ab
Snow water equivalent[1/] (cm)	47a	60b	55ab
Pocket gopher activity[2/]			
Area as winter casts (%)	2a	2a	0b
Area as summer mound (%)	3a	1ab	0b
Bare ground (%)	9a	6a	<1b
Grass and sedge species (#/½m²)	6a	5a	2b
Forb species (#/½m²)	14a	12b	5c

1/Snow depth and snow water equivalent was measured March 23, 1970, at what was thought to be the maximum snow pack for that year.

2/Estimates of pocket gopher activity measured July 4, 1971.

* Means were compared by t-test and those followed by the same letter are not significantly different at P = .05.

The percent of area occupied by winter casts in the meadow was similar to ecotone and found to be zero in the forest. Summer mounds tend to be more common in meadow than ecotone but were absent in the forest. These results are similar to the findings on crotovina distribution.

Multiple regression analyses were attempted to estimate the amount of air-dry soil brought to the soil surface based on aerial cover estimations. Aerial estimations were in square centimeters and soil weights in grams. Because the data represented a narrow range, the reliability of the equation was questioned and is, therefore, not reported. Presented in Table 12 is the average weight (g) and area (cm^2) of cast and mound samples. Values represent the weight of soil as cast or mound for a unit of area completely covered by cast or mound. Diameter of cast samples ranged from 6-8 cm and averaged 7 cm.

Meadows appear to have more bare ground (Table 11) than ecotones but are statistically similar. Forest, however, has little or no bare ground exposed. Percent bare ground relates to several factors but suggests more disturbance in the meadow than forest. The ecotone being somewhat like the meadow.

Numbers of grass and sedge species (Table 11) are nearly the same for meadow and ecotone but drop sharply in the forest. Forb species follow a similar trend.

Table 12. Mean weight of winter casts and summer mounds for areas completely covered by casts or mounds

Units	Casts weight : area			Mounds weight : area		
g : cm^2	877	:	286	1039	:	520
kg : m^2	30	:	1	20	:	1
ton : acre	134	:	1	89	:	1

Example: The average air-dry weight of casts is 30 kg when casts completely cover one square meter.

CORRELATIONS - Frequently the false assumption is made that because two variables are related, a change in one causes a change in the other (Huntsberger 1967). Snow depth was significantly related to several variables measured in this study and it is hoped that the data are not misinterpreted to mean that a difference in one always causes an effect on the other. Because snow depth was measured once during a year when winter precipitation was above average, correlations show some relative relationships with snow, not its absolute effects.

LODGEPOLE PINE - Fig. 9 shows that mean survival of planted lodgepole pine seedlings (2-0 stock) increased with increasing snow depth. Snow depth was classified in 20 cm intervals extending from 80 cm to 240 cm. Mean survival of planted seedlings is the mean percent survival at four or more planting locations in each 20 cm snow class. Nine of the 89 observations represent inadequate samples (less than four per class) could not be classified; therefore, the graph represents 80 observations.

Equation 4 was developed from single observations representing the snow gradient in Fig. 9. It predicts a 7.2% increase in survival of planted lodgepole pine seedling with a 10% increase in mean snow depth.

Equation (4)

% survival = -25.17 + .46 (snow depth, cm)

R^2	= .319	correlation coefficient squared
$s_{y \cdot x}$	= 27.4	standard error
t	= 6.05	t-value for regression coefficient
n	= 80	sample size

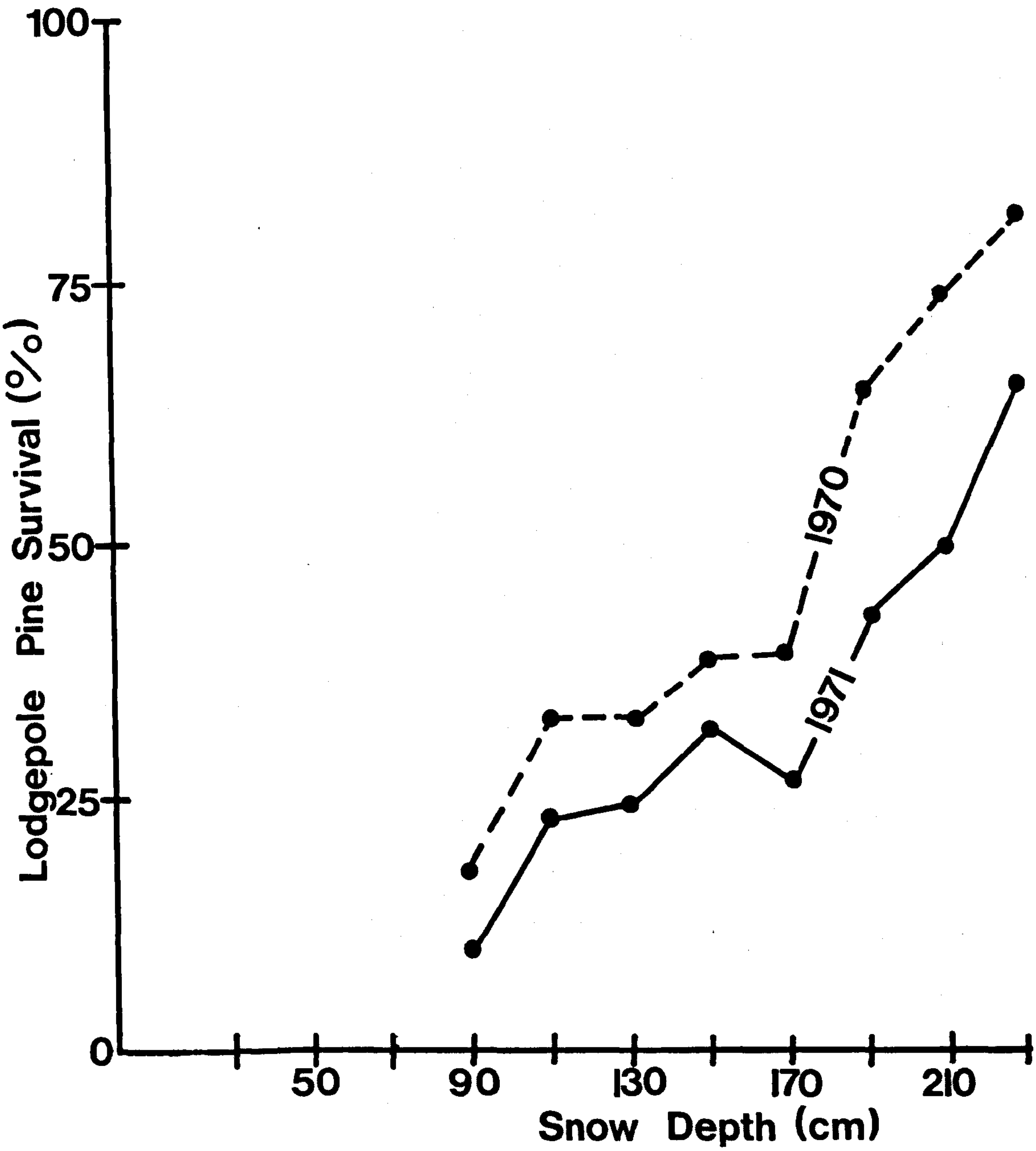

Fig. 9. Mean survival of lodgepole pine as related to snow depth.

This equation represents data from only one year and is not recommended as a method of predicting survival of planted stock from snow depth measurements. The purpose of this equation was to show the relative slope of survival as related to snow depth. A few observations of survival where snow depth was greater than 240 cm suggest that survival was not increased as predicted by Equation 4. Survival may actually decrease at deeper snow depths. Billings and Bliss (1959) have observed that conifer reproduction was uncommon at deep snow sites, a relationship partly explained by growing season length. The important conclusion is that within the 80-240 snow depth gradient, survival was significantly increased with increasing snow depth.

Some multiple regression techniques were applied to data representing all 89 planting locations. Because the results were similar to the above statistics and did not change the conclusion, they are only briefly mentioned. A total of 50 variables based on the 89 samples were tested as possible factors that would explain the variation in the survival of lodgepole pine. An equation fitting 15 variables was developed and the standard error was 20.4 as compared to 30.4 after fitting just snow depth for the same data. The decrease in error may be to an advantage if the absolute effect could be predicted. But for these studies the relative relationship of snow depth with other variables was emphasized.

LODGEPOLE PINE, SOIL, AND MICROCLIMATE - The following correlations are based on 74 observations from forest, ecotone, and meadow, and correlation coefficients (r-value) shown are significantly different from zero at the 5% level.

Shown in Table 13 are relationships of lodgepole pine survival (1970-1971) and snow depth with microclimatic and soil characteristics of the A_1 horizon. All characteristics correlated with snow depth are in each case also correlated with lodgepole pine survival and in the same direction, i.e., positive or negative. Most of the correlations are left to the reader's interest but generally lodgepole pine survival was best on sites that were cool, high in phosphorus, and low in calcium and magnesium.

Correlations of lodgepole pine survival (1970-1971) and snow with available soil moisture at different dates and depths are shown in Table 14. Snow depth was weakly correlated with available moisture in the spring (see July 13, 1969 and June 14, 1970), but strong relationships appear during August 1970.

Lodgepole pine survival in 1970 and 1971 follow the same trend and appear to increase with more available soil moisture in August. An interesting relationship is that beginning on August 3, 1970, survival was more strongly correlated with soil moisture in the top 50 cm than from 50-90 cm. Then on August 30, 1970, the relationships were stronger at 50-70 cm and weaker at 10-30 cm on August 3. This may indicate that

Table 13. Correlation coefficients for snow depth and survival of lodgepole pine with microclimatic and soil characteristics**

	Snow Depth	Survival Lodgepole Pine 1970	1971
Microclimate			
Snow depth	1.000	.403	.430
Soil Temperature 50 cm			
June	-.416	-.542	-.545
July	-.247*	-.486	-.512
August	-.365	-.543	-.576
September	--	--	--
Growing season	-.388	-.560	-.579
Evaporation, August	--	-.382	-.446
Soil A_1 Horizon			
Sand, %	--	--	--
Silt, %	--	-.269*	-.232*
Clay, %	--	.335	.330
1/3-bar, %	--	-.420	-.430
15-bar, %	--	-.481	-.467
pH	-.352	-.469	-.372
Organic matter, %	--	-.339	-.330
Phosphorus, ppm	.228*	.442	.448
Potassium, ppm	--	--	--
Calcium, ppm	--	-.309	-.283*
Magnesium, ppm	-.423	-.376	-.424

* r-values significant at the 5% level; all others at the 1% level.

**Correlation coefficients are based on 74 observations that include data from meadow, ecotone, and forest.

Table 14. Correlation coefficients for snow depth and survival of lodgepole pine with available soil moisture at different dates and depths**

Date	Soil Depth (cm)	Snow	1970	1971
July 13, 1969	10-30	--	--	--
	30-50	.267*	--	--
	50-70	.304	--	--
	70-90	--	--	--
	rooting	--	--	--
October 8, 1969	10-30	--	--	--
	30-50	.449	--	.262*
	50-70	.372	--	--
	70-90	.359	--	--
	rooting	.447	--	--
June 14, 1970	10-30	.333	--	--
	30-50	.342	--	--
	50-70	.289*	--	--
	70-90	--	--	--
	rooting	--	--	--
August 3, 1970	10-30	.437	.370	.388
	30-50	.560	.364	.386
	50-70	.605	.250*	.273*
	70-90	.539	--	--
	rooting	.645	.351	.397
August 17, 1970	10-30	.517	.471	.511
	30-50	.516	.422	.469
	50-70	.579	.279*	.318
	70-90	.563	--	--
	rooting	.599	.333	.335

Table 14. Concluded

Date	Soil Depth (cm)	Snow	1970	1971
August 30, 1970	10-30	.279*	.348	.360
	30-50	.378	.360	.399
	50-70	.430	.312	.360
	70-90	.575	--	--
	rooting	.535	.318	.324

* r-values significant at the 5% level; all others are significant at the 1% level.

**Correlation coefficients are based on 74 observations that include meadow, ecotone, and forest.

rooting = Observed depth of rooting.

lodgepole pine seedlings extract water from the upper 50 cm early in the season and at deeper depths later. At the time of planting seedlings, roots varied from 20-50 cm in length.

SNOW-SOIL-VEGETATION-MICROCLIMATE - The following correlations are based on data representing 100 observations, resulting from extrapolating transect end data to "nearby" sites. Each r-value is significantly different from zero at the 5% level unless otherwise stated and has been shown for all sites, for 34 meadow sites, 33 ecotone sites, and 33 forest sites.

SNOW AND SOIL - Correlations of snow depth and soil characteristics of the A_1 horizon are given in Table 15. Also included in the table is elevation, depth to bedrock and rooting, % of area as mounds and casts, and % bare ground. Correlations of snow depth with soil characteristics show no apparent trends between vegetation types. Characteristics related to snow depth in the forest were texture, number of very fine and fine roots, and calcium; in the ecotone, texture, pH, and phosphorus; and in the meadow, number of very fine and fine roots, pH, phosphorus, magnesium, and sodium.

Frequency of pocket gopher mounds and % bare ground is positively correlated with snow depth in the meadow only, whereas winter cast frequency was not correlated.

Table 15. Correlation coefficients for snow depth with soil characteristics and site characteristics**

	Snow Depth			
	All Sites	Meadow	Ecotone	Forest
	n=100	n=34	n=33	n=33
Soil Characteristics of A_1 Horizons				
Sand lab., %				.644
Silt lab., %			.345*	-.393*
Clay lab., %				.738
Sand field, %			.504	
Clay field, %	-.425	-.378*	.827	-.700
Saturation %				.462
1/3-bar %			-.405*	
15-bar %				
Roots, very fine		-.421*		.353*
Roots, fine		-.353*		.353*
Roots, medium				
pH	-.402	-.551	-.772	
Organic matter, %				
Phosphorus, ppm	.210*	.362*	.841	
Potassium, ppm				
Calcium, ppm				.484
Magnesium, ppm	-.382	-.545		
Sodium, ppm	.205*	.440		
Site Characteristics				
Elevation	.323		-.837	.789
Bedrock				
Rooting				
Mounds %	-.199*	.346*		
Casts %				
Bare ground %		.386*		

* r-values significant at the 5% level; all others at the 1% level.

