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Interim Progress Report
March 1975

THE SAN JUAN ECOLOGY PROJECT

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by
Colorado State University
Fort Collins, Colorado 80521

in cooperation with
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and
Department of Biological Science, Fort Lewis College, Durango, Colorado

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15. Supplementary Notes

This document is a compendium of related physical and biological studies which are attempting to assess the ecological impact of the Upper Colorado River Basin Pilot Project. It represents a cooperative effort between Colorado State University, the University of Colorado and Fort Lewis College.

16. Abstract

The results of the San Juan Ecology Project's third operational year are presented in this report. The project is administered as two major teams, the Forest and Alpine Tundra Ecosystems. Above timberline, it was found that an artificial increase in snowpack, produced by snow fences, does affect plant production, plant decomposition, seed germinability and early season phenological development; no effects on late season phenology were noted. Below timber line, herbaceous plants at higher elevations and on north slopes mature and flower at a smaller size than those of the same species at lower elevations and on south slopes (i.e. areas of shorter-lying snow). Several phenological parameters of spruce and aspen growth are apparently related to seasonal snow variation through changes in air and soil temperature. It has been shown that the early snowmelt period is definitely one of high moisture stress in trees; a model is being developed to relate this stress to environmental variables. Allometric equations have been developed to relate tree biomass production to tree diameter and height, so that biomass may be related to snowpack variation. Forest phytosociological studies indicate that long term increases in moisture may gradually alter forest composition, e.g. from fir to spruce and from stable to successional aspen and fir. Above treeline, population characteristics of pocket gophers are being related to snow depths. Below treeline, evidence is accumulating that, within limits, population size of some small mammals under study is inversely related to snow depth. Elk appear to prefer oak communities on south aspects, where penetrable snowdepth is less than 35 cm. at time of maximum accumulation, but they will tolerate up to 70 cm. depth if all available areas are under deep snow cover. Geomorphological studies indicate that summer erosion is the overriding factor in alpine soil movement, and that the San Juan area is not likely to be strongly influenced by the degree of climatic change which could be brought about by an increase in snowpack. An ecological overview is attempting to relate characteristics of alpine and forest study sites to the whole target area. No significant increases in silver concentration have been found on the target area after three winters of seeding, but definite increases have occurred in vegetation and litter at the generator site under study. No deleterious effects of silver iodide additions have been noted, either at the generator sites or in field application plots. The possibility of microbial conversion of insoluble to soluble silver forms has been observed.

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THE SAN JUAN ECOLOGY PROJECT

An Evaluation of the Ecological Impact of Weather Modification in the Upper Colorado River Basin

Interim Progress Report
for the Period
January 1973 - June 1974

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1. INTRODUCTION

The San Juan Ecology Project was at the three-quarter mark of its anticipated four-year life after the 1973 field season. As part of the Bureau of Reclamation's Upper Colorado River Basin Pilot Project, it is expected to provide technical information on the likely ecological consequences of increasing winter snowpack in the San Juan Mountains of southwestern Colorado. Its conclusions will hopefully play a part in the decision making process pertaining to an operational program of snow augmentation in the Upper Colorado River Basin.

This report contains the results of the third field season's research, and is a sequel to three previous reports in this series. It presents the conclusions of a number of cooperative projects which are attempting to establish valid relationships between snowpack variation, plant and animal communities, and abiotic processes or parameters.

Few changes were initiated in the past year. Most projects have accumulated sufficient data to permit at least partial modelling of the basic processes involved, and it is anticipated that several models will be available by the end of the project. These include plant distribution relationships with snowpack, alpine soil movement, tree moisture stress relations with temperature and soil moisture, and silver distribution in surface soil. While complete quantification of matter or energy flows could not be undertaken here, the development of partial-process models will hopefully develop to the stage where they will be applicable in other areas.

It should be stressed that no 'control' time or area could be used in this study, that seeding commenced concurrently with the ecological investigations and that only a limited number of organisms were selected for study. The rationale for these selections has been discussed in the three previous reports of the project.

Two studies in the Forest Ecosystems terminate with this report - the phytosociology and tree biomass projects. The former is a benchmark study which largely met its objectives in two field seasons, and the latter used standard and tested methods which permitted completion of objectives in three field season.

Intensive study sites are located in three major areas in the forest ecosystems network (sites 3,4 and 5, Fig i), and in two alpine basins on the Continental Divide (sites 1 and 2, Fig i). Several projects, such as the ecological overview, dendrology and silver studies, are concerned with larger segments of the original target area.

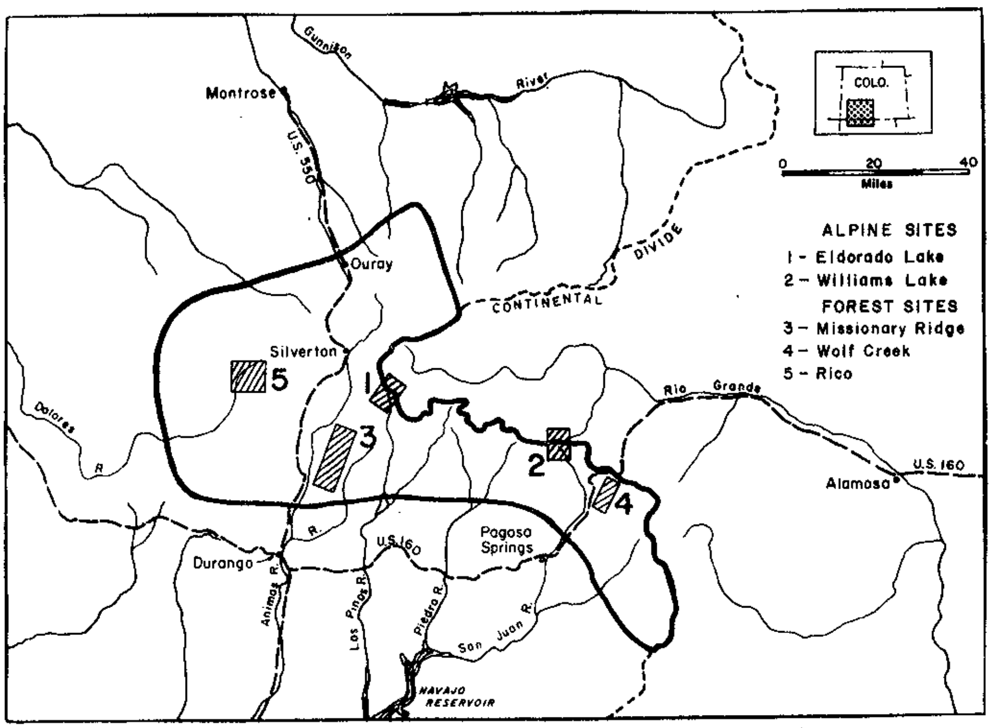

Figure i. San Juan cloud seeding target area, intensive study area.

2. OBJECTIVES

The objectives of the San Juan Ecology Project remain unchanged, namely to determine the effect of increased snowfall on the major biotic and related physical ecosystem components of the San Juan Mountains target area, with emphasis on those components which are of economic and/or public interest to man. Because of the large variation in the annual snowfall of the area, and the relatively small anticipated increase as a result of seeding, the effects of snow variation, rather than those of snow increases, are being investigated here.

3. ORGANIZATION

The project is organized under two main groups, a Forest Ecosystems Team and an Alpine Tundra Ecosystem Team. Colorado State University and Fort Lewis College combine in the former, while the University of Colorado, through its Institute of Artic and Alpine Research, is responsible for the latter.

During the reporting period, overall administration of the project was conducted through the Project Coordinator (Dr. H. Leo Teller, Colorado State University) and the two Team Leaders: Forest Ecosystems - Dr. Harold W. Steinhoff, Colorado State University; Alpine Tundra Ecosystems - Dr. Jack D. Ives, University of Colorado.

Major decisions concerning the whole project were made by a Steering Committee, which included the Project Coordinator as Chairman, the two team leaders, and three other members: Dr. Herbert E. Owen, Fort Lewis College; Dr. C. Patrick Reid, Colorado State University; and Dr. Patrick J. Webber, University of Colorado. Mr. R. Carl James, as Project Monitor, provided liaison between the Project and the Bureau of Reclamation.

Liaison was maintained with the Medicine Bow (University of Wyoming) and the Montana State University weather modification ecology teams, and with various agencies, such as the Forest Service and the National Center for Atmospheric Research, which are also concerned with weather modification effects.

The fourth annual SJEP Technical Conference was held on November 29, 1973 at the University of Colorado. In addition, each of the Teams hold regular seminars through the year, where principal investigators and graduate research assistants discuss current developments in their work and consider problems of general interest. During the 1973 summer, exchange visits of project personnel and university administrators were made to intensive sites in both ecosystems.

Dr. H. Leo Teller took special leave from CSU for an assignment with UNESCO, Paris, so he resigned as Coordinator on July 1, 1974. Dr. Harold W. Steinhoff was named Coordinator and was responsible for compilation and publication of this report.

4. EFFECTS OF SNOWPACK VARIATION ON THE FOREST ECOSYSTEMS

4.1 INTRODUCTION (Dr. Harold Steinhoff, Team Leader)

Changes of biomass of trees, forage, elk, and small mammals in relation to snowpack variation, continue as the primary concern of research efforts in the forest ecosystems of the San Juans. Often indirect approaches must be used, such as the study of phenology to determine when growth begins, the measurement of moisture stress as an indicator of growth rates, or the change in winter distribution of elk. Details of the research approach and findings to date for each of the ecosystem components mentioned above are found in the project reports which follow. The general rationale for study and the nature of the spruce-fir and aspen ecosystems which are of primary concern are described in the first Interim Progress Report of December, 1971. Data on characteristics of intensive study sites, and summarized climate variables of the general area are found in the second Interim Progress Report of March 1973.

4.1.1 Study Areas

Description of study areas and representative maps of plot location are found in the second Interim Report.

4.1.2 Microclimatic Data and Analyses

The year-week has been chosen as the compilation interval for all climatic data in the forest ecosystems. Daily data are available but are too detailed for most ecologic uses. Monthly summaries obscure too much. Temperature sums above 0°C are accumlated beginning each January 1. Precipitation is accumlated each October 1.

A complete data set was needed for the cumulative temperatures and precipitation analyses. Therefore missing data were recovered by prediction from the most comparable weather station. Correlations of year-weekly precipitation among the six intensive study sites, six nearby Western Scientific Services sites, and four adjacent U.S. Weather Service sites are shown in Table 1.

Multiple stepwise regressions last year revealed that usually only the one best correlated station was necessary to produce a prediction equation. Little improvement was noted in adding multiple stations. Therefore prediction equations were developed for each intensive site, using the stations which correlated best with it, (Table 2).

Figure 1 represents an attempt to picture the yearly climates of Durango graphically. Deviations from the mean of monthly precipitation are plotted along the x-axis and of monthly mean temperature along the y-axis. The resultant patterns shows how each month related to the long-term mean in the combination of temperature and precipitation. Winter months such as those in 1972-73 all fall in the lower right quadrant, an indication of high precipitation and low temperature. The weather in 1970-71 was consistently closer to "normal", with all months clustered fairly close to the intersection of the mean precipitation and temperature line.

4.1.3 Summary

1972-73 was characterized by unusually heavy rains which saturated the soil in October just before freeze-up, and by snow depths 150 to 200% of normal. Temperatures followed an average regime. Snowmelt was delayed by from two to six weeks by the deeper snowpacks.

Table 1. Correlation of weekly precipitation among 17 weather station sites near Durango and Wolf Creek, June 1971 to December 1973.

	Intensive Study Sites						Western Sci. Serv.						U.S. Weather Service				
	Top Park	Little Bear		Middle Fork	Wolf Creek		Missionary Ridge Lime Mesa	Missionary Ridge Kroeger Park	Wallace Lake	Wolf Creek Ski	Wolf Creek E.Hiway	W.Hiway	Durango	Silverton	Tacoma	Val-Dam	Pagosa Spgs
	M35	M32S	M32A	M29	W31	W33	JHI	KGI	KG 2 KG 3	KP2	KP3	KO3	Drno	Sltn	Tcma	Val Dam	PagS
M35	1.00	0.93	0.90	0.77	0.76	0.88	0.94	0.91	0.85	0.84	0.84	0.72	0.78	0.76	0.85	0.77	0.78
M32S		1.00	0.91	0.72	0.74	0.90	0.94	0.95	0.78	0.78	0.78	0.78	0.78	0.83	0.89	0.76	0.76
M32A			1.00	0.70	0.72	0.90	0.90	0.97	0.74	0.77	0.76	0.83	0.82	0.86	0.89	0.78	0.76
M29				1.00	0.90	0.68	0.68	0.74	0.92	0.89	0.92	0.70	0.71	0.66	0.74	0.76	0.83
W31					1.00	0.74	0.73	0.78	0.91	0.93	0.92	0.70	0.69	0.71	0.78	0.75	0.85
W33						1.00	0.91	0.89	0.80	0.80	0.79	0.68	0.79	0.75	0.84	0.72	0.77
JHI							1.00	0.90	0.78	0.78	0.78	0.72	0.75	0.80	0.85	0.75	0.76
KGI								1.00	0.79	0.79	0.79	0.84	0.83	0.88	0.91	0.84	0.81
KG2 &3									1.00	0.96	0.95	0.67	0.66	0.65	0.78	0.78	0.87
KP2										1.00	0.94	0.74	0.70	0.69	0.83	0.83	0.93
KP3											1.00	0.70	0.68	0.68	0.82	0.80	0.87
KO3												1.00	0.73	0.84	0.86	0.80	0.74
Drngo													1.00	0.78	0.80	0.72	0.72
Sltn														1.00	0.85	0.74	0.76
Toma															1.00	0.85	0.84
ValDm																1.00	0.81
PagS																	1.00

Table 2. Prediction equation for recovering missing weekly total precipitation data for intensive study sites.

Weekly Total Precipitation Prediction Equation, Inches 1/	Correlation Coefficient, r	F-Value Computed	F.05
M35 = 0.07 + 0.89 M32S	0.93	479.15	3.98
M35 = 0.03 + 0.76 JHI	0.94	320.72	3.98
M35 = 0.18 + 1.17 TCMA	0.85	316.98	3.93
M32S =0.06 + 0.91 M35	0.93	479.15	3.93
M32S =0.01 + 1.00 M32A	0.91	845.49	3.93
M32S =0.04 + 1.18 KGI	0.95	781.51	3.98
M32S =0.02 + 0.80 JHI	0.94	294.09	3.98
M32S =0.22 + 1.05 TCMA	0.89	175.46	3.90
M32A =0.05 + 0.87 M32S	0.91	827.95	3.90
M32A =0.02 + 1.10 KGI	0.97	852.65	3.98
M32A =0.19 + 1.07 TCMA	0.89	281.19	3.93
M29 = 0.07 + 0.47 W31	0.90	113.33	3.93
M29 = 0.01 + 0.75 M35	0.77	557.58	3.93
M29 = 0.01 + 0.87 KG2&3	0.92		3.98
M29 = 0.06 + 1.10 PAGS	0.83	196.89	3.90
W31 = 0.32 + 1.06 M29	0.90	113.33	3.93
W31 = 0.01 + 0.74 KP2	0.93	424.89	9.98
W31 = 0.23 + 1.60 PAGS	0.85	155.40	3.93
W33 = 0.20 + 0.87 M32S	0.93	155.34	3.93
W33 = 0.11 + 0.77 JHI	0.91	80.77	3.99
W33 = 0.30 + 1.05 TCMA	0.84	115.30	3.93

1/ Expressed in inches rather than mm because WSS and USWS Station data are in inches.