SNOW AND VEGETATION - Table 16 shows plant species that increase or decrease along the snow gradient for combined forest, ecotone, and meadow sites. The reader is directed to the last two columns of Table 16 where r-values and their significance levels are shown. These r-values are based on 8 observations (snow classes). The snow gradient in Table 16 is the same as the one in Fig. 9 for lodgepole pine survival. Nine observations were eliminated because they represent less than 4 study sites in a snow class. Therefore, the frequencies were based on 113 study sites.

Plant species frequency correlated with snow depth, Table 17, was based on 100 (nearby sites) observations. Correlations are shown for vegetational classifications combined (n = 100) and for meadow, ecotone, and forest data seperately. An important correlation was the positive association of snow depth and native lodgepole pine seedling density in the meadow. Similarity of response for plant species in meadow and ecotone to snow depth (i.e., r-values for a species correlated with snow in meadow and ecotone have the same sign) suggest the steepest gradient of community change is from ecotone to forest rather than ecotone to meadow.

SNOW AND MICROCLIMATE - Correlations of microclimatic data with snow depth in Table 18 show cooler soil temperatures (50 cm depth) and higher summer precipitation associated with snow depth in the forest. Ecotone correlations show a trend of lower summer precipitation with

Table 16. Mean frequency of plant species in eight 20 cm snow classes and their correlation coefficients*

Plant Species	80-	100-	120-	140-	160-	180-	200-	220-	r	P
	Species Frequency									
FOREST TYPE										
Alpine fir >2m[1/]	2.5	3.0	1.1	3.0	0.5	0.8	1.1	0.7	-.70	5
Vaccinium	5	3	38	14	21	8	8	0	-.22	NS
Alpine fir <0.5m[1/]	645	1820	5300	1740	286	173	1250	47	-.40	NS
Alpine fir 2-0.5m[1/]	2.8	3.0	2.0	3.6	1.9	1.8	6.9	0.9	.06	NS
Thalictrum	7	14	15	20	4	3	6	0.0	-.61	10
Arnica	22	19	23	29	9	10.0	6	0.0	-.83	1
Lodgepole >2m[1/]	2.2	2	4.2	3.6	2.6	2.8	2.9	2.3	.00	NS
bryophytes	12	22	0	20	2	8	20	29	.31	NS
ECOTONE TYPE										
Carex geyeri	65	39	38	70	32	69	94	89	.62	10
Lodgepole 2-0.5 m[1/]	0.2	2.9	0.8	3.4	0.8	2.2	4.6	4.9	.70	5
Erythronium	0	17	36	57	34	47	61	86	.90	.05
Lodgepole <0.5m[1/]	48	127	2	1433	64	136	283	382	.13	NS
Senecio	2	0	8	2	5	9	9	32	.75	5
Agrostis	2	25	10	5	4	.4	8	36	.31	NS
Polygonum bi	80	19	11	5	11	13	12	14	-.58	25
Festuca	17	53	36	48	45	48	61	71	.81	2.5
Lupinus	77	39	21	16	20	21	31	68	-.13	NS
Achillea	77	67	60	70	80	67	81	96	.60	25
Viola	0	8	10	20	46	46	56	43	.91	.05
Galium	20	11	17	23	29	27	20	43	.74	2.5
Claytonia	50	25	38	52	55	72	76	86	.88	.05
Danthonia	80	64	15	18	21	24	26	32	-.61	25
Campanula	57	44	21	25	48	36	48	25	-.30	NS
Potentilla	0	42	33	29	32	7	5	14	-.30	NS
Arenaria	80	53	21	12	20	22	19	21	-.72	5
Koeleria	25	6	4	5	9	13	11	7	-.29	NS
Phleum	0	0	8	16	16	19	25	18	.90	.05
MEADOW TYPE										
Delphinium	2	3	10	5	30	36	33	21	.71	5
Geranium	0	3	25	34	29	26	11	18	.38	NS
Antennaria	47	31	10	7	12	10	11	7	-.75	5

Table 16. Concluded

Plant Species	80-	100-	120-	140-	160-	180-	200-	220-	r	P
	Snow Classes									
	Species Frequency									
MEADOW TYPE cont.										
Taraxacium	10	8	27	18	21	5	8	11	-.23	NS
Thlaspi	52	17	11	7	30	17	23	29	-.19	NS
Stipa	30	19	10	25	52	46	42	29	.49	25
Agoseris	60	25	17	14	7	16	23	29	-.43	NS
Collomia	0	11	17	2	29	19	16	18	.56	25
Dodecatheon	17	50	16	7	2	3	0	0	-.72	5
Spergula	0	0	4	11	25	16	19	21	.87	.05
Myosotis	55	50	42	25	27	19	9	7	-.98	.05
Polygonum do	0	22	27	21	41	40	20	29	.56	25
Carex	20	42	33	16	29	14	11	11	-.67	10
Melica	0	0	19	12	12	17	16	14	.68	10
Bromus	0	0	38	30	61	36	31	32	.58	25
Poa	45	8	13	12	7	7	3	4	-.73	5
Agropyron	0	0	35	14	30	22	5	4	.05	NS
Cerastium	80	33	42	21	14	10	0	4	-.89	.05
Lithophrogma	0	0	29	16	16	1	6	0	-.14	NS

1/Data represent number/100m^2.

r = Correlation coefficient.

P = Probability level (%).

* = Correlation coefficients were based on a sample size of 8 (snow classes). Data are from 113 study sites.

Table 17. Correlation coefficients for snow depth and plant species frequency

Plant Species	Snow Depth			
	All Sites	Meadow	Ecotone	Forest
	n=100	n=34	n=33	n=33
Forest Type				
Alpine fir >2.0m				
Vaccinium				
Alpine fir <0.5m				
Alpine fir 2-0.5m				.354*
Thalictrum	.279			
Arnica	-.239*			-.470
Lodgepole >2.0m				-.398
bryophytes				
Ecotone Type				
Carex geyeri	.274		.762	
Lodgepole 2-0.5m				
Erythronium			.591	
Lodgepole <0.5m		.358*		
Senecio				
Agrostis			-.503	
Polygonum bi				.413
Festuca		-.519		
Lupinus		-.710	-.373*	
Achillea		-.453		.506
Viola	.265	.659	.562	
Galium				
Claytonia			.700	
Danthonia	-.321	-.656	-.542	
Campanula			-.404	
Potentilla			-.540	
Arenaria	-.298	-.776	-.588	
Koeleria				.515
Phleum		.402*	.369*	
Meadow Type				
Delphinium		.390*	.480	
Geranium			.438*	-.371*
Antennaria	-.246	-.519	-.585	
Taraxacum				
Thlaspi		-.346*		.354*

Table 17. Concluded

Plant Species	Snow Depth All Sites	Meadow	Ecotone	Forest
	n=100	n=34	n=33	n=33
Meadow Type cont.				
Stipa		.438	.509	
Agoseris		-.510		
Collomia		.451	.386*	
Dodecatheon	-.337	-.532	-.840	
Spergula		.585	.389*	
Myosotis	-.354	-.523	-.630	-.416*
Polygonum		..594	.405*	
Carex	-.198*		-.726	
Melica		.430*		
Bromus		.743	.366*	
Poa				
Agropyron	-.236			
Cerastium	-.413	-.709	-.564	
Lithophragma				

*r-values significant at the 5% level; all others are significant at the 1% level.

Table 18. Correlation coefficients for snow depth and microclimate

	Microclimate 1970	Snow Depth All Sites	Meadow	Ecotone	Forest
		n=100	n=34	n=33	n=33
June	Temperature				
	Air max.	-.254	.378*		
	Air min.				
	Soil max.				
	Soil min.				
	Soil 50 cm	-.389		-.387*	-.744
	Precipitation			-.586	.674
July	Temperature				
	Air max.				
	Air min.	-.240*	-.417*		
	Soil max.				
	Soil min.				
	Soil 50 cm	-.242*			-.570
	Precipitation	.376	.536		.718
August	Temperature				
	Air max.	-.221*			
	Air min.	-.253*	-.464		
	Soil max.				
	Soil min.				
	Soil 50 cm	-.350			-.748
	Precipitation	-.226*		-.794	.773
	Evaporation				-.650
September	Temperature				
	Air max.	-.210*			
	Air min.	-.208*			
	Soil max.				
	Soil min.			.353*	
	Soil 50 cm	-.398			-.723
	Precipitation			-.693	.456
	Growing season 50 cm soil temp.	-.357			-.786

*r-values significant at the 5% level; all others at the 1% level.

increasing snow depth.

Winter precipitation is ordinarily not correlated with summer precipitation. Correlations of winter and summer precipitation in this study are assumed to be the result of interception differences. For example, an open-forest stand would receive more snow on the ground than a closed stand (Berndt 1965). Summer precipitation in the open stand measured near the forest floor would also be higher. A dense stand of trees in the ecotone, however, could accumulate more drifting snow than a sparse stand but would receive less summer precipitation on the ground due to increased interception.

SNOW AND SOIL MOISTURE - Correlations of snow depth with available soil moisture early in the growing season (July 13, 1969 and June 14, 1970) for all vegetation types are weak or not significant (Table 19). The early spring correlations support the assumption that soils of all three vegetation types reached field capacity (all soils have about the same moisture content) at the beginning of the growing season, regardless of snow depth. However, soil moisture measured in August (all types combined) was positively associated with snow depth. Correlations for each individual vegetation type indicate that forest soil moisture was the most strongly correlated with snow depth, meadow less, and the ecotone the least in August, e.g., see August 24, 1970.

Table 19. Correlation coefficients for snow depth and available soil moisture at different dates and soil depths

Date and Soil Depth (cm)	Snow Depth All Sites	Meadow	Ecotone	Forest
	n=100	n=34	n=33	n=33
July 13, 1969				
10-30		-.648	-.631	
30-50			-.710	.689
50-70	.246*			.411*
70-90				
90-110	-.203*	-.467		
rooting				
October 8, 1969				
10-30	.292		.677	
30-50	.401		-.396*	.567
50-70	.302	.360*	-.546	.431*
70-90	.283		-.460	.513
90-100				.499
rooting	.359	.360*		.406*
June 14, 1970				
10-30	.296			.671
30-50	.255*		-.511	.680
50-70	.230*			.415*
70-90				
90-110				
rooting				
August 3, 1970				
10-30	.434		.612	.662
30-50	.523			.828
50-70	.551			.794
70-90	.450	.385*		.596
90-110				
rooting	.492			.642

Table 19. Concluded

Date and Soil Depth (cm)	Snow Depth All Sites	Meadow	Ecotone	Forest
	n=100	n=34	n=33	n=33
August 17, 1970				
10-30	.489	-.539	.561	.708
30-50	.460		-.534	.762
50-70	.521			.763
70-90	.459	.399*		.610
90-110				.369*
rooting	.407			.486
August 24, 1970				
10-30	.521	-.388*	.586	.666
30-50	.430	.362*	-.374*	.655
50-70	.512			.726
70-90	.462	.442		.595
90-110	.214*			.457
rooting	.408			.460
August 31, 1970				
10-30	.290	-.571	.571	.612
30-50	.306		-.689	.683
50-70	.380		-.386*	.772
70-90	.430	.428*		.603
90-110				
rooting	.332			.434*
Growing season use			-.398*	.485

*r-values significant at the 5% level; all others at the 1% level.

DISCUSSION

The underlying assumption for this study was that weather modification will have its most significant effects on the ecology of this study area where it changes the status of factors that maintain the present vegetational pattern. It is recognized that factors maintaining a community are often not the same as those contributing to its origin (Billings and Mark 1957). It is also assumed that many factors that limit the distribution of one community will be the maintaining factors for another. Thus, stability of vegetational patterns is the result of factors that consistently differ between vegetation types. Patten (1963) proposed this idea of stability and stated that, "For a vegetational type to be self-perpetuating, it must have established an environment within itself that allows the growth of its own associated species and tends to exclude others." When that environment can be affected by man, community change can be expected. Cox (1933) stated, based on work at James Peak in Colorado, that "The whole matter of distribution of species and communities is intimately connected with the presence or absence of a winter snow cover and with the time at which the snow disappears in summer." One way in which snow influences the distribution of plant communities is through its relationship with soil moisture as suggested by Marr (1964).

SOIL MOISTURE - Patten (1963) concluded that the major factor contributing to maintenance of the vegetational pattern in the Madison Range, an area less than 100 miles south of the Bangtail area, was soil moisture availability, which in turn was dependent on many other factors. Other authors recognizing soil moisture as a factor of vegetational pattern include Taber, et. al. (1961), Marr (1964), Nimlos and Pattie (1965), Griffin (1967), Smith (1969), and Sander (1970).

One of the factors affecting the availability of soil moisture is the plant community itself. Daubenmire (1968) suggested that vegetative types closely reflect soil moisture regimes. This same conclusion is indicated by the different moisture patterns measured under the Bangtail forests, ecotones, and meadows. Surface soil moisture distribution in this study seemed consistent with Patten's (1963) findings, i.e., meadow soils reached a critical moisture level earlier in the growing season than ecotone or forest soils. Herring's (1970) data appeared to show that in central Washington grassy openings reached a lower soil moisture level sooner than stands of Ponderosa Pine (*Pinus ponderosa*) at soil depths of 9 to 21 inches. However, he concluded that the soil moisture regime for the entire profile during the growing season was similar under grass and pine. Measurements of total moisture depletion from soils in the present study agree with the results of Johnston, Tew, and Doty (1969), for their comparison of Douglas Fir (*Pseudotsuga menziesii*) and herbaceous grass types at 6100 feet in Utah, i.e., evapotranspiration was greatest from the meadow during the growing season. However, they found the reverse was true at higher elevations. The annual depletion of water from forest soils has been considered to be greater than from soils of open areas (Bethlahmy 1962). The Bangtail data does not provide a basis to make these estimations. Reduced water loss from open grassland soil is suggested by Brown and Thompson (1965) in Colorado, however, they indicated that their forest and meadow soils were not comparable. This was because of differences in available water holding capacity, similar to the conclusion of Patten (1963).

Soil texture is another factor contributing to soil moisture availability (Patten 1963). Because texture was nearly constant at the Bangtail study sites, it is not discussed as a factor influencing soil moisture.

The important finding of this study was that available soil moisture in the later part of the growing season was associated with variation in depth of accumulated snow. In the spring, available soil moisture did not vary among vegetation types even though winter precipitation did vary. In August, however, soil moisture differences were observed. These differences are assumed to be partly explained by a "lag" in snow melt. A deeper snow pack takes longer to melt and thereby delays the season of soil moisture stress. In effect, a critically low moisture level is not reached until later in the growing season. This effect of delayed melt is enhanced when snow accumulates[7/] under trees in forest or ecotone

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[7/]Sometimes what appears as a winter snow drift in the spring is no more than late snow melt resulting from nearby shade. P. E. Farnes, personal communication.

(Anderson 1956, Anderson Rice, and West 1958). Patten (1963) observed a similar effect where shade and snow banks were associated with high amounts of soil moisture well into July. Variable shading is thought to partly explain why snow depth and soil moisture were not statistically related or was negatively related several times in the ecotone. Some ecotones had comparable snow depths but different soil moisture availability in August. This was probably the result of differential shading. Berndt (1965) indicates that increased snow accumulation with a delay of melt has its maximum benefits in openings smaller than 5 acres.

The idea of late melting snow affecting late season soil moisture (Marr 1964) explains why "snow fence"[8/] is used to redistribute snow for late season water use or water yield (Martinelli 1959, 1964, 1965, Anderson 1963, Berndt 1964, Gary and Coltharp 1967, Hoover 1967, Rasmussen 1969, Siddoway 1970, Berndt and Swank 1970, Swank and Booth 1970).

It is then concluded that available soil moisture in the late growing season (after August 1 for this area) will be increased as winter precipitation is increased. The increase can be a result of late melt, shade or a combination of both.

TREE INVASION - Available soil moisture has been suggested by

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[8/] "Snow fence," suggesting contour trenching, fence, and vegetative manipulation.

several authors as a limiting factor for lodgepole pine establishment in open grassland (Clements 1910, Smithers 1961, Lavender 1958, Patten 1963, 1969). This same conclusion is supported by the relationships of lodgepole pine survival with available soil moisture shown in Table 11. Therefore, the survival of planted lodgepole pine on the Bangtail, enhanced by snow depth, is explained in part by the relationship of snow and the availability of late season soil moisture. If the survival of planted seedlings was representative of the survival of native seedlings, then the major ecological effect of increasing winter precipitation would be forest invasion into meadow. This ecological effect was interpreted as an increase in the rate of invasion because lodgepole pine have been intermittently invading meadow areas for years.

The ideal place to see meadow invaded by forest was in the transition area. In this study, they are called ecotones; Scheichtl (1967) calls them the Kampfzone, "struggling zones," and Odum (1959) the tension zone. Whatever the name, soil characteristics of the area support the hypothesis that forest tends to invade meadow. The presences of crotovinas and the lack of charcoal suggests a soil developed under grassland. Soils of the forested area also indicate recent (perhaps less than 1,000 years) development under a forest type of vegetation. A thin O horizon is present, but the A_2 horizon is poorly expressed or lacking. The A_1 lacks evidence of plates, and the B_2 blocks are not coated with gray silt. These are recognized morphological differences between a Gray

Wooded soil associated with forest vegetation and Chestnut soils common to grassland (White, Johnson, and Nichols 1969). The gradual decrease of organic matter with soil depth in the forest is also suggestive of grassland influence (Hole and Nielsen 1970). Patten (1963, 1969) stated that lodgepole pine invasion is usually in sagebrush areas rather than open grassland because of soil similarities under sagebrush and pine. The soil textural characteristics of the Bangtail are quite uniform and should not be a limiting factor as suggested for the Madison Range.

Seedling invasion into meadows proceeds very slowly. Lodgepole pine is a shade intolerant species (Clements 1910, Smithers 1961, Tackle 1961, Sweet and Wareing 1968), and seedlings might be expected in open areas. However, the young seedlings are uncommon to interiors of the open grassland[9/] but are common to areas presently having a few scattered trees. Therefore, the increased rate of invasion of pine will be most evident near (within 20 m) the ecotone.

EFFECTS OF TREE INVASION - A result of tree invasion is, at first, an expansion of what has been called ecotone and a reduction of meadows. These first effects of an extensive ecotone could result in the redistribution of snow into drifts. Late melting snow drifts have the potential of increasing the summer water yield of a watershed. Later, if the

[9/] Mutual observation by Dr. T. Weaver, Botany and Microbiology Department, Montana State University, and author.

meadow area is reduced and forest becomes dominant, water yield reductions will be observed. The effect is assumed to be the opposite of timber removal resulting in increased water yield (Bates and Henry 1928, Rich, Reynolds, and J. A. West 1961, Anderson 1963, Martinelli 1964). The studies at Fool Creek (Martinelli 1964) indicated that with 39 percent of the timber removed, the watershed increased its water yield by 23.5 percent. It then becomes a possibility that if the Bangtail Ridge, approximately 20 percent meadow became completely forested, partly a result of weather modification, water yield could be reduced by a figure in the 10-20 percent range. Whether or not this happens depends upon several factors and is submitted as a question rather than a conclusion.

Another result is that grazing potential will decrease as pine invades meadows. The area is presently used by cattle, sheep, and some native game (deer and moose). Elk are uncommon and were not seen in the area during this study. Recreation and aesthetic value are also potentially affected. Assuming that a beautiful scene is a result of diversity as suggested by the work of Rutherford and Shafer (196), the meadow-forest complex provides such a scene. Solid forest does not. These last factors are difficult to assess but are issues of environmental quality.

Advantages of forest invasion include an increased timber yield and reduction of spring flooding.

Fire and animal activities influence forest invasion (Patten 1963) but are assumed to have little association with an increase in winter precipitation.

FIRE - Charcoal was evident in the forest soils and uncommon in the meadow. This is similar to the findings of Patten (1963) who suggested fire as a maintainence factor for community patterns. But it seems reasonable to assume as Patten did that meadows burned along with the forest. The effect would be to destory the young conifers in the meadow, thus maintaining the meadow (Patten 1963, Griggs 1938) and perpetuating the lodgepole pine in the present forest pattern. Where man is effective in controlling fire this no longer becomes a factor maintaining the open grassland.

ANIMALS - Animal activities were observed to have both detrimental and advantageous effects on tree invasion. Gysel (1960) observed that in Rocky Mountain National Park, deer chiefly graze on shrubs and trees and thus tend to maintain open areas. Deer are common to the Bangtail and are assumed to have a similar effect. Several of the planted lodgepole pine had been eaten or broken to within 5-10 cm of the surface, which could be deer damage but could also be damage from the cattle and sheep (Young, et. al. 1942). Elk also eat young conifers (Patten 1963), but this is of little importance in the Bangtail area. Livestock grazing, as a factor responsible for changes in meadow, has been suggested by Ellison (1946) and Gomm (1962). Ellison (1946) suggests livestock are the primary cause of deterioration, however, pocket gophers promote a tendency for total production to increase. Branson and Payne (1958), working in the Bridger Range, found mountain brome to decrease but timothy and Kentucky bluegrass to increase under sheep grazing. Gopher activities caused decreases in timber oatgrass, Columbia needlegrass, yarrow and increases in mountain brome. Kuhnelt (1955) and Osburn (1959) observed that areas worked by pocket gophers have more plants with fibrous roots and few with tap roots.

Pocket gopher effects were not fully evaluated here, but it seemed they were beneficial to production in the meadow but also beneficial to tree invasion. Gophers have been conservatively estimated to displace 5 tons per acre (11,000 kg/h) of soil (Ellison 1946). Their activities are assumed to increase soil aeration, nutrient cycling, and nutrient accumulation. This last possibility is suggested as a result of nest building. A similar observation was made by Klages and McConnel (1969) who found otherwise unexplained nitrogen accumulations at the same depth as two gopher nests. Surface soil deposits acting as seed-beds are assumed to be a benefit to the survival of lodgepole pine seedlings. Scarification, a technique of removing vegetative competition, is an important seed-bed treatment used in reforestation programs (Worf 1970). The gopher is less effective than the scarifying equipment used by a logger but does provide a nearly uninhabitated area of surface soil.

"Seed-beds," resulting from winter and summer[10/] pocket gopher activity, amounted to 5 percent of the meadow area and 4 percent of the ecotone. The following estimations were made for the turnover rate of soil in the meadow. It was assumed that soil brought to surface is an expression of the pocket gophers activities in the top 15 cm of soil and that the percent of mound measured July 4 represents half of his activities during a summer.

1. Per hectare the annual air-dry weight of soil brought to the surface as cast amounts to 6000 kg (2% x 30 kg/m^2).

2. Per hectare the annual air-dry weight of soil brought to the surface as mound amounts to 12,000 kg (2 x 3% x 20 kg/m^2).

3. One hectare of soil 15 cm deep weighs 1,650,000 kg (B.D. = 1.1 g/cc).

4. Pocket gophers bring the top 15 cm of soil to the meadow surface about every 91 years (16.5/.18).

Simplifying calculations, the turnover rate is approximately 100 years or one percent of the top 15 cm of meadow soil is affected annually. It is then suggested that about one percent of the tree seedlings roots are affected by pocket gopher activity annually. The conclusion is that pocket gophers do not exercise a major influence in destroying tree seedlings but contribute to the seedbeds of these and other plants.

GRASS AND FORB - Frequency of plant species (Table 4), and species frequency correlations with snow depth (Table 16 and Table 17) are

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10/Includes the period from fall 1970 to June 1971.

representative of the relative trends of species counted. Values are not considered absolute. Frequency data of this type approach a measure of density and presence (Curtis 1959) but are limited here by sample size at a study site. With the sampling methods used in this study, a species "importance" at a site would have been a better measure of a species response to the environment than its frequency. Species importance can be determined by the combined cover-abundance scale (Braun - Blanquet 1932). Although species frequencies are only represented by four observations at a study site, the relative trends in the meadow are similar to those measured by Dr. T. Weaver.[11/]

One species, lupine (Lupinus argenteus) will be used as an example of how it is possible for the reader to determine a relationship of snow depth and plant species frequency. The reader is first directed to Table 16 (page 70). Variation in lupine frequency for the combined vegetation types is not explained by variation in snow depth (r-value not significant). This is similarily suggested in Table 17 (page 72) for the complete snow gradient expressed by 100 sites. However, in Table 17 the reader will notice that lupine frequency in meadow and ecotone areas decreases with an increase in snow depth (meadow r = -.710, ecotone r = .373). Lupine in Fig. 3 (page 34) is common to the ecotone and closely associated with Festuca, Danthonia, and Arenaria (see Fig. 4,

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[11/]Dr. T. Weaver, Botany and Microbiology Department, Montana State University, personal communication.

page 36). These species are also negatively associated with snow depth in meadow and ecotone (except for Festuca in meadow). The relationships suggest a group of species sharing a similar ecotonal environment and similar environmental requirements. Each species of the group has similar relative frequency in the three vegetational classifications and were more significantly affected by an increase of snow in the meadow than the ecotone (Table 17). Available soil moisture does not seem to be the limiting factor for these species because they decrease as it increases. These species are thought to be poor competitors with grass or forb species that increase with available soil moisture, e.g., Bromus, Stipa, Phleum, and Collomia. Species of this last group are an association (Fig. 4), and each tends to be more frequent with increasing snow depth (Table 17).

The conclusion is that variation in available soil moisture may not explain or be negatively correlated with variation in plant species frequency. The reason a species is correlated with snow depth may be explained by other factors that maintain the community pattern, e.g., growing season length[12/] (Billings and Bliss 1959) and nutrients.

[12/] Dr. T. Weaver, Botany and Microbiology Department, Montana State University, has data relating growing season length, a factor related to snow depth and melt, variation in plant species frequency, presence and production.

SUMMARY

The ecological effects of weather modification were studied for a situation where the proposed target area was a lodgepole pine zone composed of a mosaic of forest, open grassland, and areas of transition called ecotone. The effect of an increase in winter precipitation on those factors responsible for maintaining the present plant communities was emphasized. Snow depth and its relationship to characteristics of soil, vegetation, and microclimate were measured. The results of this study are summarized in the following list.

1. Soils of the study area were morphologically similar, a result of uniform parent material. Differences, when they did occur, were related to geologic structure, aspect, and microclimate (Table 1a and 1b).
2. Soils described along the transects were classified in the coarse loamy family of Typic Cryoborolls. The major differences between soils under the three vegetation types appeared in the A_1-horizon. Phosphorus distribution and pH consistently differed among types throughout the profile. Characteristics of the ecotone soils were more similar to meadow than forest soils (Table 2).
3. Charcoal, an indicator of fire history was common in the forest soils, less common in ecotone and nearly absent in meadow soils. Crotovinas, indicators of grassland were common in meadow and some ecotone soils but absent in forest.

4. Available water holding capacity of all soils, to the observed depth of rooting, was less than 20 cm of water. The estimated winter precipitation in 1970 exceeded 50 cm.
5. Moisture levels in all soils reached saturation or at least field capacity each spring (implied from Fig. 6 and 7).
6. Infiltration rates of 0.8 cm/min (19 cm/hr) were measured (Fig. 8) and surface runoff was uncommon (except were stream channels intercepted subsurface flow on bedrock).
7. Plant species frequency was determined for 12 grasses and sedges (some species are combined) and 38 forbs along transects (Table 4). Relative frequency of species for a vegetation type is shown in a diagram (Fig. 3) similar to a textural triangle. The steepest gradient of species change was from ecotone to forest whereas meadow and ecotone were similar.
8. Lodgepole pine was relatively more common to meadow and ecotone than alpine fir, whereas alpine fir was most common in the forest (Table 3 and Fig. 3). Lodgepole pine is expected to invade the meadows. Later, in the absence of fire, pine will be replaced by fir.
9. Two correlation matrices (Table 22 and Fig. 4) show plant species relationships. Species of the ecotone were positively correlated with meadow species and those of forest were distantly related to both meadow and ecotone species. Correlations between forest

species indicate that the forest community is discrete.