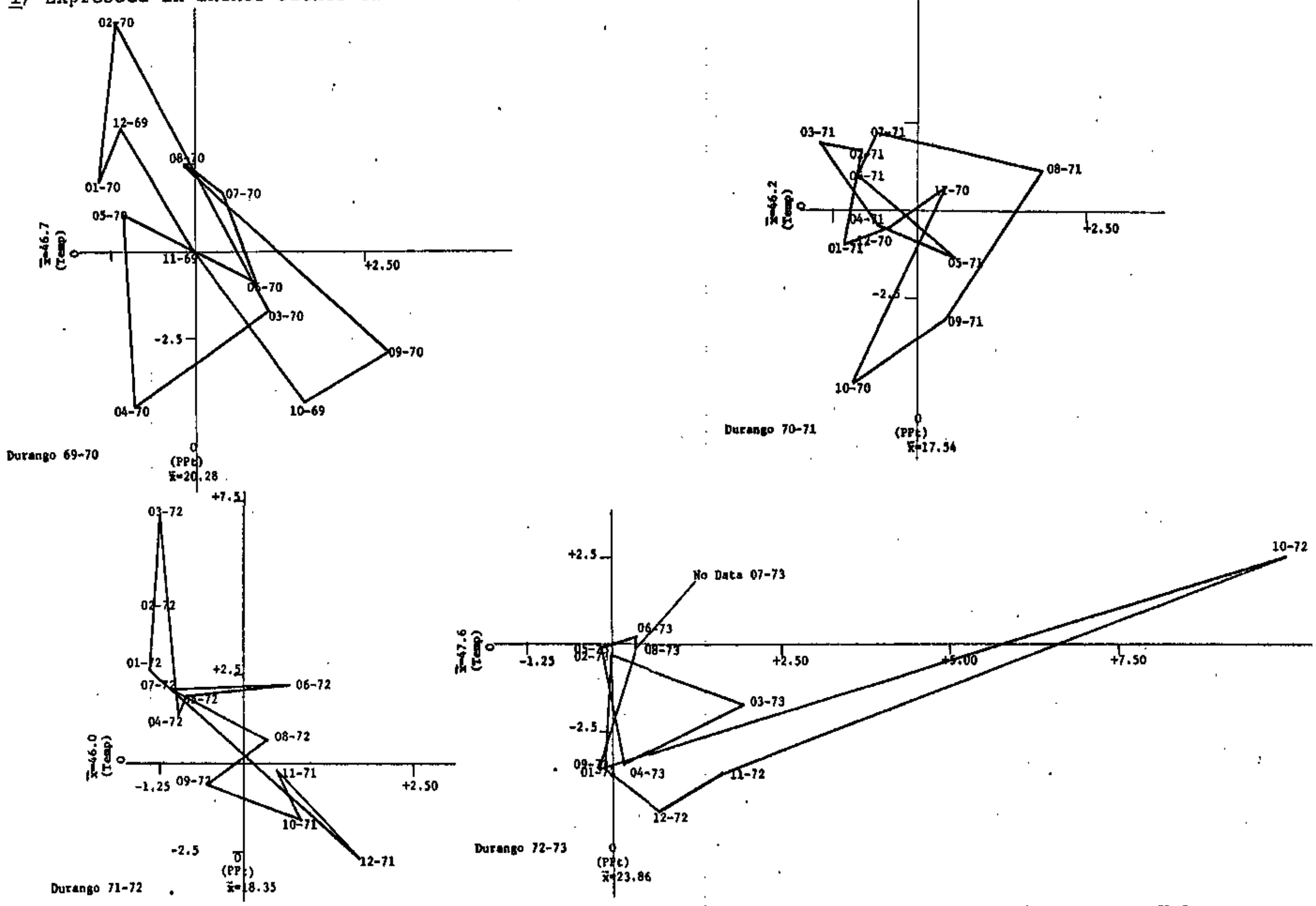

Figure 1. Monthly mean temperature-precipitation patterns for Durango during the past four years. Values are plotted as deviations from the mean for the "precipitation year", for example Oct 1969 through Sept 1970 for the upper left graph.

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4.2 PHENOLOGY (Drs. Herbert Owen and Gilbert Fechner)

4.2.1. Herbaceous Phenology (Dr. Herbert Owen)

The Herbaceous Phenology sub-project is designed to correlate the development of various plant species during the growing season with such environmental factors as air temperature, soil temperature, and soil moisture and in turn correlate these with an increase in snow quantity. The types of developmental stages which are being observed and recorded are the beginning of growth in the spring, maturing of the vegetative growth, and development of the flowers and fruits. The plant species being observed represent a cross-section of types to be found in the research area.

- Objectives

The objectives of the Phenology Project of the San Juan Ecology Project essentially remain the same as proposed after one season of field work. That is, to determine the relationship between snow depth, soil moisture and temperature, air temperature and the phenologic development of selected plant species.

- Procedures

North and south aspect sites were selected at elevations of 2900 meters, 3200 meters and 3500 meters on the Missionary Ridge study area. Plots were selected to include the desirable herbaceous and shrub species. On the Wolf Creek Pass area, north aspect sites at 3100 and 3200 meters were selected. Eight study sites were selected, with 71 plots. Over 800 observations were recorded in the growing season of 1973. Data were collected according to the following categories:

- Inflorescence development as expressed by percentage of flowers in bud, open, and/or in various stages of fruit development and seed dispersal. Generally speaking, the inflorescences are considered to be in full bloom when they reach 50% open flowers. In like manner "full fruit" is when the inflorescences contain 50% mature fruit. All data were collected at weekly intervals at all sites starting approximately 1 April 1973.

- Results

In general, the data for the 1973 growing season substantiate previous tentative conclusions; that is, a continued period of snow cover affects all phenological events in an almost linear relationship (Fig. 1, 2, 3, 4 ,5, 6).

- Again, plants of the same species on south aspects reached maximum growth and flowering maturity approximately one to three weeks ahead of north aspect plants. An exception can be found at the highest elevation where the plots are located on comparatively shallow soil. The very dry growing season conditions this year apparently caused these higher elevation plants to mature at approximately the same time on both the north and south slopes.

- Plants of the same species at the higher elevations took approximately one week to ten days less time to reach their full development and complete their season's growth than plants at lower elevations.

- Plants of the same species at higher elevations and on north aspects matured and flowered at a smaller size than plants at lower elevations and on south aspects. (Tables 2, 3, and 4).

- In some cases, the 1973 plants exhibited greater productivity (Tables 2, 3, and 4) which might reflect the greater amount of snow melt, though this is pure supposition.

- The "catch-up factor" alluded to in previous reports was noticeable in some species, but not in others. Festuca thurberi seems to particularly have this ability (Table 1). Other species had their maturing dates shifted into July and August by the late lying snow (graphs Acillea, Thlaspi) instead of in June or July as in previous years.

- An additional experiment was performed this past year in which three plots, essentially identical in all respects except one, were compared from both a phenological and a productivity standpoint (Table 1). These data typify the affect of snow cover on plant development very well. They also demonstrate the "catch-up factor" in Festuca. (Fig. 6)

Table 5 demonstrates typical correlation coefficients of the data to date. Again, this supports the primary Results statement.

The mass of data obtained defies the imagination and much more time will have to be spent in analyzing them and attempting several correlations to "pin down" phenological phenomena versus environmental factors versus an increase in snow cover relations.

This year's data definitely supports the idea that the plant's phenological attributes are going to be affected by an increase in snow cover. We now need to determine the degree to which they will be affected.

- Future Plans

Essentially, the future will consist of continuing the work now started. Techniques have been refined and changed (as indicated in last year's report) to the extent that they are now considered to be quite satisfactory.

Table 1. Festuca thurberi leaf length at 3200 m.--south aspect site. Plot B had approximately 1/2 of the snow removed and put on Plot A. Thus, Plot A had approximately twice as much snow as Plot B.

DATE	CONTROL PLOT	PLOT A	PLOT B
6 June, 1973	0.0 cm.	0.0 cm.	5.5 cm.
12 June, 1973	6.8 cm.	4.3 cm.	18.6 cm.
19 June, 1973	11.3 cm.	8.8 cm.	24.2 cm.
26 June, 1973	13.7 cm.	17.7 cm.	30.2 cm.
3 July, 1973	31.2 cm.	27.1 cm.	36.1 cm.
9 July, 1973	39.0 cm.	33.5 cm.	41.3 cm.
18 July, 1973	48.7 cm.	38.9 cm.	44.8 cm.
24 July, 1973	48.6 cm.	40.4 cm.	44.3 cm.
31 July, 1973	52.5 cm.	44.7 cm.	44.8 cm.
7 August, 1973	56.6 cm.	46.3 cm.	46.3 cm.

Table 2. Maximum leaf length of Festuca thurberi.

PLOT	1971	1972	1973
2900 M. - South	57.3 cm.	51.1 cm.	63.1 cm.
3200 M. - South	55.0 cm.	57.1 cm.	56.6 cm.
3200 M. - North	49.7 cm.	54.6 cm.	55.9 cm.
3350 M. - South	43.0 cm.	47.0 cm.	45.9 cm.
3350 M. - North	39.7 cm.	55.3 cm.	53.5 cm.

Table 3. Maximum leaf length of Swertia radiata.

PLOT	1971	1972	1973
3200 M. - South	46.4 cm.	46.4 cm.	55.9 cm.
3200 M. - North	50.7 cm.	56.6 cm.	60.4 cm.
3350 M. - South	39.0 cm.	33.3 cm.	40.1 cm.
3350 M. - North	38.4 cm.	43.0 cm.	50.9 cm.

Table 4. Maximum inflorescence height of Achillea lanulosa.

PLOT	1971	1972	1973
2900 M. - South	43.7 cm.	38.3 cm.	60.9 cm.
2900 M. - North	--	--	46.5 cm.
3200 M. - South	46.8 cm.	42.1 cm.	41.7 cm.
3200 M. - North	44.2 cm.	37.4 cm.	37.0 cm.
3350 M. - South	39.7 cm.	23.5 cm.	36.3 cm.
3350 M. - North	36.5 cm.	20.7 cm.	33.7 cm.

Table 5. Correlation between year days on which a phenological event took place and year day of 0% snowcover on the plot.

PLANT AND PHENOLOGICAL EVENT	CORRELATION COEFFICIENT
Festuca thurberi - maximum height	0.876
Helenium hoopesii - maximum inflorescence height	0.810
Mertensia fusiformis - full bloom**	0.903
Thlaspi alpestre - full bloom**	0.928

* Degrees of freedom are at least 74.

** Full bloom is defined as 50% of the inflorescence is in flower.

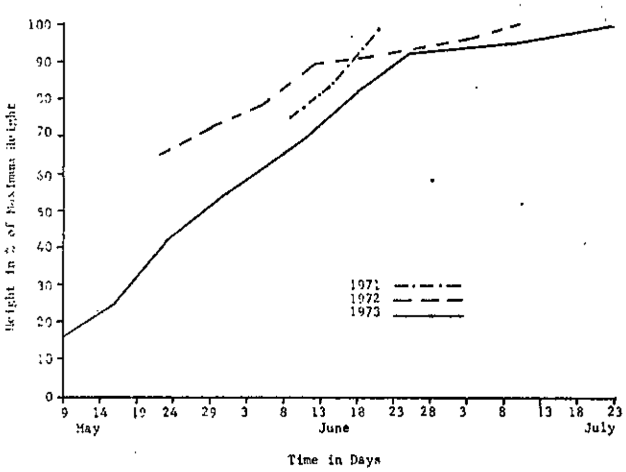

Figure 1. Plant height in Festuca thurberi at 2900 meters, south aspect.

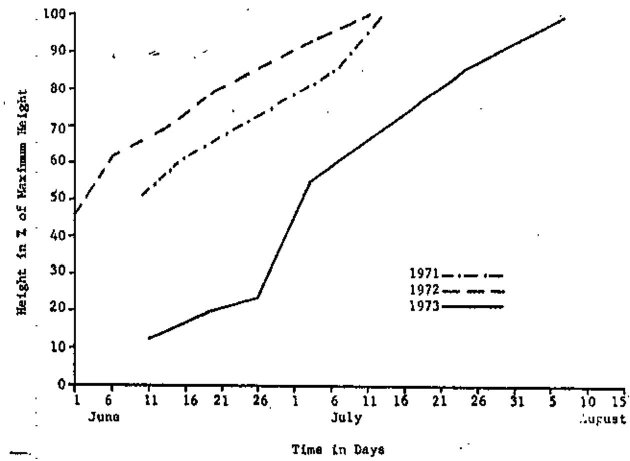

Figure 2. Plant height in Festuca thurberi at 3200 meters, south aspect.

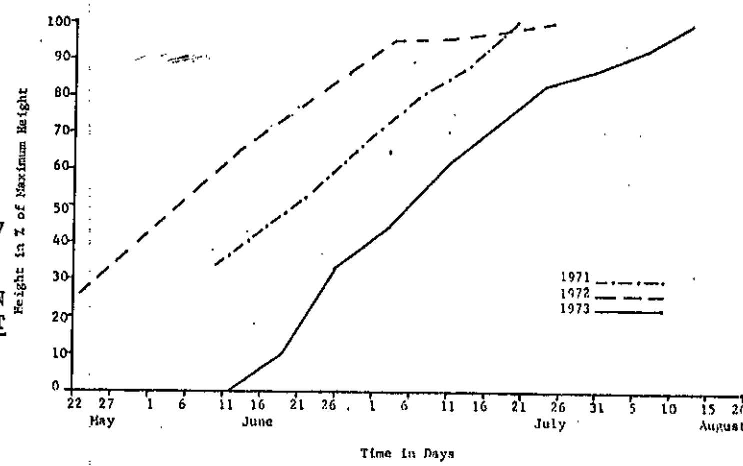

Figure 3. Plant height in Festuca thurberi at 3200 meters, north aspect.

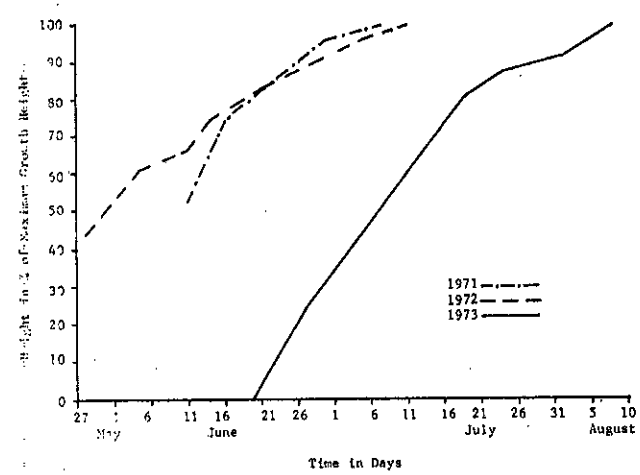

Figure 4. Plant height in Festuca thurberi at 3350 meters, south aspect

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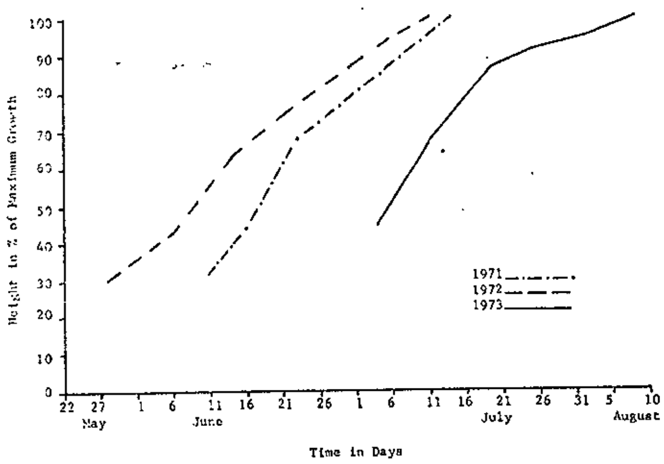

Figure 5. Plant height in Festuca thurberi at 3350 meters, north aspect.

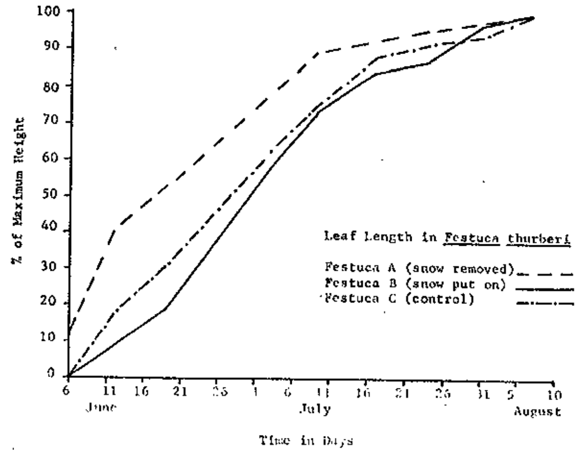

Figure 6. Effect of snow manipulation on Festuca thurberi.