10. Microclimatic measurements at the forest floor suggest that the forest climate was cooler, less variable, and less demanding than that of meadow or ecotone (Table 5). The average annual soil temperature was less than 3° C in each vegetation type.

11. Highest survival of planted lodgepole pine seedlings (2-0 stock) was in forest and ecotone (66%) and lowest in meadow (25%). Net growth of surviving trees was recorded highest for planted seedlings in meadow (Table 6).

12. Soil moisture was measured by the neutron scatter method beginning September 1968 thru September 1970. These data were reported as "available water" (measurement minus the predicted 15-bar water retention).

13. At the end of the growing season (August 31) available soil moisture in the rooting profile was highest in forest and lower in meadow and ecotone (Table 8). Soil moisture was similar in meadow and ecotone at the season's end but meadows reached a critical moisture level earlier than ecotone (Table 7 and 9).

14. Field capacity measurements were compared to estimates of 1/3-bar water retention (Table 10). Results gave three different answers. Field measurements were a more realistic measure of field capacity than the 1/3-bar retention estimations.

15. Snow depth was measured once on March 23, 1970, during a year when winter precipitation was above normal. This snow depth is a relative indication of variation from site to site. Snow depth was lowest in meadows and highest in ecotone (Table 11). The tendency for drifting snow to accumulate at the forest edge (ecotone) may explain the distribution of snow.
16. Snow water equivalent averaged 32% and ranged from 25% to 60%. The high values were recorded in drifts ranging from 3 m to 7 m deep.
17. The gradient of snow depth used in this study ranged from 75 cm - 330 cm. One station had 30 cm of snow. Average depth of snow was 160 cm and only a few areas (10%) remained covered with snow after June 15.
18. Pocket gopher activity was confined to meadow and ecotone areas and was more prevalent in the meadow (Table 11).
19. Cast and mound weights averaged 30 kg and 20 kg respectively for a square meter completely covered with casts or mounds (Table 12).
20. Gophers were estimated to bring the top 15 cm of soil to the surface every 100 years.
21. Percent bare gound exposed was higher in meadow than ecotone and nearly zero in forest (Table 11).
22. Survival of planted lodgepole pine was correlated with snow depth in all three vegetation types combined. A theoretical 7% increase in survival with a 10% increase in mean snow depth was calculated

(Fig. 9 and Equ. 4).

23. Survival of planted pine was also correlated with several soil characteristics of the A_1 horizon, microclimate, and available soil moisture at different dates and depths (Tables 13 and 14).

24. Survival of planted pine was best on cool, high phosphorus, low calcium, and low magnesium sites.

25. Planted pine survival showed a positive relationship with late season soil moisture (after August 1) and as the season progressed correlation became stronger with available water deeper in the profile.

26. Snow depth was correlated with soil characteristics of the A_1 horizon, plant species frequencies, microclimate, and available soil moisture at different dates and depths (Tables 15, 16, 17, 18, and 19). Each correlation was based on all vegetation types combined (n = 100) and for data representing meadow (n = 34), ecotone (n = 33), and forest (n = 33) sites.

27. There does not appear to be a consistent trend across vegetation types for the correlation of snow depth with soil characteristics. In meadow and ecotone as snow increases, pH and magnesium decrease, and phosphorus and sodium increase.

28. A plant species correlated with snow depth in both meadow and ecotone responded the same, i.e., with the same sign. Few forest species were correlated with snow whereas 23 were correlated in the

ecotone and 21 in the meadow.

29. Native density of lodgepole pine seedlings increases with increases in snow in the meadow.

30. Forest areas show a positive correlation between snow depth and the measured summer precipitation, whereas ecotones show a negative correlation between snow depth and measured summer precipitation.

31. Soil moisture variation in the spring was not correlated with snow depth, but late season (August) soil moisture increased with deeper snow.

32. The positive correlation of snow depth with late season soil moisture may explain, in part, why some species, e.g., lodgepole pine seedlings, were positively correlated to snow depth.

33. Late season soil moisture is one of the factors maintaining the vegetational patterns of plant communities in the Bangtail area.

CONCLUSION

Late season soil water availability, a major factor maintaining the plant communities of the Bangtail area, increased with snow depth. The correlation of snow depth and soil moisture explains, in part, why the survival of planted lodgepole pine was positively correlated with snow depth. A predicted result of augmented winter precipitation, in this area, is an increase in the rate of tree invasion into meadows. Eventually, if meadows are allowed to become completely forested, there would be decreases in grazing potential, wildlife habitat, aesthetic diversity, and water yield from the watershed.

APPENDIX I

Appendix Table 20. Soil horizons and rooting depth for profile descriptions in Meadow, Ecotone and Forest of the Bangtail study area.

Transect Number (see Fig.1)	Vegetational Classification					
	Meadow		Ecotone		Forest	
	Horizon	Depth (cm)	Horizon	Depth (cm)	Horizon	Depth (cm)
1	A_1	0- 8				
	B_1	8- 38				
	B_2	38- 81				
	C	81-110				
	R	110-				
	rooting	110				
2	A_1	0- 10	A_1	0- 10		
	B_2	10- 44	B_2	10- 42		
	C_1	44- 62	C_1	42- 77		
	C_2	62-110	R	77-		
	R	110-	rooting	107		
	rooting	130				
3	A_1	0- 11	A_1	0- 10		
	B_2	11- 31	B_2	10- 36		
	C_1	31- 80	C_1	36- 71		
	R	80-	R	71-		
	rooting	110	rooting	88		
4			A_1	0- 13	A_1	0- 13
			B_2	13- 47	B_2	13- 30
			C_1	47- 76	B_3	30- 56
			R	76-	C_1	56- 85
			rooting	90	C_2	85-130
					C_3	130-236
					R	236-
					rooting	-150
			A_1	0- 13	A_1	0- 9
			B_2	13- 36	C_1	9- 36
5			C_1	36- 70	R	36-
			R^1	70-	rooting	56
			rooting	80		

Appendix Table 20. Continued

Transect Number (see Fig.1)	Vegetational Classification					
	Meadow		Ecotone		Forest	
	Horizon	Depth (cm)	Horizon	Depth (cm)	Horizon	Depth (cm)
6			A_1	0- 23	A_1	0- 15
			C_1	23- 31	B_1	15- 46
			C_2	31- 61	B_2	46- 73
			R	61-	C_1	73-110
			rooting	80	R	110-
					rooting	115
7			A_{11}	0- 23	A_1	0- 20
			A_{12}	23- 46	B_2	20- 50
			C_1	46- 63	C_1	50- 80
			C_2	63- 81	C_2	80-150
			R	81-	R	150-
			rooting	104	rooting	105
8	A_1	0- 12			A_1	0- 20
	B_1	12- 35			B_2	20- 35
	B_2	35- 60			B_3	35- 70
	C_1	60- 94			C_1	70- 98
	R	94-			R	98-
	rooting	104			rooting	130
9	A_1	0- 23			A_1	0- 25
	B_2	23- 51			B_2	25- 51
	C_1	51-112			C_1	51- 75
	R	112-			C_2	75-105
	rooting	102			R	105-
					rooting	110
10	A_1	0- 10			A_2	0-2.5
	B_2	10- 53			A_1	2.5- 22
	C	53-125			B_2	22- 50
	R	125-			C	50-107
	rooting	120			R	107-
					rooting	107

Appendix Table 20. Concluded

Transect Number (see Fig.1)	Vegetational Classification					
	Meadow		Ecotone		Forest	
	Horizon	Depth (cm)	Horizon	Depth (cm)	Horizon	Depth (cm)
11	A_1	0- 13			A_2	0- 4
	B_2	13- 48			A_1	4- 25
	R	48-			B_2	25- 64
	rooting	99			C_1	64- 87
					R	87-
					rooting	107

Appendix Table 21. Plant species[1/] counted along transects in the Bangtail study area

Boraginaceae	
Hackelia floribunda (Lehm.) Jtn.	Many Flowered Stickseed
Myosotis sylvatica Hoffm.	Alpine Forget-Me-Not
Campanulaceae	
Campanula rotundifolia L.	Roundleaf Harebell
Caryophyllaceae	
Arenaria congesta Nutt.	Ballhead Sandwort
Cerastium arvensis L.	Field Chickweed
Silene parryi (Wats.) Maguire	Silene
Spergula arvensis L.	Field Spurry
Compositae	
Achillea millefolium L.	Yarrow
Agoseris glauca (Pursh.) D. Dietr.	Pale Agoseris
Antennaria rosea (Eat.) Greene	Rose Pusseytoes
Arnica cordifolia Hook.	Arnica
Erigeron speciosus (Lindl.) DC.	Oregon Fleabane Groundsel
Senecio integerrimus Nutt.	Lambstongue
Taraxacum officinale Weber.	Common Dandelion
Cruciferae	
Arabis holboellii Horn.	Holboell Rockcress
Thlaspi arvense L.	Fanweed
Cyperaceae	
1a Carex geyeri Boott.	Elk Sedge
2 Carex festivella Mack	Ovalhead Sedge
2 Carex podocarpa R. Br.	Sedge
Ericaceae	
Vaccinium scoparium Leiberg.	Low Red Huckleberry
Geraniaceae	
Geranium visoccissimum Fish. & Mey.	Sticky Geramium

Appendix Table 21. Continued

	Gramineae	
	Festuceae	
	Bromus marginatus Nees.	Mountain Brome
	Festuca idahoensis Elmer.	Bluebunch Fescue
	Melica spectabilis Scribn.	Purple Onion Grass
3a	Poa pratensis L.	Kentucky Bluegrass
3	Poa ampla Mèrr..	Big Bluegrass
	Hordeae	
4a	Agropyron subsecundum (Link.)Hitchc.	Beared Wheatgrass
4	Agropyron dasystachyum (Hook.)Scribn.	Thickspike Wheatgrass
	Aveneae	
1	Calamagrostis rubescens Buckl.	Pinegrass
	Danthonia intermedia Vasey.	Timber Oatgrass
5a	Koeleria cristata (L.) Pero	Junegrass
5	Trisetum spicatum (L.) Richt.	Spike Trisetum
	Agrostideae	
	Agrostis scabra Willd.	Ticklegrass
	Phleum alpinum L.	Alpine Timothy
	Stipa columbiana Macoun.	Columbia Needlegrass
	Leguminosae	
	Lupinus argenteus Pursh.	Silvery Lupine
	Liliaceae	
	Erythronium grandiflorum Pursh.	Dogtooth Lily
	Pinaceae	
	Abies lasiocarpa (Hook.) Nutt.	Alpine Fir
	Pinus contorta Dougl.	Lodgepole Pine
	Pinus flexilis James.	Limber Pine
	Pseudotsuga menziesii (Merbel) Franco. Var. glauca (Beissn.) Franco.	Douglas Fir
	Polemoniaceae	
	Collomia linearis Nutt.	Narrow Leaf Collomia
	Polygonaceae	
	Eriogonum umbellatum Torr.	Sulfur Eriogonum
	Polygonum bistortoides Pursh.	Western Bistort
	Polygonum douglasii Greene.	Douglas Knotweed
	Portulaceae	
	Claytonia lanceolata Pursh.	Western Springbeauty

Appendix Table 21. Concluded

Primulaceae	
Dodecatheon conjugens Greene	Shooting star
Ranunculaceae	
Delphinium bicolon Nutt.	Low Larkspur
Delphinium occidentale (Wats.) Wats.	Tall Larkspur
6a Thalictrum occidentale Gray.	Western Meadow Rue
Tosaceae	
Geum triflorum Pursh.	Prairiesmoke
Potentilla gracilis Dougl.	Northwest Cinguefoil
Rubiaceae	
Galium boreale L.	Bedstraw
Saxifragaceae	
Saxifrage rhomboidea Greene.	Diamondleaf Saxifrage
Lithophragma parviflora (Hook.) Nutt.	Smallflower Woodlandstar
Scrophulariaceae	
Besseya wyomingensis (A. Nels.) Rybd.	Kittentail
Collinsia parviflora Lindl.	Small-Flowered Blue-Eyed Mary
Umbelliferae	
Lomatium cous (Wats.) Coult. & Rose	Lomatium
6 Osmorhiza occidentalis (Nutt.) Torr.	Western Sweetroot
Violaceae	
Viola praemorsa Dougl.	Canary Violet

1/Species preceded by the same number were not separately identified; letter indicates dominate member corresponding to the species name used in the text.

Appendix Table 22. Correlation matrix of plant species frequency ordered from those most common in the forest to those most common in the meadow. Degree of association is indicated by r-value.

	Abies >2m	Vaccinium	Abies Seed.	Abies 2-0.5m	Thalictrum	Arnica	Pinus >2m	bryophytes	Carex geyeri	Pinus 2-0.5m	Erythronium	Pinus Seed.	Senecio	Agrostis	Polygonum bi	Festuca	Lupinus	Achillea	Viola	Galium	Claytonia	Danthonia	Campanula	Potentilla	Arenaria	Koeleria	Phleum	Delphinium	Geranium	Antennaria	Taraxacum	Thlaspi	Stipa	Agoseris	Collomia	Dodecatheon	Spergula	Myosotis	Polygonum do	Carex	Melica	Bromus	Poa	Agropyron	Cerastium	Lithophragma
Abies >2m																																														
Vaccinium																																														
Abies Seed.	.27	.41																																												
Abies 2-0.5m	.55		.27																																											
Thalictrum	.46	.28	.44	.26																																										
Arnica	.49	.32	.40	.23	.60																																									
Pinus >2m		.64	.26		.25	.34																																								
bryophytes	.27		.18	.31	.30	.30																																								
Carex geyeri	.29	.31	.24	.25	.27	.29	.43	.24																																						
Pinus 2-0.5m									.24																																					
Erythronium		.25					.37		.54	.46																																				
Pinus Seed.								.27	.19	.57	.29																																			
Senecio											.23																																			
Agrostis													.26																																	
Polygonum bi													.22	.19																																
Festuca										.19				.19																																
Lupinus													.20	.20		.60																														
Achillea													.20	.23	.28	.61	.39																													
Viola										.21	.24		.19					.28																												
Galium																		.23	.24																											
Claytonia											.29		.25		.19	.31		.44	.54																											
Danthonia														.19		.67	.51	.41																												
Campanula																.46	.27	.34				.48																								
Potentilla																		.29																												
Arenaria														.24		.66	.64	.38				.76	.52																							
Koeleria																		.20		.32																										
Phleum																		.25	.35		.39																									
Delphinium													.26					.26	.54	.20	.43		.33				.38																			
Geranium																		.26	.25		.40			.37			.34																			
Antennaria																.37	.31	.26				.46	.24		.53																					
Taraxacum																		.31			.18			.40			.24		.53																	
Thlaspi													.23			.42	.36	.36		.30		.35	.42		.47	.31	.26	.39		.29																
Stipa																		.27	.61		.43					.34	.46	.51	.22			.28														
Agoseris													.24			.32	.29	.23	.18		.33	.36	.28		.34	.32		.29		.30		.40	.33													
Collomia																			.32	.36	.33					.22	.27	.37				.23	.38													
Dodecatheon														.38		.31	.25	.22				.46	.38	.33	.55					.32																
Spergula													.18						.37	.19	.41						.27	.34				.18	.41	.29	.68											
Myosotis														.21		.47	.32	.35				.39	.34	.25	.53					.29	.24	.47		.26		.58										
Polygonum do																			.39		.47						.37	.32	.38		.19		.52		.64		.69									
Carex														.31	.23	.23		.28				.26	.33	.33	.39					.19						.66		.41								
Melica													.20						.47	.22	.40						.24	.25	.25				.45	.25	.52		.60		.63							
Bromus													.29		.18			.26	.49	.25	.45		.20				.48	.52	.43		.31		.56		.51		.54		.72		.59					
Poa															.20						.25		.28						.37		.34				.20		.31		.40	.18		.35				
Agropyron																				.27	.18						.23	.28				.29	.30	.27	.25		.28	.28	.40		.37	.45				
Cerastium																.40	.34	.30				.48	.34	.19	.58					.39	.20	.40		.30		.59		.68		.45						
Lithophragma																							.26				.19				.30				.32		.34	.21	.47	.20	.38	.44	.39	.22		

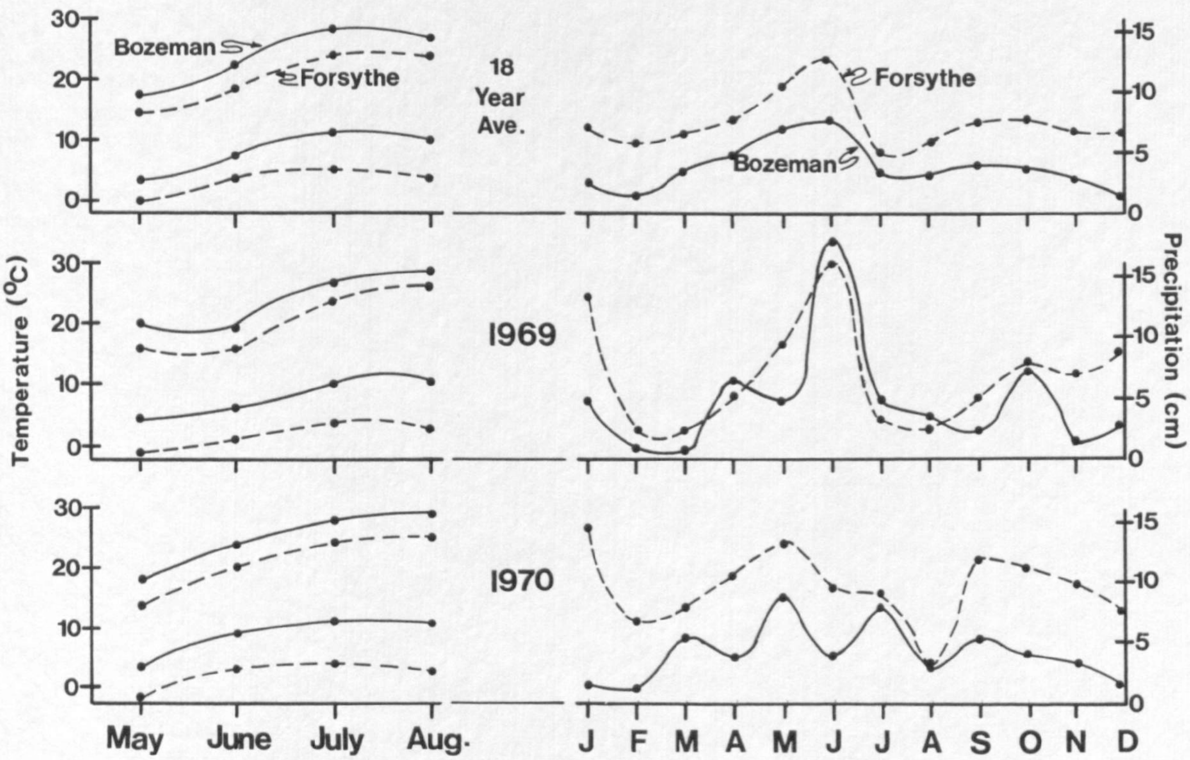

Fig. 10. Mean monthly air temperature and precipitation records measured at two weather stations. Records are for Bozeman and Bozeman 12 NE (Forsythe Ranch) and include the 18-year average (1953-1970), average for 1969 and for 1970.

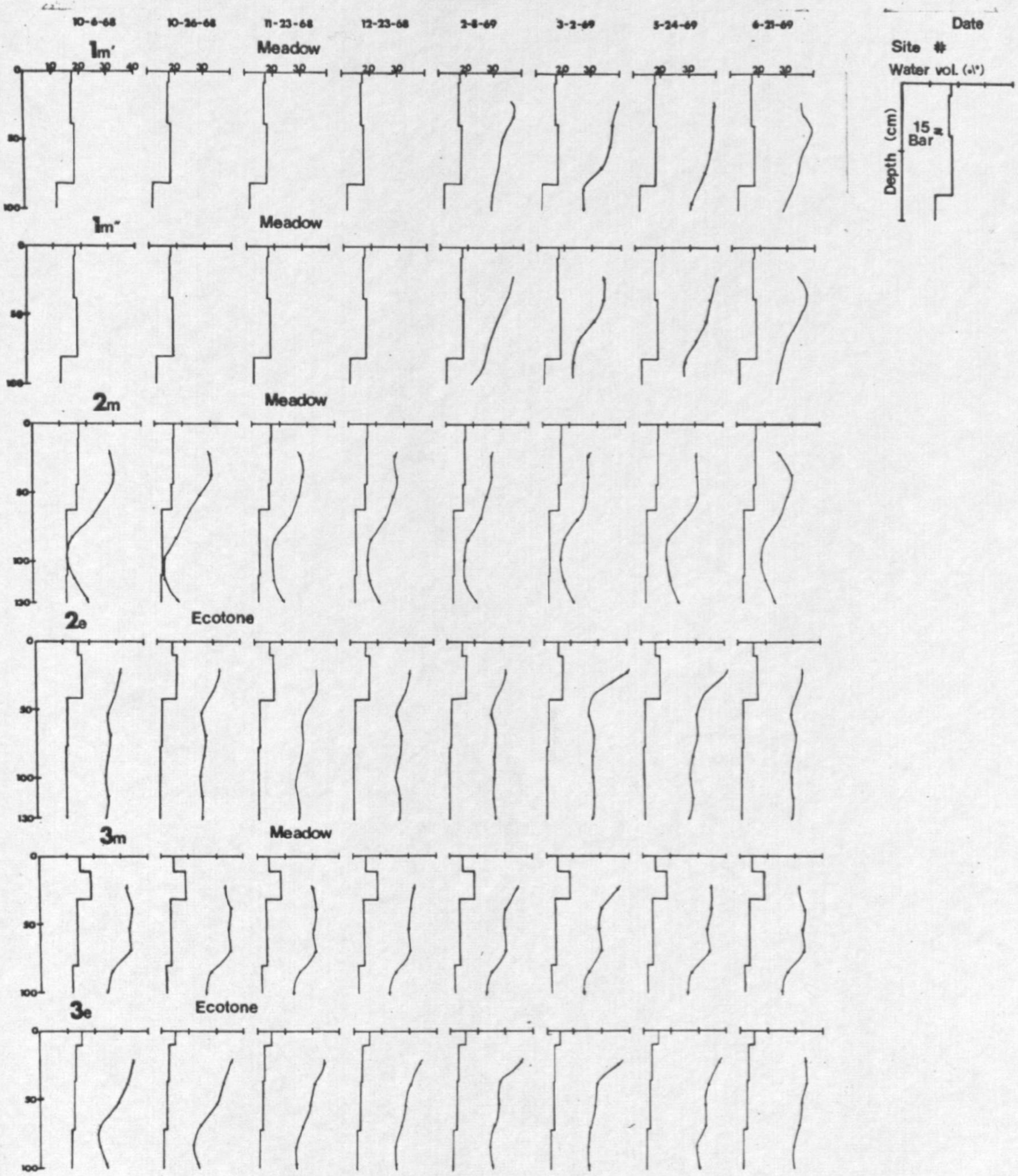

Fig. 11. Soil moisture distribution to depth of rooting for each site on dates of collection. Curves show distribution of soil moisture by volume and points on curves show field measurements. Available soil moisture is represented by the area between curve and 15-bar retention line.

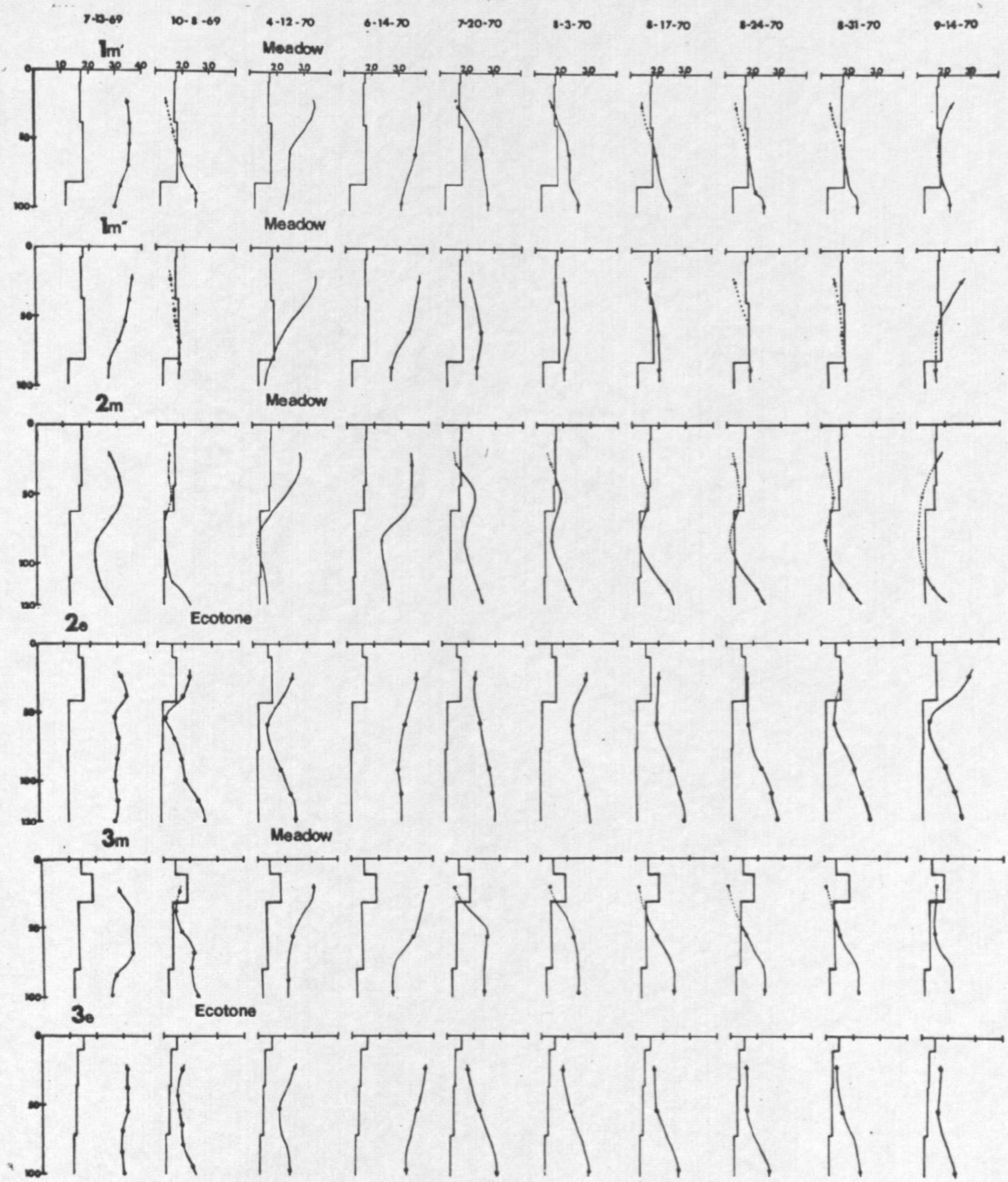

Fig. 11. Continued.