4.3.1 Introduction

Vegetation continuously responds to the physical environment and therefore any significant change in that environment through time can be expected to cause a corresponding change in vegetation. Therefore, possible increases in snowpack and snow duration, which may be brought about by the weather modification program in the San Juan Mountains, can be expected to result in adjustments in its vegetation structure and dynamics. Since the dominant plant species of this vegetation are long lived perennials, this adjustment is expected to be slow, it will probably occur over a period of many decades. The establishment of the weather modification program before adequate research had begun on the vegetation of the San Juan Mountains necessarily precludes the establishment of appropriate experiments. We are, therefore, limited to studies which show the principal environmental gradients along which vegetation responds and to determining the nature and magnitude of these responses. This knowledge will enable us to predict what changes may be expected as the physical environment of the San Juan Mountains is artificially modified. Limited time and funds also necessitated that our study be limited to the subalpine forest of these mountains.

4.3.2 Objectives

The overall objectives of this project are twofold: (1) to provide a quantitative description of the subalpine forest of the San Juan Mountains within which the results of other investigations may be expressed (Table 1); and (2), to predict the effects that weather modification may have on the composition and dynamics of this vegetation. Since the establishment of experiments was not possible, a major objective is to establish the principal environmental gradients along which the subalpine forest responds so that this information can be used to predict possible changes which may be brought about by the weather modification program. In addition, our description of the subalpine forest provides a data base (too large to be presented here), established during 1971-1973, for the detection of possible changes in vegetation associated with weather modification programs through subsequent years.

4.3.3 Methods

Data were collected from 61 sites selected over a wide range of environmental conditions. These included 20 aspen, 37 Englemann spruce-subalpine fir, 3 white fir, and 1 douglas fir dominated stands. The majority of these stands are located on Missionary Ridge, although a few were selected from the Rico and Wolf Creek Pass study areas.

Standard phytosociological techniques were used to measure tree species for density, dominance (basal area), height, vitality and age structure. These tree species were measured in 3 size classes: (1) trees (diameter at breast height (dbh) greater than or equal to 8.16 cm.), (2) saplings (dbh greater than 2.54 cm. but less than 8.16 cm.), and (3) seedlings (dbh equal to or less than 2.54 cm.). Cover and frequency were recorded for shrubs. Frequency values, in 50 x 50 cm. quadrants, were obtained for all understory species. Selected environmental parameters were recorded from each site. Snow duration data were determined for 23 sites from sequential aerial photographs from flights flown in 1971. Partial snow duration data are available for 4 additional stands. More frequent and more extensive photo coverage was expected from 1973 aerial surveys, but did not materialize.

Principal components analysis (PCA), a form of indirect gradient analysis, was used to define the major structural gradients within the vegetation, and to correlate measured environmental parameters to those gradients. The gradients defined by the principal components analysis are vegetational gradients which are determined statistically to account for as much of the variation in the vegetational data as possible. The analysis allows correlations of the measured environmental parameters with the derived vegetational gradients. Understory species data were used in the analysis since the large number of species involved provides for precise definitions of the vegetational gradients. The methodology of PCA has been used and discussed by Seal (1964), Orloci (1966), Gittens (1969), and Walker and Wehrhahn (1971).

4.3.4 Results

Our first objective of providing a quantitative description of the subalpine vegetation of the San Juan Mountains is given below in the presentation of the indirect gradient analysis. This particular method of display will probably be most useful to other workers on the project because it provides the phytosociological display on the gradients of greatest interest; namely to snow duration and related gradients. Our second objective of providing an analysis of the effects of weather modification on vegetational composition is treated below by techniques of direct gradient analyses.

- Indirect gradient analysis

Major gradients in the vegetation were derived from a principal components analysis (PCA) of the understory species frequency data. So that snow duration data could be included in the analysis, and an interpretation of snow duration effects could be made, only those stands with aerial photo coverage were used in the analysis presented here. Another PCA using 57 subalpine stands (the 23 snow duration stands plus 34 stands not within the aerial survey) was done with virtually identical results; therefore, the gradients described by the analysis of only the stands with photo coverage are presented.

Table 1 shows the first three gradients or components described by the PCA. The first component is a gradient which accounts for the maximum possible variance in the data, and each successive component accounts for as much of the remaining variance as possible. Each species has a loading on each component which is, in fact, the correlation coefficient between that species and that component (or gradient). The square of this loading is the proportion of variance of the species' data accounted for by that component. The column "h^2" is the sum squares of the first three components and is the amount of variance in the data of that species which is accounted for by the first three components. A total of 94 understory species, 5 tree species, and 10 environmental parameters was included in the PCA. For brevity the table includes only those species for which: (1) over 65% of the variance was accounted for by the first three components, or the loading on the first component was greater than 0.6, and the species was present in more than one stand on Missionary

Table 1. Factor loadings of tree and understory species and environmental variables on the first 3 components from Principal Components Analysis of understory species frequencies. The column h^2 gives the proportion of the variance of each variable (species or environmental measurement) accounted for by the first 3 components. Species' names follow Harrington (1954). Total variation extracted by three axes = .58.

Variable	Component 1	Component 2	Component 3	h^2
Tree species				
Populus tremuloides trees	.70	-.11	.21	.55
Populus tremuloides saplings	.51	.18	.11	.30
Populus tremuloides seedlings	.58	.22	.10	.39
Abies lasiocarpa trees	-.55	-.28	.14	.40
Abies lasiocarpa saplings	-.25	-.27	.06	.14
Abies lasiocarpa seedlings	-.53	-.31	.29	.49
Picea engelmannii trees	-.83	.26	.01	.75
Picea engelmannii saplings	-.13	.43	-.01	.20
Picea engelmannii seedlings	-.41	.10	.16	.20
Understory species				
Achillea lanulosa	.98	.09	.02	.96
Lathyrus leucanthus	.89	-.18	.15	.85
Campanula rotundifolia	.89	.32	.17	.92
Vicia americana	.88	-.19	.17	.84
Symphoricarpos oreophilus	.88	-.24	-.07	.83
Festuca thurberi	.83	.16	-.01	.72
Thalictrum fendleri	.80	-.18	.03	.68
Taraxacum officionale	.79	.11	-.22	.68
Lupinus argenteus	.77	-.18	.22	.68
Carex geyeri	.77	.03	.26	.66
Erigeron speciosus	.73	.15	.14	.58
Rosa spp.	.73	.10	.03	.54
Fragaria virginiana	.72	.26	.27	.66
Geranium richardsonii	.67	-.09	.07	.46
Agropyron trachycaulum	.65	.28	.18	.54
Pseudocymopteris montanus	.65	.43	.25	.67
Poa pratensis	.65	-.13	.04	.44
Bromus ciliatus	.63	-.13	.19	.45
Smilacina racemosa	.63	.15	.09	.42
Helenium hoopesii	.61	.20	.21	.45
Viola canadensis	.34	-.75	-.09	.69
Rubus idaeus	.15	-.27	-.79	.71
Chenopodium spp.	.14	-.26	-.79	.70
Capsella bursa-pastoris	.13	-.25	-.79	.70
Pachystima myrsinites	-.05	-.82	-.24	.73
Haplopappus parryi	-.08	-.49	.35	.37
Poa reflexa	-.37	.71	-.21	.69
Ranunculus glaberrimus	-.47	.60	-.33	.69
Epilobium hornemannii	-.49	.59	-.33	.69
Oxypolis fendleri	-.49	.58	-.31	.67
Juncus balticus	-.49	.59	-.32	.69
Erigeron spp.	-.50	-.46	.04	.46
Erigeron coulteri	-.52	.63	-.19	.71
Stellaria umbellata	-.62	.47	-.14	.63
Pedicularis racemosa	-.66	.20	.08	.49
Arnica cordifolia	-.69	-.45	.43	.85
Lichens	-.78	-.41	-.04	.77
Pyrola secunda	-.78	-.38	.15	.79
Polemonium pulcherrimum	-.79	.17	.28	.72
Mosses	-.83	-.16	-.17	.74
Luzula parviflora	-.85	.33	.18	.85
Monesis uniflora	-.85	.10	.08	.75
Vaccinium spp.	-.87	.07	.19	.80
Environmental measurements				
Radiation Index	.75	.46	-.01	.78
Drainage Class	.22	.09	-.14	.08
Canopy Cover	.15	-.01	-.11	.03
Percent Stone in Soil Volume	.11	-.10	-.00	.02
Percent Slope	-.27	-.54	-.14	.39
Litter and Mulch Depth	-.35	-.15	.19	.18
Elevation	-.49	-.33	.57	.67
Snow Duration	-.91	.02	.07	.84
Proportion of variation	.35	.14	.08	

Ridge; or (2) the species attained its highest frequency values in stands of medium snow duration. The reason for the second criterion is discussed below.

Species with high positive or negative loadings on a component are, of course, highly correlated, positively or negatively, with that component. Stands with loadings near zero are either not correlated to that component, or are correlated to that component in some nonlinear way, not accounted for in this analysis. The more nearly the loadings of two species correspond to each other, the closer their behavior is along the gradient defined by that component. Species with highly opposite loadings are negatively correlated with respect to their response along the gradient of the component; they are responding in an opposite way to some common factor. For example, Lathyrus leucanthus is highly positively correlated with the first component in Table 1, as is Vicia americana. They are responding to the gradient of the first component in the same way. On the other hand, Luzula parviflora is highly negatively correlated with the first component; it is responding in an opposite way from the other two species.

The proportion of the total variation accounted for by each component in Table 1 is given at the extreme bottom of the table (e.g., .3558). This proportion is the variance or latent root of that component. The sum of the variances for the first three components is the proportion of the total variation in the data accounted for by those components. This proportion is given at the bottom of the "h^2" column, and exceeds .58 in value.

A unique property of PCA is that some sets of data may be included in such a way that they do not appreciably affect the results of the analysis. This is accomplished by scaling the desired data down several orders of magnitude so that it might vary from 0 to 0.1, for example, while the rest of the data varies from 0 to 100. In this study certain environmental parameters were included in this way, as well as the density of tree species. The presence of these data do not appreciably effect the PCA and the statistical correlation between the results and the environmental parameters were obtained. The resultant correlation coefficients of the most important environmental parameters with the components (their loadings of those components) are shown near the bottom of Table 1, those of the major tree species are shown near the top of Table 1.

It can be seen from Table 1 how tree, sapling, and seedling densities correlate with the first 3 major gradients in the vegetation. Note, again, that the analysis is based on understory species frequencies and that the tree data did not play a part in establishing the PCA display. Nevertheless, the inclusion of these data allows the relation of tree species' densities with major vegetational gradients to be seen. Spruce densities are very negatively correlated with the first major vegetational gradient, as is fir, though to a lesser extent. Aspen is also fairly strongly correlated with this gradient, though in an opposite manner to that of spruce and fir.

Of particular interest to this study is snow duration. Snow duration here is determined by the index

$$SDI=(P+2C)/PC_{max}$$

where P is the first date of partial snow clearance, C is the first date of total snow clearance, and PCmax is the largest value of (P+2C) observed in any stand.

All computations were for 1971 snow data since this is the only year for which adequate photo coverage is available. Snow Duration Indices are relative positions of stands along a snow duration gradient. The absolute scale of snow duration varies from year to year. Snow Duration Indices were also calculated for the few stands covered in the 1973 photographs, and, although there were very few usable photographs in 1973, the relative positions of the stands along the snow duration gradient were not changed from their positions using only the 1971 data.

The Radiation Index values were obtained from tables (Frank and Lee, 1966) and are the ratios of the annual radiation totals to the annual maximum potential solar beam irradiation (the solar constant times the duration of sunshine for the year). This is more than a quantification of the aspect parameter; it is an estimate of an important part of the energy budget of a site and is an estimate of a parameter that has been shown to be significantly correlated to soil moisture depletion rates (Stearns and Carlson, 1960). In general, a perfectly flat stand would have a Radiation Index of about 0.48 at the latitude of the study area. Stands with southerly aspects have Radiation Indices greater than this while those with northerly aspects have Radiation Indices smaller than this. The exact magnitude of the Radiation Index for a given latitude depends on the aspect and steepness of the slope.

The Drainage Class is related to topographic position and the relative ability of a site to gain or lose water from gravitational drainage and runoff. A low Drainage Class value implies a well drained site that has little or no recharge from runoff or subsurface flow; a high Drainage Class value implies a site that will accumulate runoff or seepage or both.

The basic assumption in the interpretation of the gradients defined by the components is that the differences in species frequency at various sites is a response to differences in the environment in those sites. If differences in species composition are due to differences in the environment, and if the differences of some few environmental parameters account for much of the differences in species composition, then major gradients in species composition ought to be related to gradients of these few environmental parameters. There ought to be a high correlation between those factors causing the greatest compositional differences in the vegetation and the major gradients within the vegetation. The PCA is a multivariate statistical procedure that defines the gradients of maximum variation in the data. The inclusion of environmental parameters in the analysis allows correlation coefficients of those parameters with the gradients defined by the analysis.

As shown in Table 1, there is a high negative correlation (-.91) between snow duration and the primary gradient in the vegetation (the first component). This correlation is so high that the gradient described by the first component is interpreted as a snow duration gradient. Radiation Index and Percent Slope are highly correlated with the second component. As these two factors are not independent (percent slope is used in the calculation of the Radiation Index) this might be expected. Therefore the second component is interpreted as being a gradient of Radiation Index or simply radiation. The third component is interpreted as an elevational gradient.

- Direct gradient analysis

The result (Table 1) that the major gradient or first principal component in the vegetation is highly related to snow duration was further investigated by plotting the response of vegetational parameters directly on a snow duration gradient. Figure 1 illustrates how some species' frequency values respond to snow duration. For example, Achillea lanulosa in Figure 1(a), Fragaria virginiana in Figure 1(b) and Symphoricarpos oreophilus in Figure 1(d) all show decreases in frequency as snow lies later. Vaccinium spp. and Polemonium pulcherrimum in Figure 1(b) increase in frequency with increased snow duration. Some species, such as Geranium richardsonii in Figure 1(a), show maximum frequencies somewhere between the extremes of snow duration. Other species with this latter behavior were included in Table 1.

Species which show maximum frequencies at intermediate positions along the snow duration gradient may have very little of their variance accounted for by the PCA analysis in Table 1. The analysis assumes a statistical model that may not fit the response of every species to the major gradients. This is not to say, necessarily, that the species is not responding to factors determining the major gradients in the vegetation; the species may be responding in a manner not accounted for by the analytical model. The ecological significance of the analysis should not be judged wholly on the basis of correlation to the assumed model. In this instance, however, an important environmental parameter has been found over which many species do seem to respond. With many more stands with snow duration data, deterministic models might be derived that could predict species behavior with statistical certainty.

If the understory species are related to the snow duration gradient, the question of how the tree species behave with respect to snow duration naturally arises. Figure 2 shows the response of the densities of important tree species to snow duration. At sites where snow is clear very early, aspen is the only species present. As the snow lies later spruce and fir begin to make up a larger part of the stems present, and the number of aspen stems decreases. As snow lies even later fir becomes the most dense species. Finally, as snow continues to persist, spruce becomes the most dense species and aspen is no longer present. At the latest dates of snow duration provided for in the data, fir becomes a minor component of the dominant vegetation and spruce reaches its maximum densities.

Figure 3 shows the relationship of important tree seedling densities to snow duration. Aspen seedling densities reach their highest values in those stands where snow clears early. Aspen seedling densities decrease as snow lies late while densities of spruce and fir increase, fir with the higher densities. As snow lies very late, seedling densities of all species decrease considerably, the density of fir falling below that of spruce.

In addition to the 57 subalpine stands, 4 stands were selected that occur near timberline on Lime Mesa. These stands are beyond the extent of aerial photo coverage and no quantitative estimate can be made for their position along a snow duration gradient. In general subalpine fir is not present in these timberline stands. Here Englemann spruce forms stands in ribbons and patches, associated with rock outcrops, topography, and apparent prevailing weather influences. The parent material is limestone of the Ouray Formation. This limestone is essentially different from the parent material of the remainder of Missionary Ridge, which is primarily a limestone of the Hermosa Formation (Larsen and Cross, 1956).

The vegetational composition of these timberline stands is vastly different from the subalpine stands. Within each stand, species from subalpine and alpine meadows are found with subalpine forest species. Species diversity is consequently very high, and these stands represent a wide range of species composition. The inability of obtaining snow data for these stands, the difficulty in understory species identification due to a much belated phenology, and the apparent wide range of composition within this structural type forced the investigators, in the interest of time and economy, to concentrate studies on the lower, subalpine stands. Although no snow duration data were available for these stands, personal on-site observation in the 1973 season suggest snowmelt and phenological events several weeks later than sites 300 to 400 meters lower. A discussion is given below of the apparent influence of snow on this vegetation.