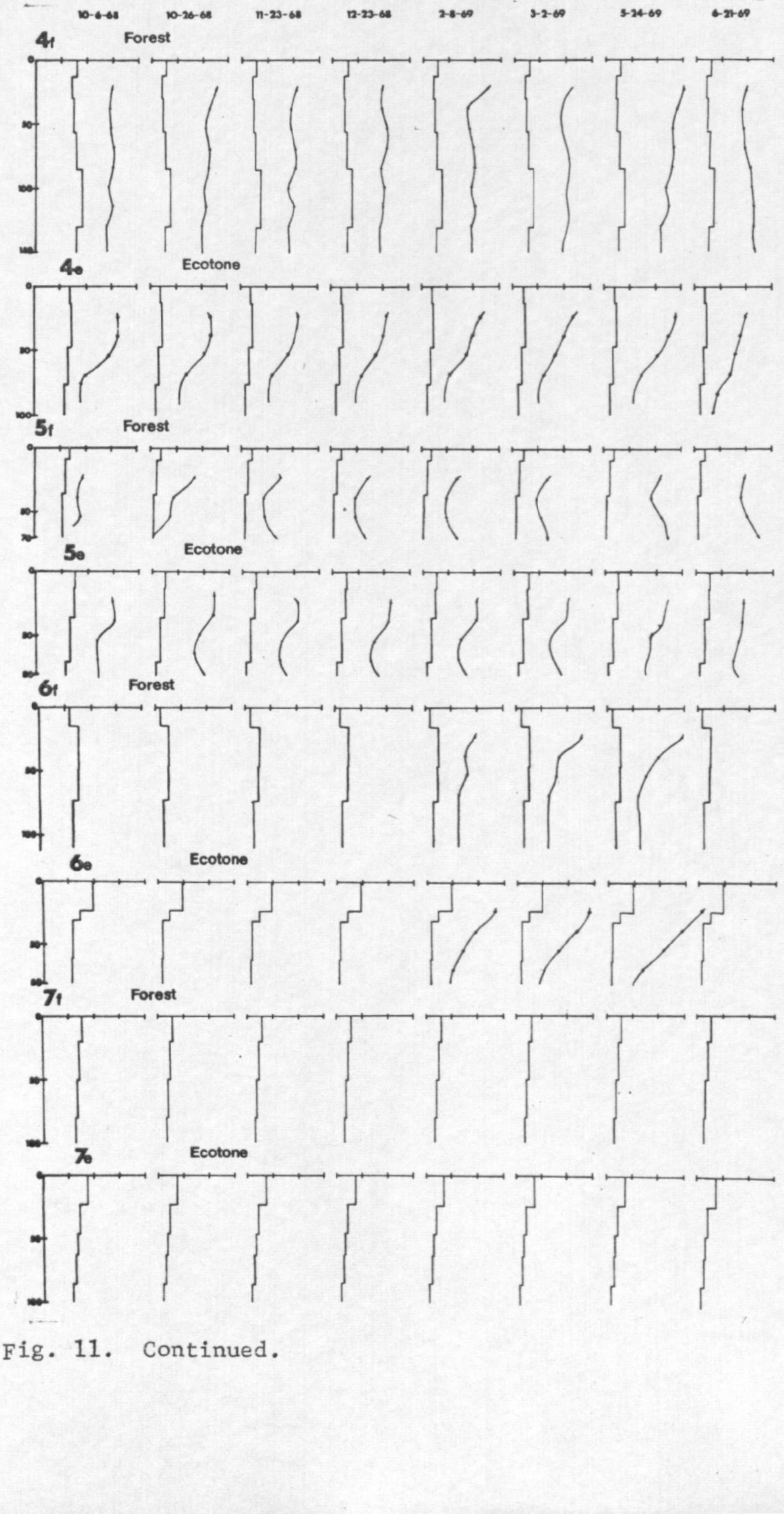

Fig. 11. Continued.

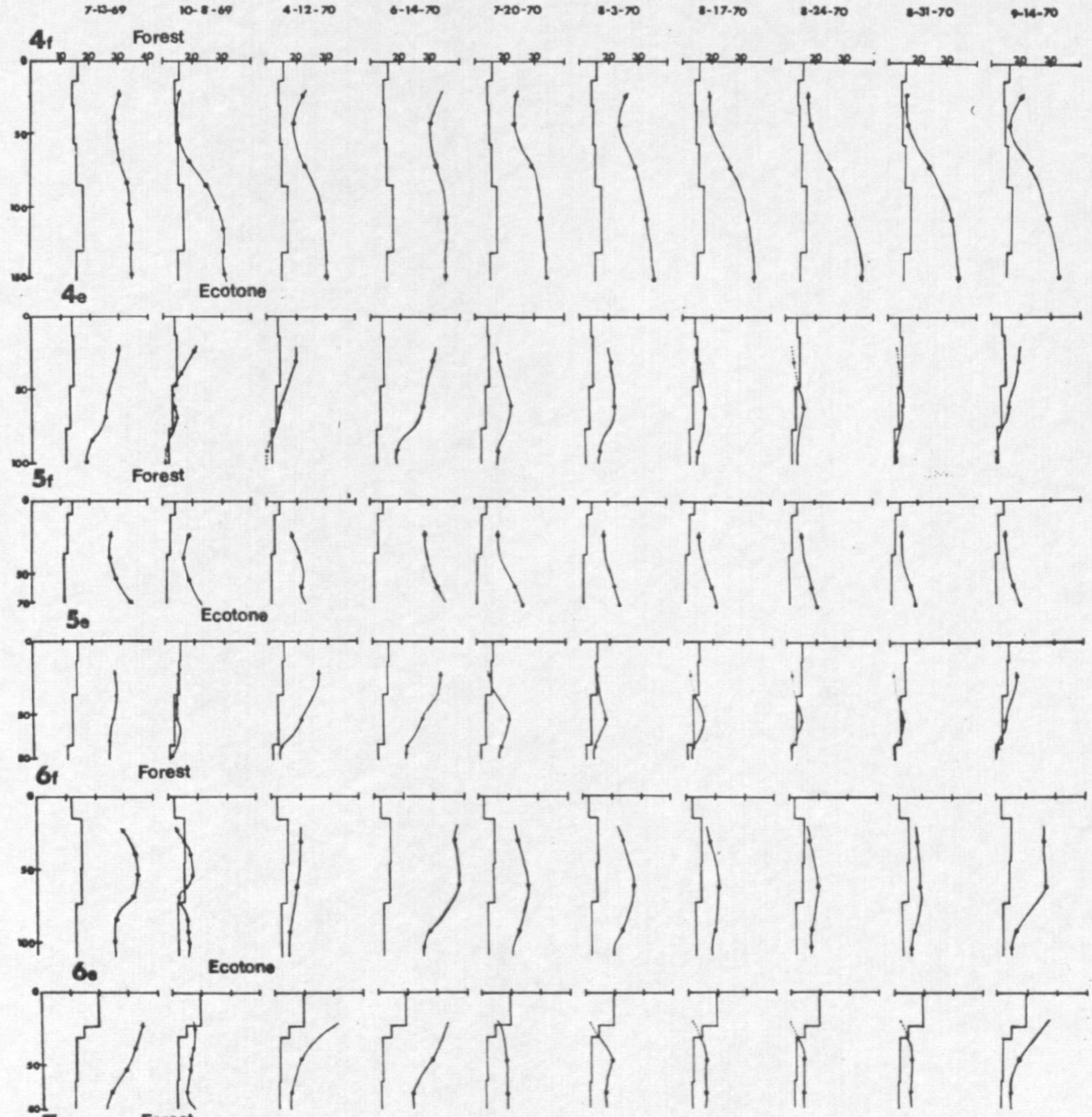

Fig. 11. Continued.

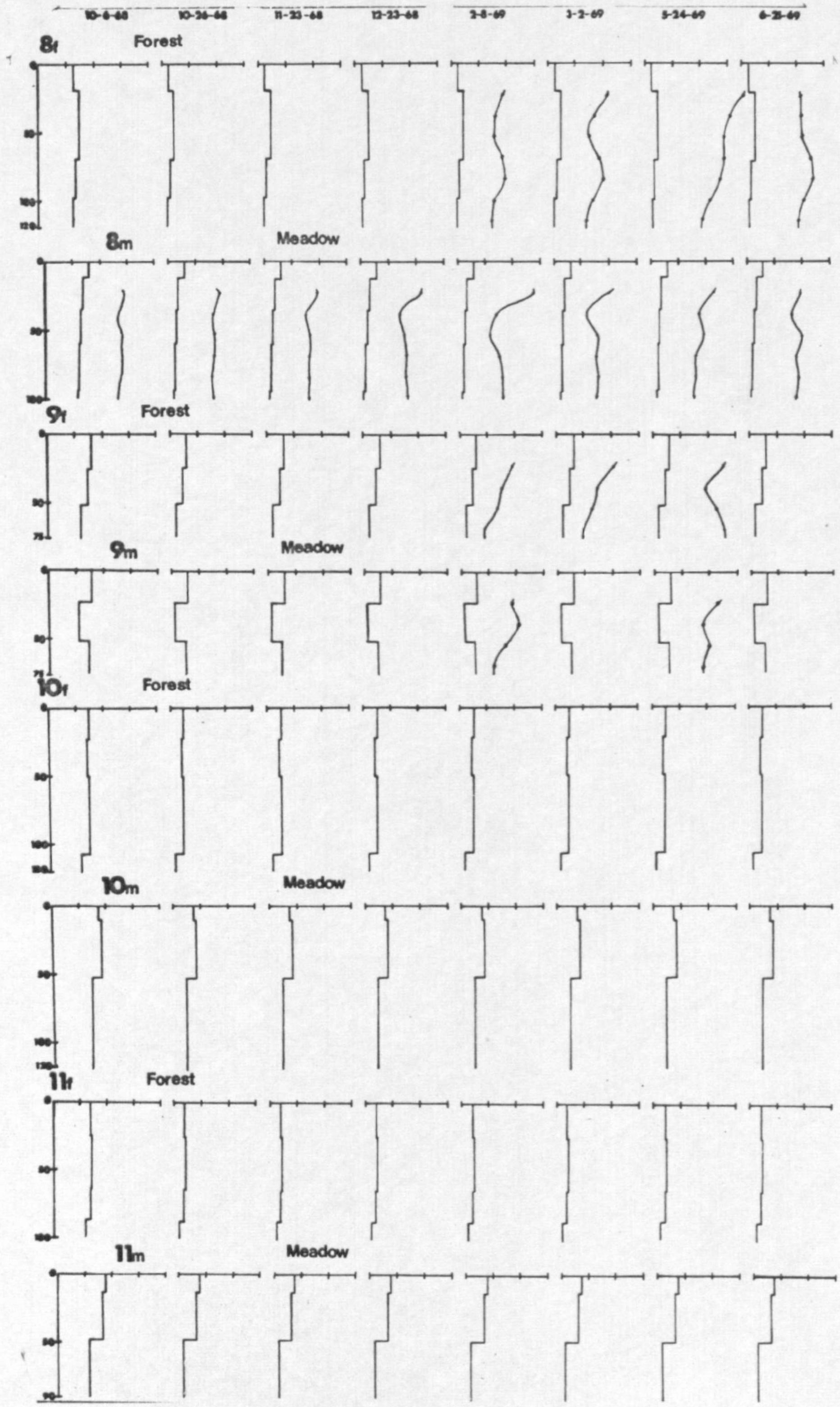

Fig. 11. Continued.

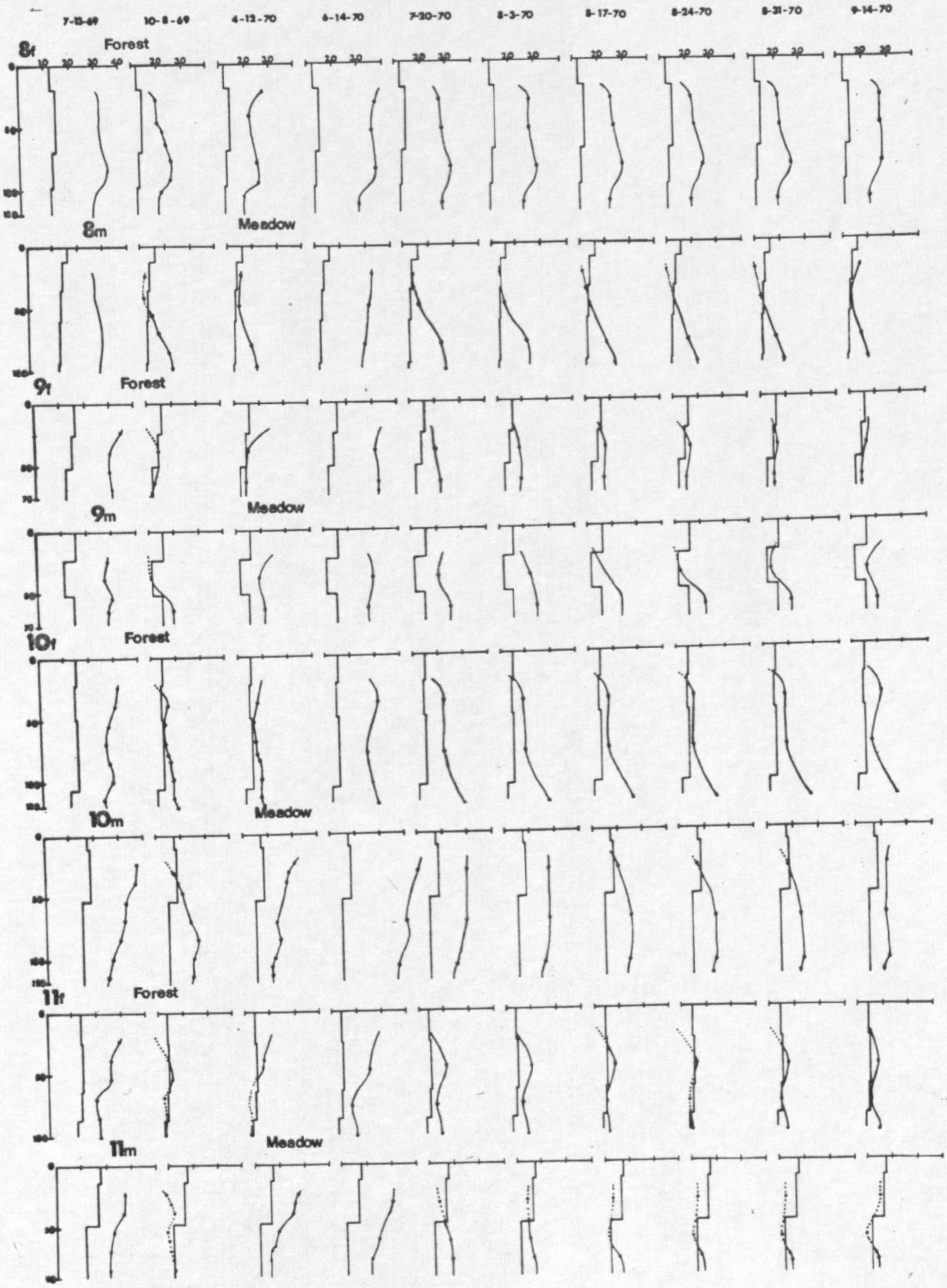

Fig. 11. Concluded.