4.3.5 Discussion

The slow response of communities dominated by long-lived perennials to manipulative experiments precluded its use in studies as short-lived as the present one. Instead, this project was organized as a process study. An understanding of how the environment is related to community composition and structure was sought and from this the effects of an increased snowfall might then be evaluated.

It was assumed that as the snowfall increased, there would be an increased snowpack resulting in a delayed snowmelt. Concomitant with this longer snow duration at a site would be the following factors:

(1) delayed soil moisture depletion.
(2) delayed rise in soil temperatures.
(3) lower light levels until site is snow free.
(4) increase in and longer duration of physical pressure on vegetation.
(5) longer duration of protection of vegetation from extremes of non-snowpack environment.
(6) increased susceptability to pathogens (snowmolds).

Each species would, of course, react differently to the above factors; as a result there would be an alteration in community structure.

It was evident from the 1972-73 snowfall that large increases in snowpack can delay snowmelt several weeks. As stated above, the same general pattern of snowmelt was noted in 1973 as in 1971. Such observations were also made in studies cited by Geiger (1971). On page 451, Geiger states:

> "The way snow melts in mountain areas is closely related to topography...; that is to say, even if the snow melts at different times in different years, the melting pattern is always the same."

In addition, Geiger cites relevant studies which relate the melting pattern of snow to phenological and vegetational differences. (These references include Friedel, 1952; Kreeb, 1954; Aulitzky, 1958; and Waldmann, 1959).

In our analysis snow duration was shown to be highly correlated with the major gradient in the vegetation. But how is snow duration related to other snow parameters? Generally speaking, snow duration at a site is a function of the water equivalent of the snowpack and the energy budget of the site. That is to say, the amount of heat (calories) needed to melt the snow is equal to the mass of the snow times the latent heat of fusion for water (80 calories/gram). Furthermore, the energy budget at the site determines the rate at which those calories are made available to melt the snow. Two parameters determined in this study that are related to the energy budget are Radiation Index and elevation. Radiation Index is an estimate of solar beam radiation, and elevation is related to air temperature through the adiabatic lapse rate.

An understanding of how snow melts is important in interpreting the effects of snow on vegetation. During the winter, the volume under the snow surface is protected from extremes of temperature by the insulating properties of the snow. The snow-ground interface at this time is warmer than anywhere in the snow itself (Geiger, 1971; Wardle, 1968). Snow melt water formed does not generally reach the soil, but is held within the snow, tending to move upward by capillary movement and vapor diffusion. This movement is caused by the temperature gradient within the snowpack (Geiger, 1971).

As the snow begins to melt in the spring, snow melt water begins to reach the ground where it infiltrates. This maintains a nearly constant temperature of about 0°C at the soil surface throughout the melt period (Wardle, 1968; Geiger, 1971).

Later in the snow melt period, when the snowpack is only a few centimeters in depth, snow tends to melt from the bottom up. Snow is relatively transparent to higher energy, short wavelength radiation which passes through the snow and is absorbed by the substrate. This results in a warming of the substrate and so a reradiation of energy of a longer wavelength. Snow absorbs these longer wavelengths and melts from the bottom upwards. Water from the melting snow infiltrates the soil, saturates it, and further melt water runs off at the surface. When the site is snow-free, soil temperatures begin to rise and moisture depletion may occur, subject to subsequent precipitation or runoff and seepage (Geiger, 1971).

These observations of snowmelt help in understanding the effects that snow might have on vegetation. The effects are different for each species, and vary in magnitude across the snow duration gradient. In general, we would expect (from the PCA) aspen trees and those species near the top of the understory species list in Table 1 to be more important in stands where snow is early to disappear. In fact, when aspen densities and understory species frequencies were plotted as a function of snow duration, this behavior was evident (Figures 1, 2, and 3). On the other hand, spruce trees and understory species near the botton of Table 1 respond positively to increased snow duration.

Where the snow disappears early the ground is early exposed to the non-snowpack environment. Soil moisture is depleted and soil temperatures rise. Those forest sites where snow is early to disappear now support only aspen trees. Conifer survival may be limited due to drought periods during the growing season, warm night temperatures, or high light intensities. The conifer seedling, with its short root system, cannot sustain the plant during long periods of drought (Noble, 1973). Spruce survival has been shown to be very poor in areas where night temperatures are warm (Helmers et al., 1970) and solarization at high light intensities may cause death of conifer seedlings (Ronco, 1970). In any case, aspen suckers, with their connections to deep root systems and their inherent tolerance of high light intensities, are more capable of surviving in such stands than are conifers.

As the snow lies later, conifer seedling survival may be enhanced. Patten (1963) found that spruce, followed by subalpine fir, became established in cool, shaded and moist areas which collected deep snow in the winter and maintained soil moisture through much of the growing season. He noted that spruce seed germination was rare under snowbanks, but that seedlings already established may grow under shallow snow because of the high shade tolerance of the species. He also noted that a year with heavy snows followed by a wet summer favors conifer establishment. Survival during the next winter is poorer in areas where the seedlings are blown free of snow, due perhaps to frost damage. Patten found that spruce seedling survival under cool, moist conditions is especially high when these conditions are maintained under high light intensities.

Tree seedling establishment of all kinds may be suppressed in areas of still later snow clearance. Brink (1959) investigated subalpine tree establishment in British Columbia and attributed their establishment to a recent climatic shift, which caused a decrease in snowpack. Subalpine trees, including subalpine fir, are becoming established in areas that are free of snow earlier than the surrounding heath. Franklin et al. (1971) investigated the invasion of subalpine meadows by trees in the Cascades. They state:

> "The snow-free period in certain subalpine meadow communities is probably the most critical factor affecting tree establishment. ...Snowpack, through its influence on length of growing season, is known to be one of the most important factors in determining the position of forest-meadow ecotones in subalpine zones. A climatic flux which reduced duration of snow cover ...would favor conifer invasion."

Other studies have shown similar suppression of seedling success at the upper extreme of the snow duration gradient. Wardle (1968) found that late lying snow delayed the growth of seedlings in the Front Range in Colorado. A month delay in snow free date resulted in a 15 day difference in the date of maximum shoot growth. He found for Niwot Ridge that although there seemed no less seedling establishment in areas of late lying snow (except where there was prolonged flooding by melt water from above), there was a higher incidence of snowmolds (*Herpotrichia* sp. and possibly *Phoma* sp.) here than in areas clear of snow earlier. Thus, seedling survival is affected by late lying snow. However, Wardle did not find a relationship between the date of snow disappearance (from around the stem base) and the phenology of either saplings or mature trees.

Snow persisted longest in stands near alpine timberline, represented in our study by those stands on Lime Mesa (those stands not covered by aerial photo survey). Billings (1969) studied vegetational pattern in such stands in the Medicine Bow Mountains of Wyoming, where he found the forest to be in ribbons and patches, a physiognomy similar to that present to a large extent on Lime Mesa. Billings explains that

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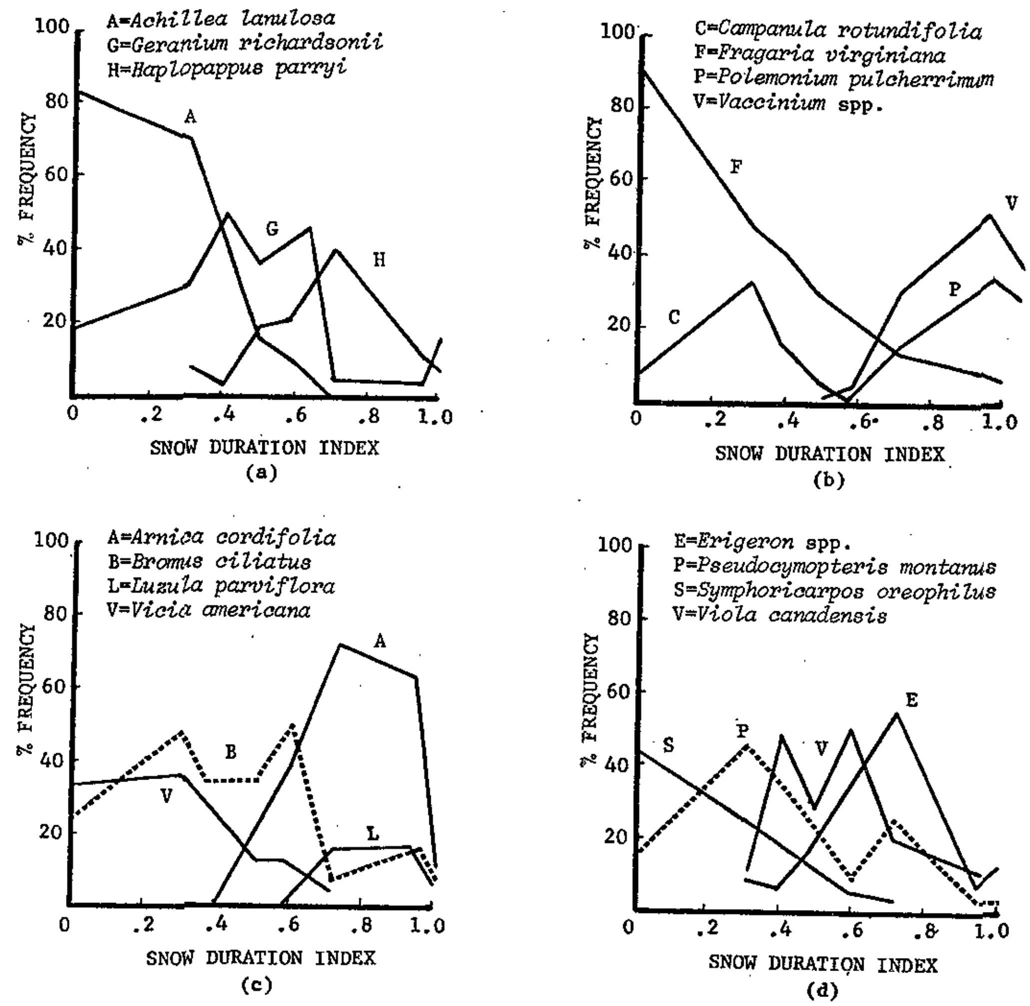

Figure 1. Relation of some understory species frequencies to the Snow Duration Index.

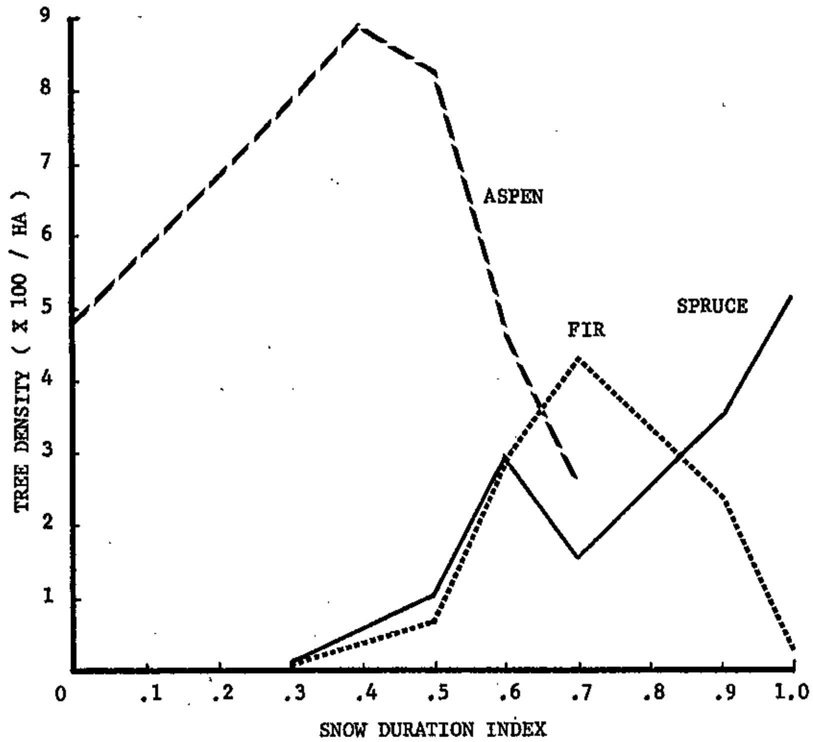

Figure 2. Relation of tree densities to Snow Duration Gradient.

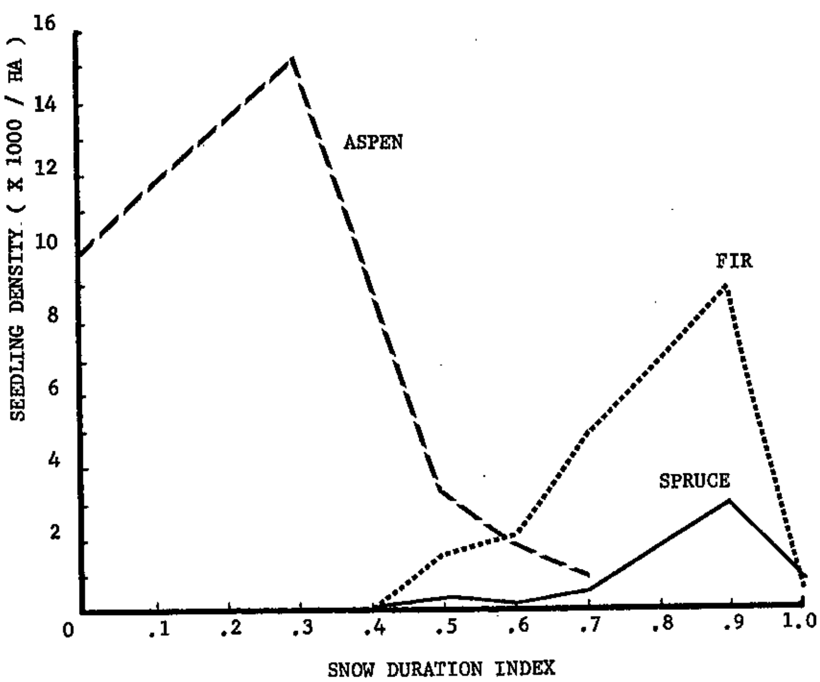

Figure 3. Relation of tree seedling densities to Snow Duration Gradient.

the pattern is a result of the removal of snow by wind from open areas and its deposition into drifts. The melt of the drifts provides a good moisture regime for seedling establishment up to where its edge occurs in June or early July. That part of the area where the drift melts later produces a wet or moist meadow vegetation typical of the "snow glade." This produces the ribbon-like pattern of the forest. Billings suggests that the ribbon forest and snow glade areas can be expected "just below climatic timberline wherever plateaus or gentle slopes are exposed to heavy snowfall, strong winter winds, and cool summers."

4.3.6 Conclusions

The results of this study attest to the significance of snow associated parameters in determining subalpine vegetation. This is supported by the work of other investigators: Aulitzky, 1958; Billings, 1968; Brink, 1959; Franklin et al., 1971; Friedel, 1952; Geiger, 1971; Patten, 1963; Waldmann, 1959; and Wardle, 1968. Of special significance in forests is the effect snow has on seedling establishment. Spruce and fir regeneration may be limited at sites now supporting only aspen trees because of the long dry periods during the growing season, warm night temperatures, or high light intensities. An increase in snowpack at these sites, which would result in increased snow duration and improved soil moisture and temperature conditions, should increase the survival of spruce and fir seedlings. Solarization effects on spruce seedlings are not as severe when moisture conditions are favorable (Ronco, 1970). Increased snowpack need not be increased continuously to assure establishment of conifer seedlings in this habitat. Seedlings established during one or two favorable growing seasons may survive if the long-term climatic conditions favor their growth. In other words, with increased snowpack there should be a tendency for stable aspen stands with little or no conifer reproduction to succeed to spruce-fir forest. Also, succession should proceed more rapidly in successional aspen stands as conditions become more favorable for the survival of the spruce and fir seedlings.

Our results indicate that within the spruce-fir forest spruce seedlings may be more tolerant of increased snow duration than are fir seedlings (Figure 3). In this case, survival of spruce seedling relative to fir seedlings would be increased, resulting in stands of higher relative densities of spruce. The resultant absolute densities that would occur as a result of increased snowpack would depend where along the snow duration gradient a given site occurs. As is typical of biological responses, the densities of spruce and fir increase up to some optimal densities and then decrease as the snow lies later. As the snow persists, conditions become less favorable for all tree seedling survival. The growing season may be shortened, the site may remain too wet from snowmelt for seedlings to survive, pathogenic attack (snowmolds) may cause increased mortality of seedlings that are established. As the snow lies very late all tree seedling establishment may be precluded. At this extreme, tree seedling establishment depends on a coincidence of good seed production and short term weather conditions.

Consistent with this response of tree species to increased snow duration, the vegetation as a whole tends to respond to increased snow duration. All species have their unique responses to heat, light and moisture regimes, and their own tolerances of extremes of environmental conditions. As some species are more adapted to what would be a slightly altered environment, they would have a tendency to respond more favorably to that environment. This would result in a change in community structure as interspecific interactions would become altered, stabilizing with respect to that environmental change only after some considerable time. As was pointed out above, many of these species are long-lived perennials. The eventual structure of a stand should be one of plants that are more highly positively correlated with snow duration. Stands would lose some species and gain others, depending on the species tolerances to snow duration and associated factors, and the outcome of the new species interactions. These may be predicted from Table 1.

4.3.7 Summary

The objectives of this study are to provide a quantitative description of the subalpine forest of the San Juan Mountains within which the results of the other investigations may be expressed and to predict the effects that weather modification may have on the composition and dynamics of this vegetation. The establishment of experiments was not feasible, due to the very slow response of communities dominated by long-lived perennials. Principal environmental gradients along which the subalpine forest responds were sought. This information was then used to predict possible changes caused by weather modification. Principal components analysis was used to determine the major gradients in the vegetation of the subalpine forests. The analysis provided correlations of measured environmental parameters with the major vegetation gradients. The gradient which accounts for the most variation in the vegetation was found to be the snow duration gradient.

The responses of several understory species over a snow duration gradient are described. Some species attain their highest values of frequency of occurrence in stands where snow disappears early. Other species had maximum frequency values where snow is very persistant. Still other species have maxima between these two extremes.

It was found that quaking aspen, subalpine fir, and Englemann spruce trees vary in their response to the snow duration gradient. Aspen is present at higher densities where the snow leaves early. As snow lies later more spruce and fir are found with the aspen. First fir and then spruce trees reach dominance in numbers as the snow persists. A similar response to snow duration was found for the seedlings of these subalpine tree species.

A species will succeed in an environment where it has the ability to become established and to maintain itself. An increased snowfall resulting in a larger snowpack and a delayed snowmelt will result in delayed soil moisture depletion and temperature rise, lower light levels until the snow is gone, an increase in and longer duration of physical pressure on the vegetation, a longer duration of protection of the vegetation by the snowpack environment, and an increased susceptability to snowmolds. Each species reacts differently to these factors. The result is an alteration in community structure.

It was concluded that an increased snowfall which resulted in a longer snow duration would favor spruce and fir seedling establishment in those aspen stands presently stable (without coniferous reproduction). Conifer seedling success would be favored more in successional aspen stands, resulting in more rapid succession to spruce-fir. In the spruce-fir forest, spruce survival might be favored where the snow lies late. The likelihood of any tree seedling establishment where the snow lies very late would be decreased.

Thus, the weather modification program in the San Juan Mountains will likely alter the species composition of the subalpine forests in those mountains. The degree and nature of this response will depend upon the nature of the alteration.

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Acknowledgments

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4.4. TREE BIOMASS (Tom Landis and Dr. E. W. Mogren)

4.4.1. Introduction and Objectives

Changes in snowfall patterns in the San Juan Mountains as a result of weather modification could potentially affect the wood production of forest communities in the subalpine zone of the target area. These possible effects of snow on forest production can be divided into two categories; direct effects where snow could alter the length of the short growing season in the subalpine, and indirect effects where snow could influence the temperature and moisture regimes of the environment which influence the production patterns of the forest. Both direct and indirect influences of snow should also be considered in a temporal context; snow effects may be cumulative in nature and may not be obvious in short-term studies.

There are two main forest types in the subalpine zone of the target area. The upper elevational forests are composed of stands of spruce-fir and in the lower elevational areas, relatively pure stands of quaking aspen are found. The spruce-fir association is composed of only two tree species, Engelmann spruce (Picea engelmannii Parry) and subalpine fir (Abies lasiocarpa (Hook.)Nutt.). These forests are mature and uneven-aged and considered climax for this region. Engelmann spruce is the dominant species, usually comprising more than 85 percent of the standing crop. Quaking aspen (Populus tremuloides Michx.) forests are varied in age and structure, but most stands are wholly aspen, with a small percentage of coniferous species in the understory. These forests represent a substantial timber resource and large areas of mature trees are suitable for commercial harvest. Therefore, the possible effects of weather modification on the wood production of these forests should be investigated.

The research objectives of the Tree Biomass Project may be best stated in terms of two null hypotheses. The first null hypothesis involves the production performance of individual spruce and aspen trees and proposes that the annual wood production of these trees is adversely affected by the direct or indirect influences of snow. The second hypothesis states that bolewood production of aspen and spruce-fir stands is affected by these same factors.

4.4.2. Results and Discussion

The experimental procedures of the project have been reported in detail in reports of previous years. They will not be discussed in this report; rather, the results and tentative conclusions of this project will now be presented.

Biomass and production of the spruce-fir association

The production relationships of this forest type were studied in more detail than the aspen type because of the extensive acreage of the spruce-fir type in the subalpine zone and therefore, this type was sampled more intensively. The following discussion deals exclusively with wood production of individual trees and stands of the spruce-fir type. Aspen production will be treated later.

Individual tree production was measured at the four intensive study sites of the San Juan Ecology Project over the past 20 years using stem analysis techniques (Figure 1).

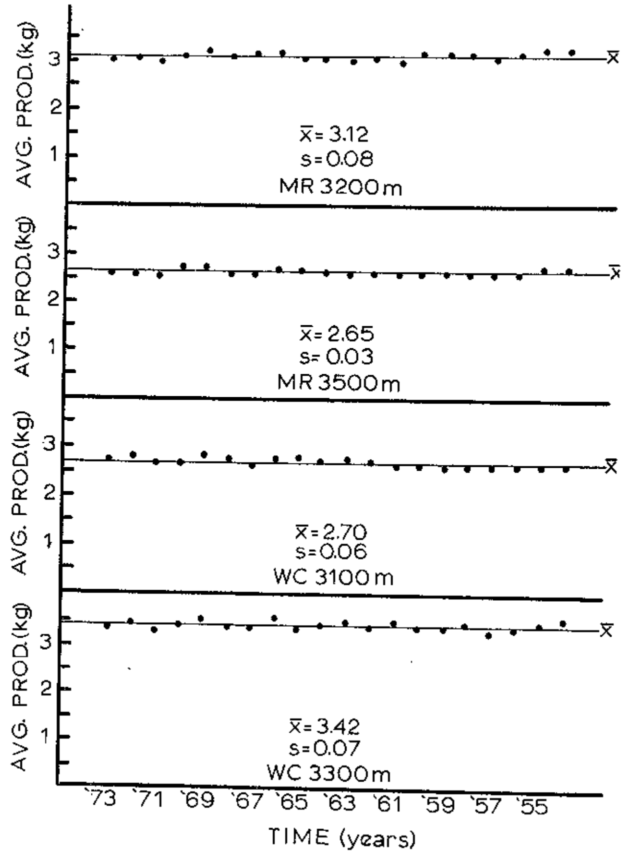

Figure 1 - Bolewood production per tree.

Annual bolewood production of five "individual production trees" at each site was averaged to provide a typical production response of individual trees to snow-related variables. The average production pattern over the 20 year study period was remarkably stable around the period mean ($\bar{x}$), as indicated by the low standard deviation values (s). These data indicate that spruce trees are quite consistent in their annual wood production although they do exhibit a 3-4 year cycle in their production during the 20 year period. This cycle could be ascribed to the seed production characteristics of the species. Heavy seed crops are produced every 2-6 years (Alexander, 1958), and these heavy seed crops could outcompete the vascular cambium for current and stored photosynthate. During these heavy seed years, the wood production would be slightly reduced and during light seed years, it would be slightly greater. Accepting this hypothesis, the production pattern of the individual spruce trees becomes even more stable.

Stand bolewood production during the 20 year study period is also shown to remain relatively constant at the four intensive study sites (Figure 2). This pattern would be anticipated because stand production reflects the cumulative response of all individual trees in the plot. Also, such constant production is an attribute of the climax seen in uneven-aged stands (Whittaker, 1970).

The bole biomass or standing crop of the four study sites was monitored since 1971 on permanent plots and these data exhibit two types of perturbations during this period (Figure 3). The first type can be seen at the 3300m location on Wolf Creek Pass, where a gradual decrease in biomass occurred due to the periodic mortality of individual trees that is common in mature climax communities. The second type of perturbation occurred at the 3500m location on Missionary Ridge where a severe loss in standing crop is shown for 1972; this loss can be attr buted to a high windstorm that caused severe windthrow on that high elevation site. Ovington (1962) stated that in mature climax forests, the biomass is fairly constant from year to year, as a result of an overall equilibrium between production and decomposition; this type of biomass pattern can be seen at the lower elevational plots at both locations. Kira et al. (1967) concluded that mortality rates in forests of cool climates fluctuate from year to year and that in certain years, several trees are lost in one year due to environmental catastrophes, such as storms. Thus, the biomass values of such forests will fluctuate over time and the equilibrium value of climax can only be recognized on a long-term basis. These subalpine forests can therefore be best described as a "disturbance climax"; the influences of snow manipulation on such a system are difficult to separate from the other environmental influences and could only be studied over a long time period.

Influences of snow on the spruce-fir association.

The direct influences of snow on the spruce-fir association can be organized into two categories; first, its effect on the length of the growing season, and second, the physical effects of snow on the trees themselves.

The snow melt pattern on the intensive study sites varied considerably between the years 1972 and 1973 (Figure 4). In 1972, the plots were free from snow almost a month earlier than the following year when snow persisted beyond the date of cambial activation as estimated by Blaue (1973). In general, snow remains much later in the season on the Wolf Creek Pass locations than on Missionary Ridge and, accepting these data, cambial initiation may often occur while snow is still on the ground. Blaue (op cit) found that the length of the growing season is set primarily by photoperiod, with variables such as temperature having a minor effect. From these data, it could be concluded that the length of the growing season is largely independent of the direct effects of persisting snow.

Direct physical influences of snow on individual trees is negligible on trees of the intermediate class or greater; however, saplings and seedlings can be adversely affected by extended periods of snow coverage which increase the probability of snow breakage, snow mold infection, or simply elimination of sunlight. These conditions were observed to increase definitely on the biomass plots in the heavy snow year of 1973, compared to the other years of the study. Considering the small stature and hence, small wood production, of trees of these size classes, the wood production of the stand as a whole is not significantly affected. Such events should be noted, however, because these smaller trees represent the future of these stands and any such damage could reduce the number of trees available for replacing those lost in the overstory.

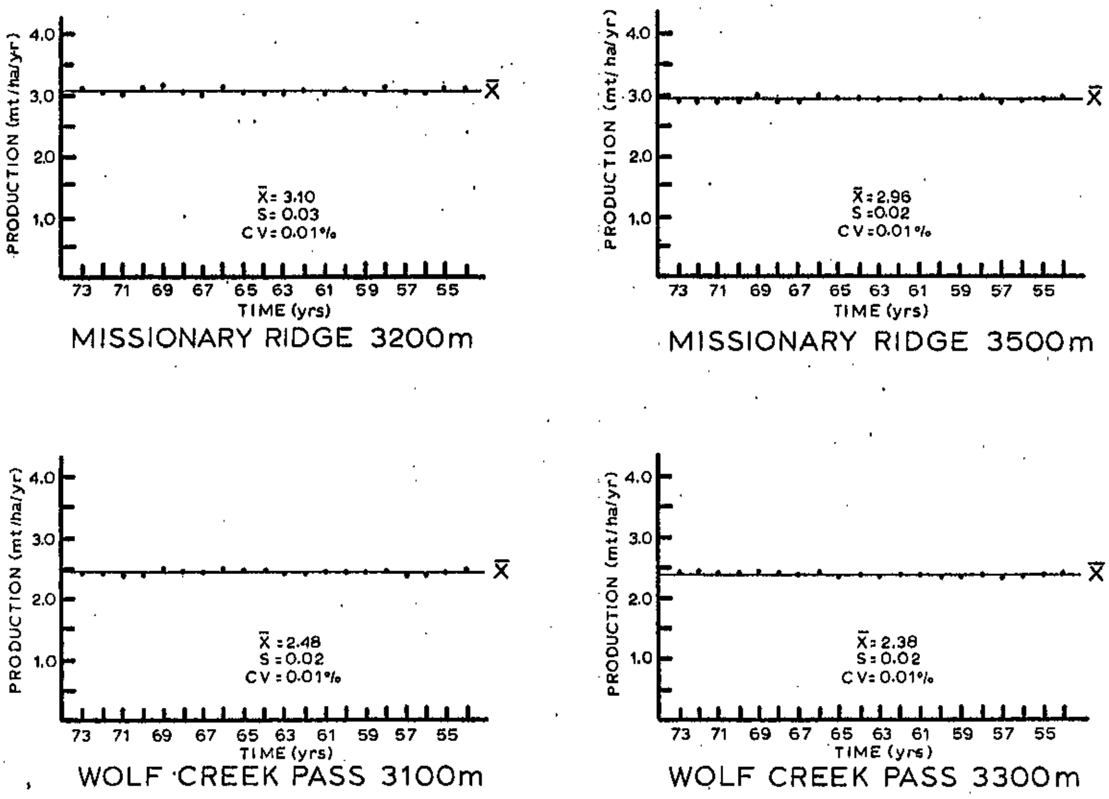

Figure 2. Stand bolewood production by sampling location

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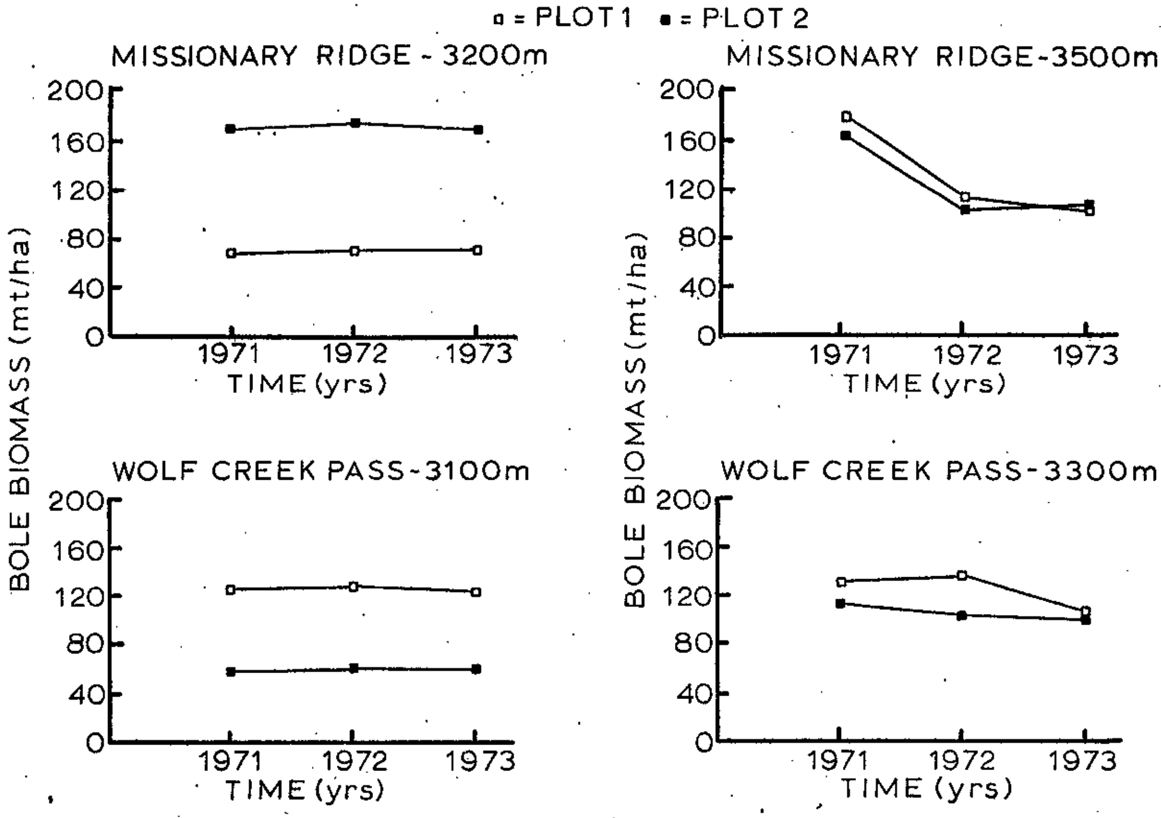

Figure 3. Biomass changes over time at the study locations.

gradual decrease in biomass occurred due to the periodic mortality of individual trees that is common in mature climax communities. The second type of perturbation occurred at the 3500m location on Missionary Ridge where a severe loss in standing crop is shown for 1972; this loss can be attributed to a high windstorm that caused severe windthrow on that high elevation site. Ovington (1962) stated that in mature climax forests, the biomass is fairly constant from year to year, as a result of an overall equilibrium between production and decomposition; this type of biomass pattern can be seen at the lower elevational plots at both locations. Kira et al. (1967) concluded that mortality rates in forests of cool climates fluctuate from year to year and that in certain years, several trees are lost in one year due to environmental catastrophes, such as storms. Thus, the biomass values of such forests will fluctuate over time and the equilibrium value of climax can only be recognized on a long-term basis. These subalpine forests can therefore be best described as a "disturbance climax"; the influences of snow manipulation on such a system are difficult to separate from the other environmental influences and could only be studied over a long time period.