APPENDIX II

KRUMMHOLZ COMMUNITIES IN THE BRIDGER RANGE AREA, MONTANA

Included as part of the study, "Ecological Effects of Weather Modification," a krummholz community was studied. Similar areas have been called "arborescent hedge-row" by Arno (1966) in the Bitterroot Mountains along the Idaho-Montana border, "ribbon forest" and "snow-glade" by Billings (1969) in the Medicine Bow Mountains of Wyoming and "krummholz" communities by Habeck and Choate (1953) in Glacier National Park. These communities in the Bridger Range area, Montana, were found in one area locally called the Bangtail Mesa. The mesa, pictured in Plate 1, is one of the largest open meadows on the Bangtail Ridge, an area of approximately 80 hectares. Forests enclosing meadow that resemble the shape of a "fairy-ring" of mushrooms are called krummholz (Ger. crooked wood) communities here, because branches at the perimeters are gnarled and grotesquely shaped. These branches are thought to advance the stands through vegetative reproduction such as branch layering (Habeck and Choate 1963).

The objective of these studies was first to characterize an environment receiving 2-3 times the average snow depth of the open meadow. A second and minor objective was to develop a theory of krummholz community origin on the Bangtail Ridge.

RESULTS - The following data are given for three sites at the krummholz community, elevation 2400 m, pictured in the center, far right of Plate 1. Stations were located along a 90 m transect (#12) following the fall line and shown diagramatically in Fig. 12. Station 12 m' is downslope (lee-side, interior), 12 f in the trees, and 12 m" upslope (wind-side, exterior).

Soil moisture curves are shown in Fig. 13 for dates of collection, and these same data are presented in Table 23 as % available soil moisture for each 20 cm depth to the depth of rooting. Soil profile characteristics are presented in Tables 24, 25, and 26, and microclimatic measurements in Table 27. Grass and forb species were not counted, therefore plant species data are not included. However, the forest is dominated by alpine fir and seedling were never observed in the community.

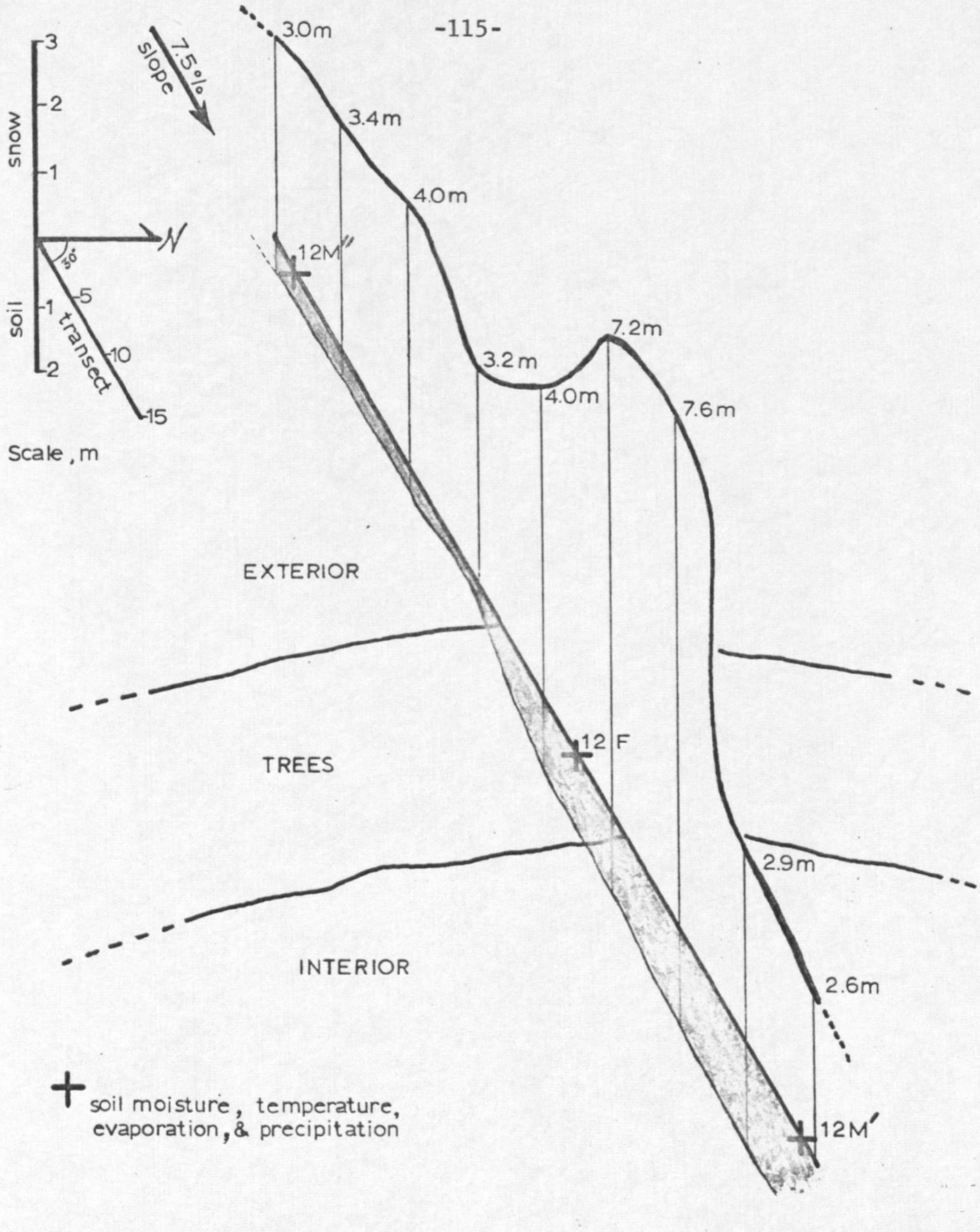

Fig. 12 Transect 12, krummholz community, with soil depth (shaded area), maximum snow depth (measured 3-23-70) and three study site locations. Note there are two scales in the figure.

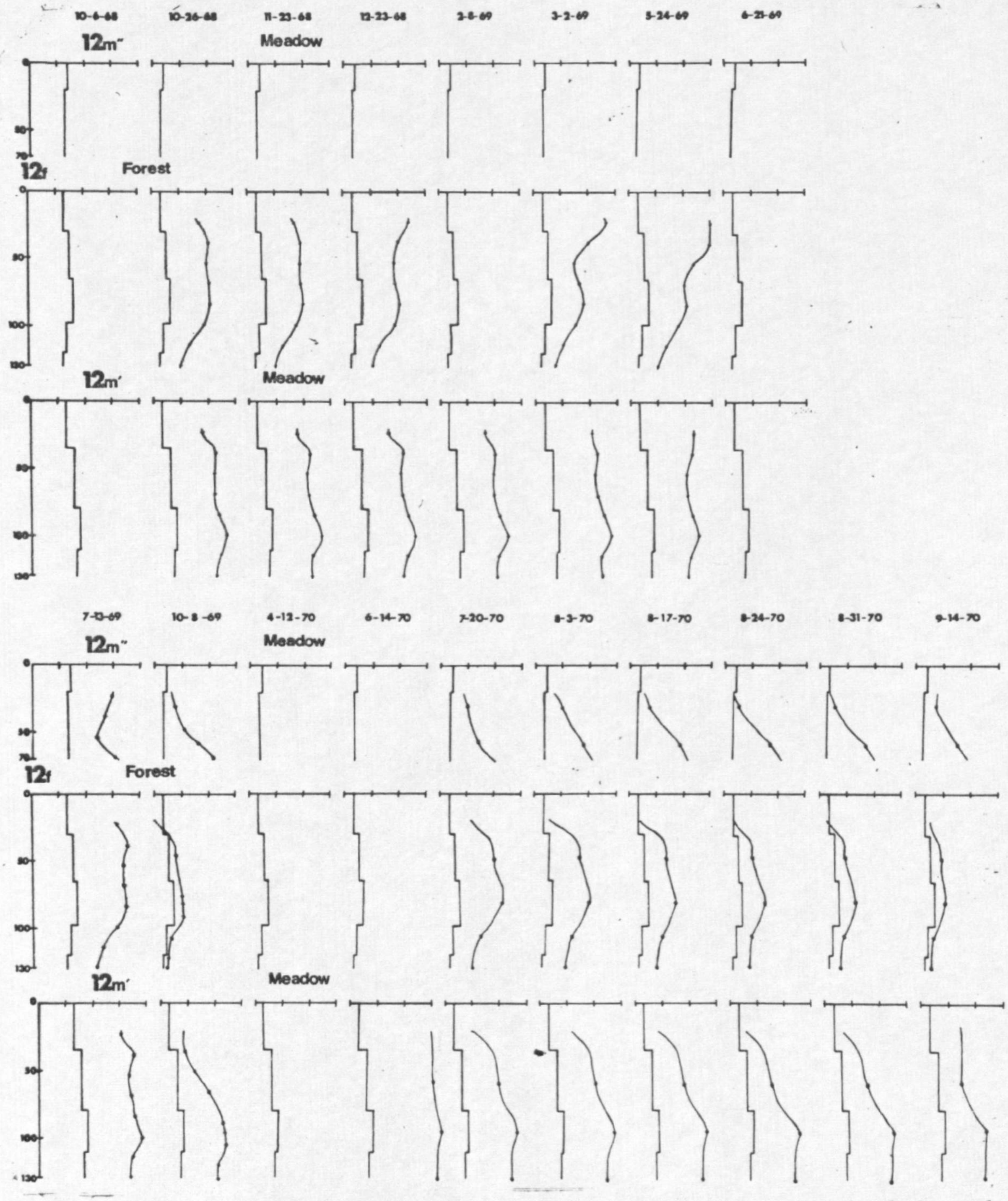

Fig. 13. Soil moisture distribution to depth of rooting for each krummholz site on dates of collection. Curves show distribution of soil moisture by volume and points on curves show field measurements.

Appendix Table 23. Available soil moisture for each 20 cm depth to the depth of rooting for 3 krummholz sites and the average in the open meadow

Date	Location			
	12m'	12f	12m"	M
Depth, cm	% Available Water Vol.			
10-26-68				
20	14.3	13.0	--	14.0
40	16.4	15.1	--	16.5
60	15.9	14.6	--	15.0
80	14.7	14.1	--	12.5
100	18.2	14.3		10.5
120	16.3	8.1		10.5
140	15.3			
root	20.7	15.1	--	13.8
11-23-68				
20	13.8	13.0	--	13.0
40	15.9	14.3	--	15.0
60	14.9	14.1	--	14.5
80	14.7	13.8	--	12.5
100	17.7	13.6		11.5
120	15.3	7.6		
140	15.3			
root	20.0	14.6	--	13.4
12-23-68				
20	12.8	20.5	--	15.0
40	14.9	14.6	--	14.0
60	14.4	13.6	--	13.5
80	14.2	13.6	--	12.0
100	17.2	14.1		11.5
120	14.8	7.6		
140	14.3			
root	19.1	16.4	--	13.4

Appendix Table 23. Continued

Date	Location 12m'	12f	12m"	M
Depth, cm	% Available Water Vol.			
2-8-69				
20	13.3	--	--	17.5
40	13.9	--	--	15.0
60	13.4	--	--	11.5
80	12.7	--	--	10.0
100	16.2	--		11.5
120	13.8	--		
140	13.3			
root	18.0	--	--	12.8
3-2-69				
20	15.8	24.5	--	18.0
40	14.4	16.1	--	14.5
60	13.9	12.1	--	14.0
80	14.2	13.6	--	10.0
100	17.2	13.1		15.0
120	14.8	7.6		
140	15.3			
root	19.6	12.3	--	13.7
5-24-69				
20	19.8	26.5	--	20.0
40	15.9	24.1	--	19.0
60	14.4	16.6	--	17.5
80	13.7	14.6	--	13.5
100	16.7	13.6		17.0
120	13.8	8.1		
140	13.3			
root	20.2	20.0	--	17.0
7-13-69				
20	17.8	17.5	15.7	13.5
40	19.4	21.3	13.2	15.5
60	18.8	19.1	13.3	15.0
80	17.2	18.6	18.3	13.0
100	20.2	17.1		13.0
120	17.3	11.1		
140	17.3			
root	23.9	19.9	10.3	14.1

Appendix Table 23. Continued

Date	Location 12m'	12f	12m"	M
Depth, cm	% Available Water Vol.			
7-30-69				
20	6.8	8.0	7.2	--
40	13.4	15.3	10.9	--
60	14.9	15.1	14.3	--
80	15.7	15.6	20.3	--
100	19.2	15.1		--
120	17.3	9.6		
140	17.3			
root	19.2	14.9	8.5	--
10-8-69				
20	5.3	-3.5	1.9	-1.5
40	3.4	2.1	5.7	-0.5
60	9.9	2.8	13.8	2.0
80	12.7	3.1	18.3	4.0
100	15.2	4.1		8.0
120	13.8	0.6		
140	13.8			
root	13.4	1.8	6.1	2.4
6-14-70				
20	24.3	--	--	19.5
40	21.4	--	--	19.5
60	21.9	--	--	17.0
80	21.2	--	--	14.5
100	22.7	--		18.5
120	22.8	--		
140	22.8			
root	29.1	--	--	16.7
7-20-70				
20	6.8	8.0	4.2	1.0
40	12.4	14.1	7.7	5.0
60	13.9	15.6	11.3	8.0
80	15.7	16.1	16.8	9.0
100	18.2	13.1		11.5
120	17.8	8.1		
140	17.8			
root	18.7	14.2	6.3	6.8