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The direct influences of snow on the spruce-fir association can be organized into two categories; first, its effect on the length of the growing season, and second, the physical effects of snow on the trees themselves.

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Direct physical influences of snow on individual trees is negligible on trees of the intermediate class or greater; however, saplings and seedlings can be adversely affected by extended periods of snow coverage which increase the probability of snow breakage, snow mold infection, or simply elimination of sunlight. These conditions were observed to increase definitely on the biomass plots in the heavy snow year of 1973, compared to the other years of the study. Considering the small stature and hence, small wood production, of trees of these size classes, the wood production of the stand as a whole is not significantly affected. Such events should be noted, however, because these smaller trees represent the future of these stands and any such damage could reduce the number of trees available for replacing those lost in the overstory.

Indirect effects of snow on wood production are those influences on the forest microclimate including modification of the soil temperature and soil water regimes during the early part of the growing season. The influences of these factors on the physiology of trees during the growing season are being analyzed by the Tree Moisture Stress Project and are included in the report of the next section.

Regardless of influences of snow within a given growing season, the bolewood production of individual trees of the spruce-fir association has been shown to remain relatively constant over the past 20 years

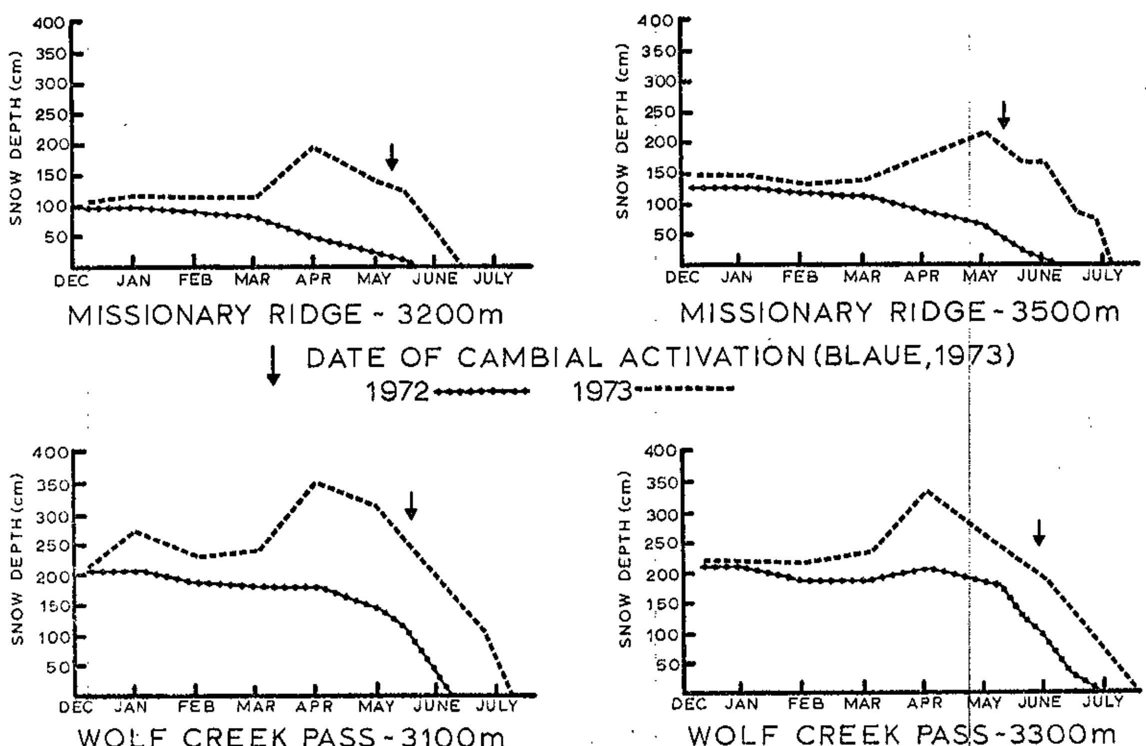

Figure 4 - Snow depth and duration at intensive sites, 1972-1973

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(Fig. 1). These data indicate that bolewood production on a yearly basis was not significantly influenced by varying environmental factors, including those influenced by changes in snow parameters. It has been suggested that cambial activation may begin with snow still on the ground. Sometimes, this snow persists for some time into the growing season (Fig. 4). If this persistent snow influences cambial cell division and expansion early in the growing season, this delay in growth may be compensated for by more rapid growth later in the season, resulting in a comparable amount of wood produced each year. In another study with Engelmann spruce Gary (1974) found that the growing season was long enough to overcome any inhibitive effect due to late-lying snow and that there was no significant difference in growth between snow-covered and snow-free plots. This type of "catch-up factor" has also been suggested for other subalpine plant species (Owen, 1973).

This constant annual wood production can probably be ascribed to the intrinsic genetic controls of the species themselves. These spruce and fir trees have genetically adapted over long periods of ecologic time to the environmental conditions of the subalpine and thus, the amount of wood produced each year appears to be fixed.

4.4.3. Conclusions and Recommendations

Individual trees of the Engelmann spruce-subalpine fir association were shown to exhibit relatively constant bolewood production on a yearly basis. This constant production is attributed to the genetic properties of the species themselves, rather than controlled by factors of the environment. Therefore, changes in snow parameters probably do not affect the wood production of individual spruce trees on a year to year basis.

Bolewood production of spruce-fir stands was also shown to remain constant over the 20 year study period. This trend is probably a function of genetic control also, because stand production is a reflection of the cumulative responses of the individual trees. Such constant production is also a result of the climax status of these forests; uneven-aged climax forests typically exhibit a constant production over time with minor fluctuations resulting from individual tree mortality.

Bole biomass values for these stands were shown to exhibit severe perturbations in standing crop values and these sudden losses in biomass were attributed to catastrophic events such as windthrow, insect outbreak, or fire. Therefore, these forests could be characterized as a "disturbance climax" in which the spruce and fir trees dominate the site and reproduce under their own shade, but show severe fluctuations in standing crop because of disturbance events. It is debatable as to whether changes in snowpack conditions could positively or negatively influence these disturbance events.

These conclusions must be conditional, however, due to the short time period of this study. Cumulative effects of snow manipulation could not be evidenced in a study of this duration and detrimental effects of direct snow on sapling and seedlings could affect the future status of these forests. Therefore, it is recommended that future studies be conducted on seedling establishment and early growth. Also, the cell deposition pattern within the growing season should be investigated to reveal possible delayed cambial activity in years of late snow melt.

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4.5 MOISTURE STRESS AS AN INDICATOR OF THE EFFECTS OF SNOW ON BIOMASS PRODUCTION OF FOREST TREES (Dr. C.P.P. Reid and A.K. Evans)

4.5.1. Specific Objectives

The overall objective of this investigation, in conjunction with the Tree Biomass and Tree Phenology projects, is to determine and evaluate the effects of snow quantity on the growth of Engelmann spruce (Picea engelmannii Parry) and quaking aspen (Populus tremuloides Michx.). Increases in snowpack should affect the moisture status of the tree which should, in turn, affect tree growth. The Moisture Stress Project is designed specifically to provide information concerning the effects of microclimate and snowpack changes on the water status of the tree. The three basic hypotheses being investigated, as stated in the Interim Progress Reports of 1971 and 1972 (Reid and Evans, 1971; Reid and Evans, 1973), are:

- Increases in snowpack will cause delayed snowmelt which will provide increased soil moisture later in the growing season and therefore increased biomass production through reduced moisture stress.

- Increases in snowpack will cause delayed snowmelt resulting in lower air and soil temperatures later into the spring causing decreased water uptake, increased water stress, and reduced growth.

- Changes in water stress will reflect changes in growth patterns and these changes can be efficiently monitored by the pressure chamber technique.

This project is attempting to answer specifically the following questions:

(1) How does moisture stress of spruce and aspen relate to varying snowpack?

(2) How is moisture stress related to all environmental variables?

(3) How can moisture stress related to spring snowpack be separated from that related to summer weather patterns?

In conjunction with Tree Biomass and Tree Phenology projects the following questions are being pursued:

(4) How is moisture stress in spruce and aspen related to periodic growth through the season and subsequent annual increment?

(5) Will a significant increase or reduction in growth of spruce and aspen occur with a one week delay in snowmelt?

4.5.2 Methods

Moisture stress was monitored by the pressure chamber technique on each of six study sites (4 spruce, 2 aspen) through the growing seasons of 1971 and 1972. Moisture stress was determined weekly in the early season and biweekly in the late season by sampling both the north and south sides of the crown of five trees on each site. In 1973, intensive study of one site during the snowmelt period was carried out rather than the continued monitoring of all sites. Site 2 (M3200-Spruce) was monitored every third day from May 15 through the end of snowmelt, and weekly through the remainder of the growing season.

A laboratory experiment was conducted in early 1974 to determine the effects of cold soil temperatures on root resistance to water flow in Engelmann spruce seedlings. The pressure chamber was immersed in a large water bath at three different temperatures (0, 7.5, and 15°C). Intact root systems with the tops removed were placed in water in the pressure chamber. Three bars pressure was applied and the rate of water movement through the roots and up the stem was measured by collecting the exudate. This procedure gave an excellent means of assessing root resistance to water flow at varying temperatures.

4.5.3. Results and Discussion

General Model Considerations

The growing season for trees in the subalpine forests under study can be divided into two parts in relation to moisture stress, the early or snowmelt period and the later or midsummer period. In answer to question (3) above, it can be stated simply that the sets of environmental factors most important in controlling water stress are different in the two periods. Also, the early period water stress is primarily controlled by factors relating to snow, while in the midsummer period, stress is primarily controlled by daily weather. Therefore, a water stress model for the subalpine forest must consist of two submodels, one for each of the two periods. It is important to note that the emphasis in this study has been placed on Engelmann spruce. Early season data for aspen are difficult to obtain because our technique is based on use of leaf samples. A limited number of early season twig samples have been taken from aspen, but the emerging foliage and branches are rapidly depleted. Because it will be difficult to establish conclusive relationships for the early season part of the aspen model, our emphasis will continue to be on spruce. The two submodels for spruce will now be considered separately beginning with the midsummer season.

Midsummer Water Stress

Extensive statistical analysis of the 1972 season data on Site 1 (M3500-Spruce) has resulted in a simple model and significant insight into the environmental parameters controlling water stress in the midsummer season (Evans, 1973). Other sites, including aspen, show similar relationships although the Missionary Ridge spruce and aspen sites appear to be more similar to each other than either is to the Wolf Creek spruce sites.

The significance of a low temperature effect, as introduced in the 1972 Interim Progress Report (Reid and Evans, 1973), became apparent. Air or soil temperatures which approached freezing caused a reversal in the normal pattern of decreasing water stress with decreasing temperature (evaporative demand). Because this reversal was rather abrupt, it was possible to remove these data from further midsummer analysis. The low temperature effect data are a combination of two additional data populations. Some of the high stress data may be attributed to reduced water uptake from cold soils and should therefore be included in the data population of early season water stress. The remainder is due to an error in the pressure chamber technique when working at temperatures near freezing, which has been reported by Evans and Reid (1974). Midsummer water stress and

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a variety of the measured environmental data were submitted to factor analysis which delineated two major patterns of variability, which will be referred to as Factor 1 and Factor 2. Factor 1 represented all those variables which varied diurnally with solar radiation input and were associated with atmospheric evaporative demand and energy budget of the tree crown. Factor 2 represented the deep soil regime which varies on a seasonal basis and included soil water and deep soil temperature. Water stress was primarily associated with Factor 1, but was affected to some degree by Factor 2. The following conceptual linear model is proposed:

Water Stress = $B_0 + B_1$ (atmospheric factor) and B_2 (deep soil factor) + E_{ij}.

Correlation analysis showed high individual correlations between water stress and all Factor 1 variables, with individual R^2 values up to .68, but extremely low correlations for Factor 2 variables. The four best individual variables were ranked as follows: surface soil temperature > air temperature > vapor pressure deficit > solar radiation. This ranking may have indicated greater dependence on sensible energy and leaf temperature than on evaporative demand. The two, two-variable combinations with highest correlations included both a Factor 1 and a Factor 2 variable. It is important to note that Factor 2 greatly increased in importance in the presence of Factor 1. This substantiated the proposed model.

Prediction models were then constructed by stepwise multiple regression based on the conceptual model. Significant models with R^2 values up to .87 were produced with up to nine environmental variables. A practical four-variable model with two variables representing each factor was finally developed with an $R^2 = .81$. The four variables were surface soil temperature, and -15 cm soil water content. This model is ecologically sound because water loss and water absorption are both represented, water stress being the sum of the difference between the two processes. The model can be used for predicting water stress through the midsummer season from basic weather data, as long as it is not extrapolated beyond the range of the original data.

Snowmelt Period Water Stress

Figure 1 demonstrates the maximum and minimum daily water stress on Site 2 (M3200-Spruce) for the 1973 growing season. Water stress in negative bars is represented on the ordinate and date on the abscissa. Percent snow cover and snow depth in decimeters are expressed as shaded areas at the top of the figure. The period from July 19 through September 13 will not be discussed as it represents the midsummer season previously covered. The period from May 15 through July 11 represents the snowmelt period.

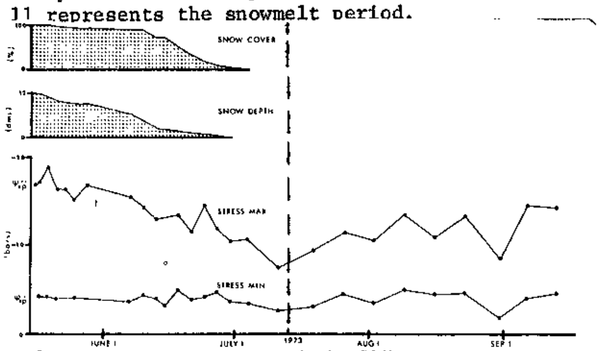

Figure 1. Seasonal tree moisture stress, maximum and minimum as related to snow depth and cover.

By examination of the figure, the relationship to snow becomes apparent. Minimum (predawn) water stress remained fairly constant across the snowmelt period which is probably due to a fairly constant high level of soil water. This demonstrates that the trees were always able to recover satisfactorily from midday water stress during the period. The most significant information of Figure 1 is the maximum daily water stress. It is apparent from the figure that maximum daily water stress decreased almost 50% over the snowmelt period in a fairly linear manner. It is also important to note that this decrease is highly correlated with the decrease in snow cover ($R^2 = .62$) and snow depth ($R^2 = .74$). It is probable that this phenomenon is an expression of the second hypothesis presented above, i.e., cold soil temperatures increase the root resistance to water flow which causes higher water stress levels. As the snow melts and more soil becomes exposed to radiation, the average soil temperature across the site increases, allowing root resistance to decrease, water uptake rate to increase, and midday water stress to decrease.

As previously stated, water stress is an expression of the difference between water loss through transpiration and water uptake through root absorption. During the snow melt period, transpiration should be increasing due to the increasing evaporative demand of the atmosphere (not shown in Figure 1). Since water stress decreases, it must be assumed that uptake is not constant, but is actually increasing more rapidly than transpiration. As any change in soil water would cause a water stress change in the opposite direction, it might be concluded that the pattern exhibited during snowmelt is possibly due to some intrinsic factor, however, it is more likely a result of increasing soil temperatures as more of the soil surface becomes free of snow.

The root resistance laboratory study, using Engelmann spruce seed under simulated snowmelt conditions was initiated to determine the validity of this assumption. Preliminary examination of the results indicates that the mean rate of water movement into and through the root systems was approximately three times greater with water at 7.5°C as with water at 0.5°C. The mean rate at 15°C was slightly higher than the 7.5° rate, but the variance was exceptionally high. These results substantiate the conclusion that the high water stress levels under snowpack are caused by soil temperatures near freezing during periods of high transpirational demand.

The implications of these spring water stress patterns to tree growth are very important. Since the trees are able to recover from water stress at night, no immediate severe effect on cell division and cell enlargement would be expected due to delayed snowmelt. The primary effect would likely be a significant reduction in photosynthesis. Many investigators have shown that photosynthesis is reduced to zero at water stress levels in the range of -15 to -25 bars. This could have a significant effect on growth later in the current season and on the subsequent season's growth. The timing of the major phenologic events will be very important in determining if this high stress period will have an important effect on growth. If cambial initiation and bud burst are related to environmental temperatures and/or water stress, they will be delayed due to increased snow, although trees may be able to adjust their growing season. However, this does not appear to be the case. If these events are controlled by photoperiod and occur at approximately the same time every year, significant problems could arise if the high stress period was extended late enough into the summer period by increased snowpack. These phenologic events currently occur after the period of high water stress. If they occurred during the period of high stress, a significant growth reduction might occur. Further coordination with the Tree Biomass and Tree Phenology projects will be necessary to examine these implications.

4.5.4. Proposed Future Research

Little additional field data will be collected during the upcoming year except to fill some gaps of missing information. The majority of effort will be concentrated on computer analysis of data for all six plots and analysis and interpretation of the root resistance study. When the tree core information becomes available, it will be correlated with moisture stress.

4.5.5 Summary

The growing season of Engelmann spruce can be divided into two parts concerning water stress, the snowmelt period and the midsummer period. Water stress during the midsummer period is primarily determined by daily weather and expressed as two factors, one atmospheric and the other deep soil. A regression model was developed to predict water stress during this period from the following variables ($R^2 = .81$): surface soil temperature, air temperature, -25 soil temperature, and -15 cm soil water.

The snowmelt period is characterized by high levels of midday water stress which become less severe as snowmelt proceeds and more soil is bared of snow. The 50% reduction in midday stress over this period is probably due to lowered root resistance to water flow caused by increasing soil temperatures. This theory is substantiated by preliminary analysis of root resistance studies which demonstrated a rate of water movement through roots at 7.5°C about 3X greater than at 0.5°C.

The major effect of these high stress levels during snowmelt would be in photosynthesis reduction rather than cell division since trees were able to rehydrate at night. As long as this high stress period occurs before the beginning of major phenological activity, little change in growth would be expected. If delayed snowmelt from snowpack augmentations resulted in the high stress period being extended later into the year, occurrence of phenological events during this stress period could result in a significant alteration of growth pattern.

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4.6 ELK (Dr. Harold Steinhoff, James Sweeney, John Sweeney)

4.6.1 Job 1. Winter Distribution (James M. Sweeney)

- Objective

To answer the following questions:

1) What elevations, aspects, and vegetative types are occupied by elk through the winter as related to the varying snowpack?

2) What is the critical depth of snow for elk on Missionary Ridge?

- Hypotheses

1) The upper elevational limit of elk in winter is dependent upon a critical snow depth, that depth most likely being between 65 and 75 cm.

2) The critical snow depth for elk varies significantly with abundance of available food, snow hardness, and degree of slope.

3) Elk tend to occur on a south aspect where food is available.

- Findings

Elevation-

Down slope migration patterns of elk in the winter vary with severity of the winter. "Severity" would include total precipitation, frequency of storms, and rate of baring of the winter range. The elevation at which elk occur during winter is related to a snow line of a certain critical depth. The location of this critical snow line is in turn related to snowfall patterns during the winter.

Depth of the snowpack at the Top Park fescue study site has proven indicative of winter conditions (Fig. 1). In the first winter of study (1970-71), maximum snow depth (11 decimeters) was not reached until Feb. 27, and decreased from that date on. This could be broadly classified as a mild winter. In the last two winters (1971-72 and 1972-73) a greater depth (14 dm and 16 dm respectively) was reached at an earlier date (Jan. 8 and 6 respectively). The snow was almost this deep already in early December.

The winter of 1971-72 reached a peak on January 8 and decreased from that date on. It could be classed as severe at first, but mild at the end. The last winter, however, should be described as severe throughout. Instead of showing a decrease in snow after January, the snow depth continued to increase until March 31 to a maximum depth of approximately 24 dm.

This past winter's flights (15.9 hrs. flight time) over the study area resulted in 465 elk sightings. These sightings indicate that elk began their down slope migration at a time similar to the previous winter of 1971-72 (Fig. 2). By January, however, the

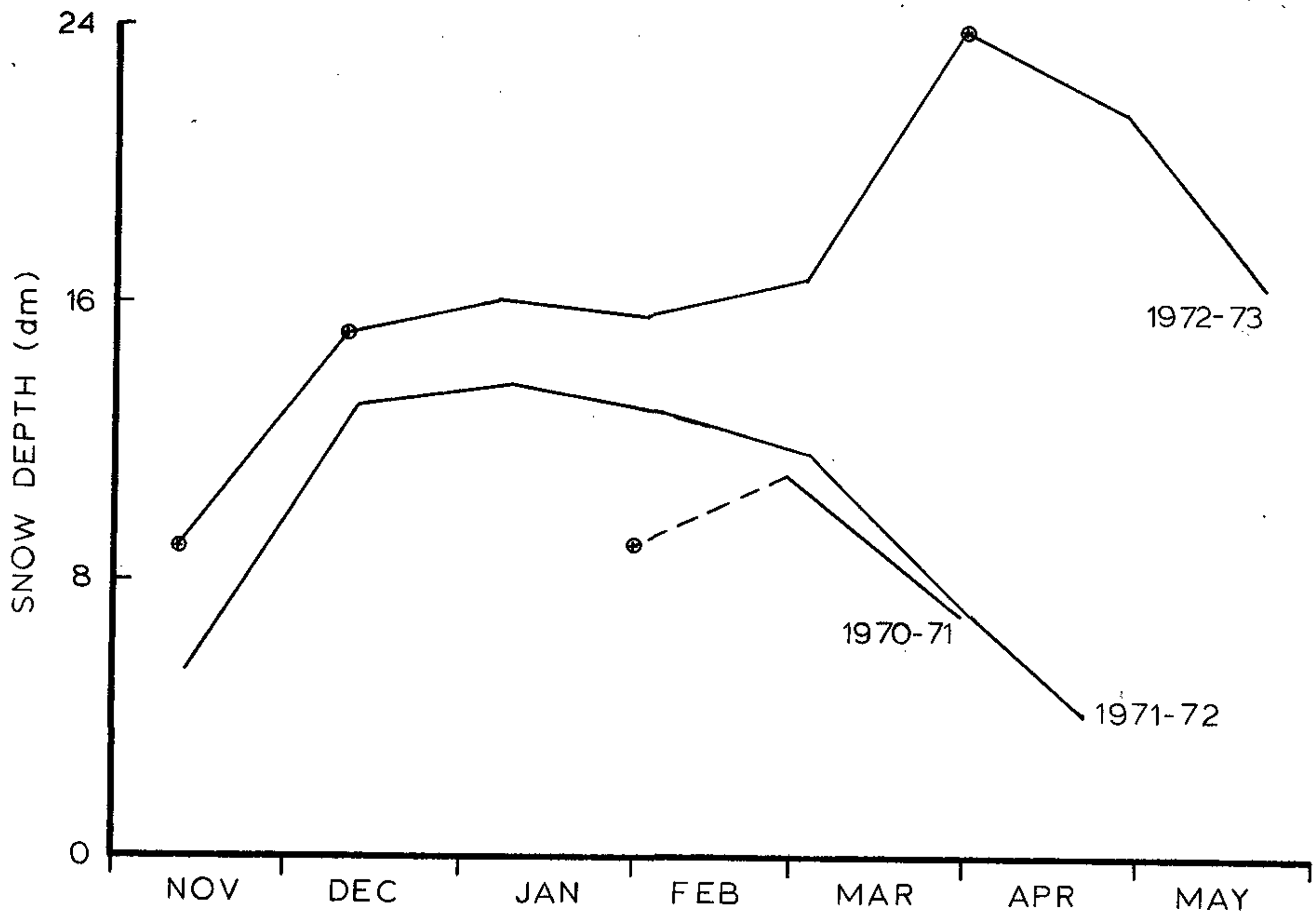

Figure 1. Snow depth at The Top Park fescue study site, Missionary Ridge.

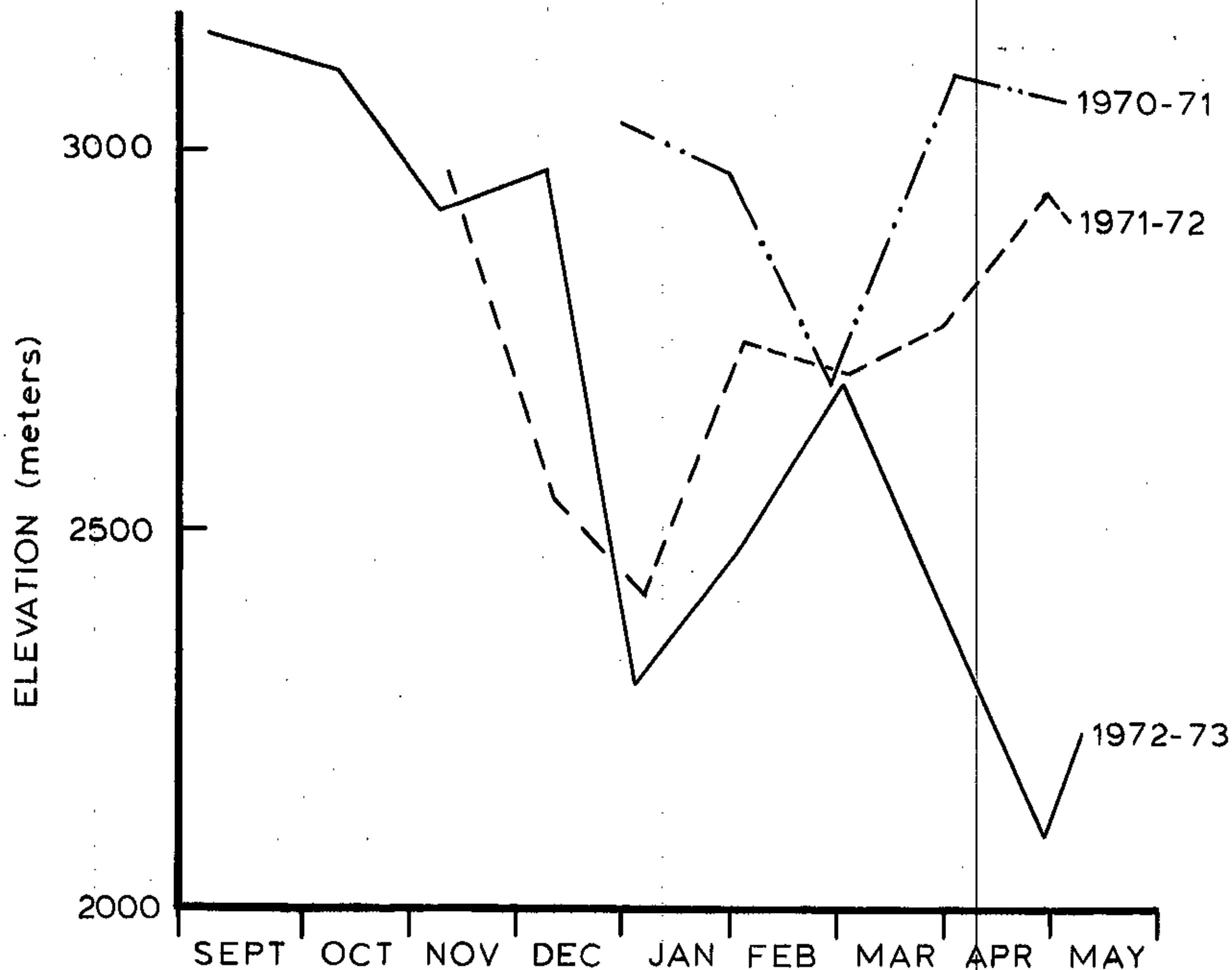

Figure 2. Elevation of wintering elk on Missionary Ridge.

elk had proceeded to a lower elevation (2300 meters) than either of the previous two winters. This reflects the severity of the 1972-73 winter. As in previous winters, elk again moved up and utilized the open, south facing, oak brush slopes (approximately 2675 meters elevation) during February and March. This past winter, however, in contrast to the earlier two winters, heavy storms continued through April. As a result, rather than continuing a slow up-slope migration as seen in 1970-71 and 1971-72 elk migrated down to the valley floor.

Habitat and Aspect -

Tables 1 and 2 show that habitats and aspects occupied in 1972-73 were very similar to those reported for previous years.

Table 1. Percentage of elk sighted in each habitat type on Missionary Ridge, winter 1972-73.

Date	Total No.	Mean Elev. (meters)	Habitat Fescue	Oak	Aspen	Conifer
9-10-72	63	3125	54	27	3	16
10-10-72	112	3100	65	8	7	20
11-10-72	43	2900	12	67	21	
12-10-72	35	2950		43	51	6
1- 5-73	74	2300		51	4	45
2- 2-73	28	2475	4	39	7	50
3- 2-73	19	2675		84		16
3-30-73	35	2400		80		20
4-27-73	56	2100	54	21		25
		Total %	31	38	9	22

Table 2. Percentage of elk sighted on each aspect of Missionary Ridge, winter 1972-73.

Date	Total No.	Mean Elev. (meters)	Aspect 1/ East	South	West
9-10-72	63	3125		75	25
10-10-72	112	3100	21	30	49
11-10-72	43	2900		77	23
12-10-72	35	2950		86	14
1- 5-73	74	2300	27	27	58
2- 2-73	28	2475		39	61
3- 2-73	19	2675		42	58
3-30-73	35	2400		54	46
4-27-73 2/	56	2100			46
		Total %	5	42	43

1/ None were seen on north aspects.
2/ Readings for this date do not include elk sighted (54%) in the valley, and therefore not considered on any given aspect.

In all, there seems to be an indication that fescue and/or oak habitats on south aspects are used to a higher degree than other habitat types or aspects during the winter period. Snow on south aspects quite often melts off between storms, except in years of heavy accumulation. As a result, they provide a more favorable winter habitat with the decreased snow cover, increased food availability, and increased temperatures.