Appendix.Table 23. Continued

Date	Location 12m'	12f	12m"	M
Depth, cm	% Available Water Vol.			
8-3-70				
20	7.8	2.5	2.2	0.5
40	12.4	11.1	8.7	3.5
60	13.9	12.6	14.5	6.5
80	15.2	13.6	17.8	7.5
100	18.2	11.6		10.5
120	16.8	7.1		
140	16.8			
root	18.5	11.0	6.9	5.6
8-17-70				
20	4.8	0.5	0.7	-3.5
40	9.9	8.1	7.2	0.0
60	11.9	8.6	15.5	3.0
80	14.2	10.1	17.8	5.5
100	17.2	9.1		8.5
120	16.8	5.6		
140	16.8			
root	16.6	7.9	6.5	2.8
8-24-70				
20	2.8	0.1	-1.3	-5.0
40	6.9	4.6	4.7	-1.5
60	9.4	6.1	14.3	2.0
80	11.7	8.1	17.3	4.0
100	16.2	7.1		7.5
120	16.3	4.6		
140	16.3			
root	14.3	5.7	5.3	1.5
8-31-70				
20	3.3	-1.0	-1.3	-3.5
40	6.9	4.1	4.7	-1.5
60	9.4	5.1	13.3	0.5
80	11.7	6.1	16.5	4.0
100	16.2	6.1		6.5
120	16.3	3.1		
140	16.3			
root	14.4	4.4	5.0	1.4

Appendix.Table 23. Concluded

Date	Location: 12m'	12f	12m"	M
Depth, cm	% Available Water Vol.			
9-14-70				
20	11.3	1.5	3.7	4.0
40	8.4	3.1	6.2	1.5
60	8.9	4.1	12.3	0.5
80	11.2	3.6	15.5	3.0
100	15.2	3.1		5.5
120	15.8	0.6		
140	15.8			
root	15.7	3.1	6.0	2.9

Location		Rooting Depth, cm
12m'	Krummholz interior	136
12f	Krummholz forest	120
12m"	Krummholz exterior	80
M	Meadow (average)	100

root = Depth of rooting (water as cm)

Appendix Table 24. Characteristics of each soil horizon described in the krummholz community interior, site 12 m'

Site 12m' Characteristics	Horizon A1	Ab	B1	B2	C1	R
Depth, cm	0-35	35-43	43-78	78-110	110-150	150
Texture, %						
(Sand-clay)						
Laboratory	79- 8	71- 8	60-10	56- 8	60-10	
Field	-- 15	-- 18	-- 20	-- 23	-- 20	
Rock >2mm, %						
Laboratory	1	1	1	5	18	81
Field	1	1	1	5	20	90
Bulk Density, g/cc						
Laboratory	1.36	1.28	1.29	1.30	1.49	
Field	1.35	1.33	1.27	1.19	1.52	
Saturation, %	38	43	36	42	34	
1/3-bar, %	16.5	21.1	21.0	25.2	20.4	
15-bar, %	9.8	12.5	12.6	14.8	12.5	
Structure	MVFG	MVFG	MVFG	VWCP	MMFG	
Color, M 10YR	3/3	3/2	3/3	3/2	3/3	
Color, D 10YR	5/3	5/4	6/4	5/3	5/3	
Roots, density	VF&F	VF&F	VF&F	VF	VF	
	4-14	4-14	4-14	1-3	1	
Pores, density	VF	VF	VF	VF	VF	
	>14	1-3	>14	>14	>14	
pH 5.15	5.22	4.91	4.92	4.76		
Organic Matter, %	3.09	4.24	2.74	4.01	2.40	
Phosphorous, ppm	28	42	65	96	39	
Potassium, ppm	280	180	180	190	200	
Calcium, ppm	2660	2256	1992	1284	3380	
Magnesium, ppm	409	449	468	282	574	
Sodium, ppm	115	138	207	161	138	

Appendix Table 25. Characteristics of each soil horizon described in the krummholz community forest, site 12 f

Site 12 f Characteristics	Horizon A1	B1	B2	C1	R
Depth, cm	0-30	30-65	65-98	98-120	120
Texture, %					
(Sand-clay)					
Laboratory	66-12	69- 7	68- 7	67- 7.	
Field	65-12	50-20	45-23	55-18	
Rock >2mm; %.					
Laboratory	1	1	2	45	63
Field	1	1	2	50	70
Bulk density, g/cc					
Laboratory	1.19	1.33	1.33	1.25	
Field	1.09	1.26	1.28	1.42	
Saturation, %	40.0	40.0	43.0	34.0	
1/3-bar, %	21.0	20.3	21.9	18.5	
15-bar, %	12.3	11.9	12.8	11.7	
Structure	MVFG	MFG	WMSBK	MFG	
Color, m 10YR	3/2	3/3	3/4	4/3	
Color, D 10YR	5/4	5/3	5/3	6/4	
Roots, density	FMC&VC 4-14	F&M/C 1-3/4-14	F&M/C 1 1-3	F&M 1	
Pores, density	VF 1-3	VF 14	VF&F 4-14	VF 1-3	
pH	4.85	5.00	5.05	5.00	
Organic matter, %	4.01	3.32	4.01	2.05	
Phosphorous, ppm	48	62	65	45	
Potassium, ppm	520	400	340	280	
Calcium, ppm	1704	1128	1128	1584	
Magnesium, ppm	391	263	253	379	
Sodium, ppm	115	161	138	138	

Appendix Table 26. Characteristics of each soil horizon described in the krummholz community exterior, site 12 m"

Site 12 m" Characteristics	Horizon A1	C1	R
Depth, cm	0-20	20-40	40
Texture, %			
(Sand-clay)			
Laboratory	73- 6	65-12	64-12
Field	60-18	50-20	50-20
Rock >2mm, %			
Laboratory	16	68	81
Field	18	75	90
Bulk density, g/cc			
Laboratory	1.41	1.50	1.97
Field	1.29	--	--
Saturation, %	43.0	40.0	40.0
1/3-bar, %	20.4	21.1	21.6
15-bar, %	12.0	12.3	12.7
Structure	MFG	MFG	MFG
Color, M 10YR	3/3	3/4	3/2
Color, D 10YR	5/4	5/4	4/2
Roots, density	VF 4-14	VF 1-3	VF-1
Pores, density	VF 1- 3	none	none
pH	5.33	5.08	5.30
Organic matter, %	3.90	3.90	4.01
Phosphorous, ppm	31	36	10
Potassium, ppm	200	140	100
Calcium, ppm	2880	5540	5840
Magnesium, ppm	498	900	900
Sodium, ppm	138	184	207

Appendix Table 27. Microclimatic measurements at 3 krummholz sites

Period 1970	5 cm Soil Temperature °C						50 cm Air Temperature °C					
	Maximum			Minimum			Maximum			Minimum		
	12m'	12f	12m"	12m'	12f	12m"	12m'	12f	12m"	12m'	12f	12m"
6/8 -6/11		snow			snow			snow			snow	
6/11-6/14	2	1	-1	-2	1	-1		snow			snow	
6/14-6/23	16	2	7	1	1	-7	24	17	--	5	3	--
6/23-6/30	18	8	11	10	1	-1	28	25	--	-2	-4	--
6/30-7/15	20	11	13	8	3	-2	28	22	--	0	-3	--
7/15-7/20	22	12	15	12	8	4	29	24	--	8	7	--
7/20-7/27	22	14	15	11	8	-1	27	19	--	2	-1	--
7/27-7/31	21	12	14	12	9	2	26	18	--	4	3	--
7/31-8/7	23	13	18	12	9	3	18	24	19	7	6	6
8/7 -8/10	23	14	18	12	10	3	29	23	28	2	2	1
8/10-8/17	22	14	14	12	11	4	28	22	28	2	3	1
8/17-8/24	22	14	14	12	11	4	29	22	26	6	2	2
8/24-8/31	22	14	16	12	11	3	29	23	24	4	3	2
8/31-9/7	13	12	18	9	8	1	26	18	21	1	-1	0
9/7-9/14	4	9	12	3	3	-7	17	10	13	-12	-12	-12

Appendix Table 27. Concluded

	50 cm Soil Temperature ^{o}C			Precipitation (cm)			Evaporation (cm/day)		
	12m'	12f	12m"	12m'	12f	12m"	12m'	12f	12m"
6/8 -6/11	0.4	0.2	--	--	--	--	--	--	--
6/11-6/14	0.4	0.2	--	--	--	--	--	--	--
6/14-6/23	6.2	0.3	--	1.2	--	--	--	--	--
6/23-6/30	9.2	0.4	--	1.5	0.5	1.5	.56	.21	.86
6/30-7/15	10.8	5.9	--	2.2	1.6	2.4	.35	.17	.49
7/15-7/20	--	--	--	0.5	0.2	0.4	--	.22	1.00
7/20-7/27	12.4	7.0	--	2.8	2.0	2.8	--	.23	--
7/27-7/31	--	--	--	3.1	2.6	2.9	--	--	--
7/31-8/7	13.2	7.9	15.5	0.0	0.0	0.0	--	--	--
8/7 -8/10	--	--	--	0.5	0.9	0.4	--	--	--
8/10-8/17	13.1	8.6	15.5	0.0	0.0	0.0	.51	.29	.71
8/17-8/24	12.6	8.8	15.1	0.0	0.0	0.0	.40	.22	.66
8/24-8/31	12.3	8.8	14.4	1.3	0.6	1.3	.36	.26	.59
8/31-9/7	10.9	7.9	11.2	0.6	0.5	0.6	.24	.24	.40
9/7-9/14	5.9	4.4	3.8	6.5	5.0	4.7	--	--	--

ORIGIN - Two theories for the origin of krummholz communities are proposed here for evaluation in future studies. The first theory explains a circular formation ("fairy-ring") as being the result of a single tree or a group of trees extending a circular perimeter by vegetative reproduction. A small group of trees become established in a meadow wet spot resulting from possibly a topographical change. Through branch layering the perimeter advances and the center is left open. Snow persist longest near (5 m) the lee-side (interior) of the trees causing a shortened growing season that could explain the lack of reproduction in the interior. A similar situation of a short growing season, caused by late snow melt, reducing conifer reproduction was observed by Billings and Bliss (1959). Krummholz is also most evident in this 5 m zone. Presence of a burried A-horizon, darkened with charcoal, in the community interior supports the idea that trees once occupied the "center." Several small groups of trees (15-50 trees) in the area appear to be opening near their center.

A criticism of the theory is that a "rank" of trees (tree-ribbon described by Billings 1969) approximately 20 m wide appear to be only slightly convex and nearly perpendicular to the prevailing wind. In other words, the "fairy ring" is elliptic and trees appear to advance from a straight rank rather than from a circle.

The second theory supports the idea that the tree-ring is actually long (100 m) ranks of trees, nearly connected at their ends, appearing

ring-like. A rank can either establish as the front of the existing forest, and later meadow develop behind it or establish itself upwind from the existing forest edge at locations were snow accumulation (soil moisture) and growing season is sufficient. Assuming the ranks move up-wind (up-slope here), then both theories can explain the presence of the burried A-horizon. A second rank (other "half" of the ring) may develop from the snow accumulations associated to the up-slope or down-slope region of the first rank. This theory then suggests a rank moving away (upslope) from the existent forest resulting in a series of tree ranks or the tree ranks are relics marking the front of a receding forest.

A criticism of the rank theory is that new ranks were not observed. The origin of these communities is thought to be given by aging the tree "rings" or "ranks" and should be emphasized in future studies.

ENVIRONMENT - In general, the soil moisture and microclimatic data show what might be expected if the present 150 cm snow pack is doubled or tripled. An important point to note is the increase of available soil moisture in the meadow interior as compared to open meadows late in the growing season. The krummholz community is an environment released from a snow cover less than four months a year (July-October). Thus, it is protected and to such an extent that plant production is low compared to the open meadow. Similar results were found by Billings and Bliss (1959) in the Big Horn Mountains of Wyoming and Weaver[13] on the Bangtail Ridge.

The community is a park within a park and provides an "excellent" confined shelter for camping, picnics, domestic animals, and aesthetic scenes. During the winter, accumulated snow is a challenge to the snowmobiler, but more important, large drifts nearly twice the density of the average snow pack melt 4-8 weeks later than the open meadow. The effects of delayed melt are to decrease spring water yield and increase summer flow.

WATER - A few assumptions and generalizations are made to give the reader an idea of the impact of krummholz communities on water yield. Accumulated snow associated with the community ranges from 10 ft (3 m) to 25 ft (8 m). In one acre, a conservative estimate of the average snow depth is 15 ft (4.5 m) which has about a 50% snow water equivalent. This amounts to 7.5 (.50 x 15') acre feet of water. Therefore, snow water associated with the krummholz community exceeds the snow water of the open meadow by 5 times. Open meadow has 1.5 acre feet (.30 x 5') of water.

Snow in the krummholz community may persist 2 months longer than open meadow, affecting late season runoff. In terms of water for the

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[13] Dr. T. Weaver, Botany and Microbiology, has compared production of late melting sites to ones melting earlier in the area.

downstream user, the natural drifts provide at least 5 times more water than nondrifted and deliver water when it is most needed, late in the season.

Similar to other biological systems that man uses or manipulates, "There Is No Free Lunch." The water has its price. As a result of delayed snow melt, grass production may be inadequate for livestock grazing.

The small parks are often used for bedding sheep but the real potential of these areas is providing recreational shelters, aesthetic scenes and water.

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