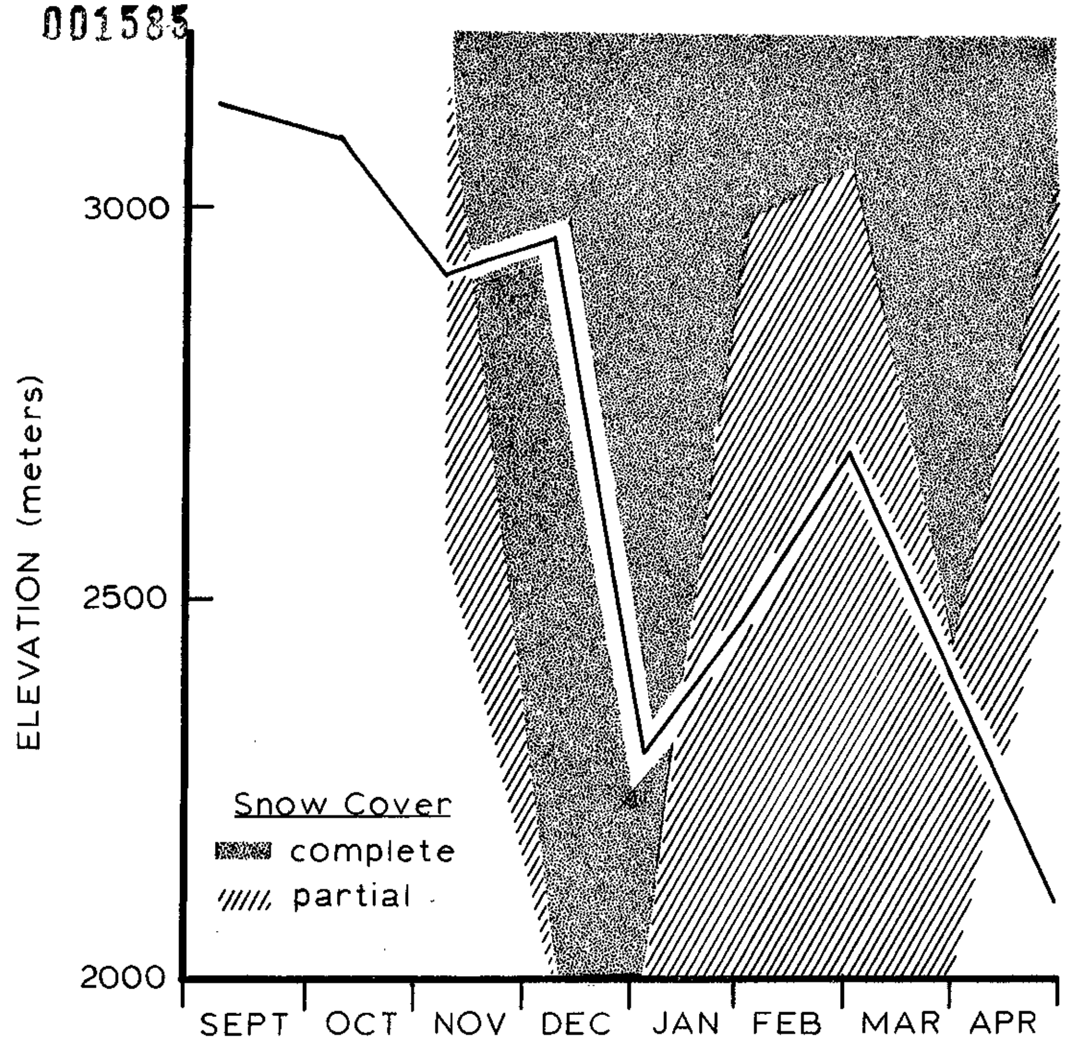

Figure 3. Elevation of wintering elk as related to snow cover, 1972-73.

Critical Snow Depth -

In 1970-71, all winter sightings of elk were in areas with less than 35 cm of penetrable snow cover. In one case, elk were seen in an area with 55 cm of total snow cover; however, a hard layer (75 kg ram hardness) 25 cm below the snow surface limited hoof penetration to 15-20 cm. During the second winter season (1971-72) elk were found in areas of sparse to no snow cover, with one exception. In this instance, elk were located with a snow cover averaging 50 cm. deep. Twenty-one of 25 ram profiles taken in this area showed a ram hardness of 1 kg or less throughout the snowpack, which indicates light powder snow remaining four profiles registered ram hardnesses between 1 and 5 kg. Hoof penetration in this area averaged between 36 cm and 32 cm. This past winter (1972-73) elk were again located in areas of sparse to no snow cover, when this type of habitat was available. However, during December and January Missionary Ridge was blanketed by a complete snow cover down to and including the valley (Fig. 3). During this period elk were found in snow depths of 50 to 90 cm. One area of elk usage which was not reachable by investigating teams was estimated from snow stake readings to have as much as 110 cm of snow. In three instances, hard layers (5 kg hardness and 6 cm thickness) were delineated at the ground surface, but in general the snowpack was again light (1 kg). Hoof penetration in these areas ranged from 36 cm to 65 cm and averaged 51 cm. In areas with 70 cm or more snow, there was evidence of impaired mobility; but it is not known whether or not this was deleterious.

These snow depth readings indicate that a depth of 35 - 40 cm of penetrable snow will cause elk on Missionary Ridge to move to more winter range with a lesser depth. This then could be considered the "response depth" of snow for elk in this area. (Previous reports have labeled this the "critical depth" of snow for elk. However, it now seems more appropriate to save the term "critical depth" for that depth of snow which may prohibit the use of an area by elk.) Snow depths of 40 to 60 cm apparently do not pose undue stress, and are readily traversed for food and shelter, when more exposed areas are not available. Areas with 70 cm or more of penetrable snow probably represent an added winter stress, and are usually avoided. Seventy centimeters of penetrable snow then represents the critical depth of snow for elk on Missionary Ridge.

4.6.2 Job 2. Calving (James M. Sweeney)

- Objective

Our objective is to answer the following questions:

1) Is the spring upward movement by elk on Missionary Ridge related to the receding snow line?

2) How is elk calving related to varying snowpack

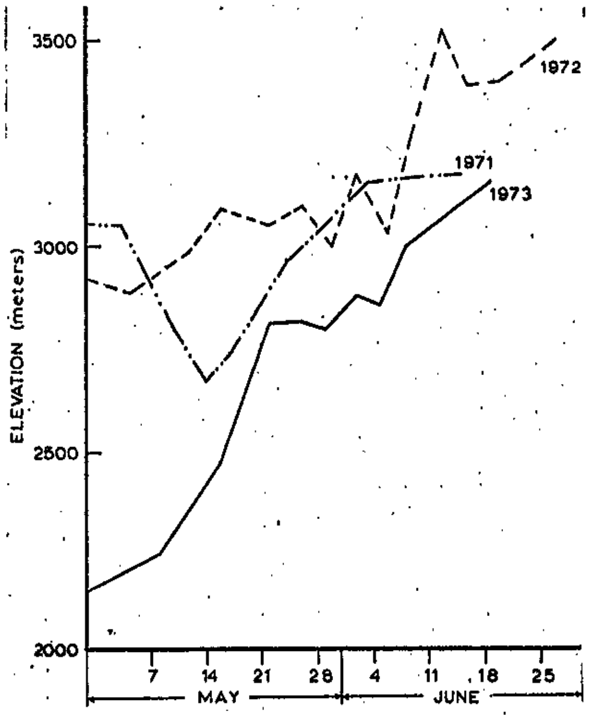

Figure 4. Spring elevations of elk on Missionary Ridge.

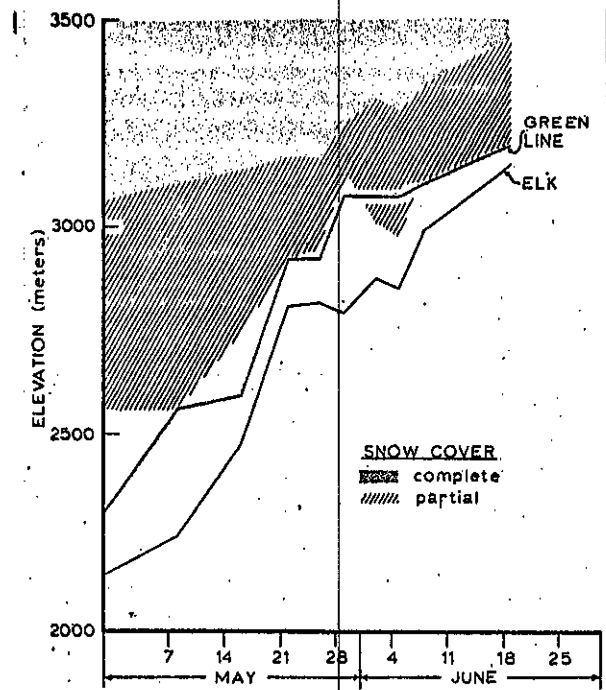

Figure 5. Spring elevation of elk as related to snow cover and green line, 1973.

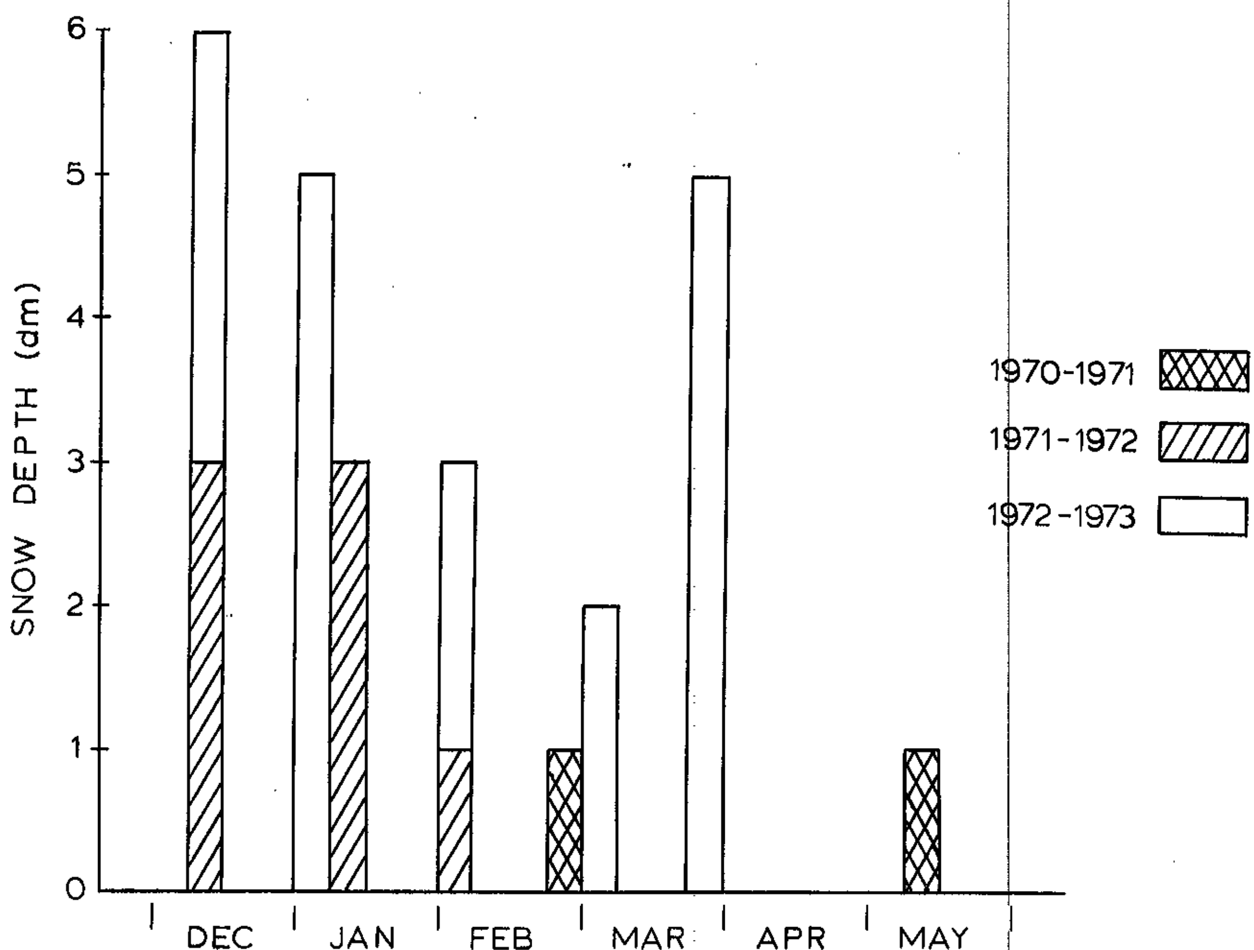

Figure 6. Monthly snow depths at Oak Study Site, Missionary Ridge.

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on Missionary Ridge?

- Hypotheses

1) Spring movement of elk back into the high summering areas is directly correlated to the receding snow line.

2) Elk calving areas are favorable sites below the zone of partial snow cover (ZPSC), and there is no shortage of calving areas below the ZPSC each year on Missionary Ridge.

- Findings

Spring Movements -

Through the spring of 1973, 1080 elk sightings (25 calves) were recorded during 21.75 hrs. of flight time. These observations, along with the 1129 sightings from the first two springs, indicate that spring movement of elk back into the high summering areas is associated more strongly with the greening up of the open fescue parks, than directly with a receding snow line.

The first spring of study (1971) followed a mild winter. As a result, at the beginning of the spring elk were found at relatively high elevations (3050 meters). With the onset of new growth at lower elevations, the elk were observed to migrate down slope into the newly green meadows (Fig. 4). Movement back into the high country generally followed the initiation of growth in the higher meadows. In 1973, elk were again high (2900 meters) in early spring. However, they were not observed to move down slope as they did in 1971. The spring (1972) was unseasonably warm, and green up of the higher meadows had occurred at an earlier date, negating the need for elk to migrate to obtain new growth. The receding snow line for both of these springs was well above the elevation of elk and new growth, and was not considered a direct influence on movement patterns.

The spring of 1973 was quite different from the previous two springs. Following a severe winter, the elk were concentrated in the valley (2100 meters). Movement back into the high country was again associated with greening up of the higher meadows even though the initiation of growth was later than previous springs (Fig. 5). Because of the heavy accumulation of snow during the winter and the late spring, the advancing green line was closely associated with the lower limit of the receding zone of partial snow cover (ZPSC). In this instance, the receding ZPSC may have limited to some degree the movement of elk, particularly those animals which exhibit the tendency to migrate higher and earlier than the average herd. However, the majority of animals were located an average of 150 meters below the ZPSC and green line throughout the spring.

Calving -

Data collected to date indicate that calving on Missionary Ridge follows the general pattern reported in the literature. Compilation of aerial and ground observations indicates that calving on the study area occurs between mid-May and mid-June at an elevation of 2900 to 3200 meters.

For the three calving seasons studied, there appeared to be ample habitat available for calving below the snow line. The prime calving areas were open each spring. The receding snow line for 1971 and 1972 was well above the calving areas, but in 1973 the lower portion of the ZPSC was still within the upper calving areas. The lower border of the ZPSC, however, is characterized by having snow cover only in protected areas on north facing slopes. As such, the receding snowpack probably presented little if any physical limitation to the location of calving.

These data indicate that snow probably does not limit the actual location of calving on Missionary Ridge. Perhaps of greater importance is the possible deleterious influence of late spring snow storms on calving success, through the creation of a cold, wet environment for the newborn calf.

4.6.3 Job 3. Oak (John R. Sweeney)

- Objective

To answer the following questions:

1) What is the present structure of typical oak stands at the upper elevational limits of oak?

2) How are significant phenologic events, which are related to growth and browse production of oak, related to varying snowpacks?

3) How do varying snowpacks affect annual productivity of oak on the target area?

4) How will varying snowpack affect the survival of oak on Missionary Ridge?

- Hypotheses

1) Annual productivity of oak will be increased in the first few years of consistently greater annual snowfall.

2) Oak survival will be decreased in the long term by increased snow because of superior competition from aspen or ponderosa pine.

- Findings

Community Structure-

The phytosociology of oak stands at their upper limits was described in the 1973 Interim Progress Report.

Phenology-

The amount of winter precipitation does not appear to affect initiation of growth in oak. Even though the snowfall of 1972-73 (61.34 cm of water) was more than twice that of 70-71 (24.64 cm of water), soil moistures at -50 cm and -90 cm depth were near a water potential of -2 bars after snow melt each year. The seasonal pattern of snowfall, however, probably does affect growth initiation in that the frequency and amounts of snow storms influence the date of final snow melt. In 1970-71 only one decimeter of snow was detected on the plots in late February (Fig. 6) but three late season storms deposited a total of 1 dm on the plots in mid-May and final snow melt did not occur until May 13. The winter of 1972-73 was a heavy snow year and at least 2 dm of snow were recorded on the plots each month. Five dm were recorded in late March. As a result of the large snowpack final melt did not occur until May 5. Seventy-five percent bud burst in the oak was recorded on June 9 for both 1971 and 1973 (Table 3). The only snowfall in 1971-72 came in the early part of the season and the plots were clear of snow by as early as March . Initiation of growth was recorded on May 28, 12 days earlier than the other two years.

The date of final snow melt influences the timing of growth initiation in oak by the effect of melt water on soil temperatures which is probably one of the more important factors affecting growth initiation. Data for the springs of 1972 and 1973 indicate that soil temperatures at -50 cm and -90 cm must be at or above 5 C for two to three weeks prior to the onset of growth (Fig. 7). The initiation of growth in 1972 did not occur earlier in that season possibly due to insufficient day length. Temperature sums, or the number of degree-days above 0 C also can influence the initiation of growth by its affect on snow melt, warming of the soil, and on bud temperatures. Monthly temperature sums recorded at the Durango Station were higher in 1972 than in 1971 and 1973, and for the last two years temperature sums of at least 343 degree-days were recorded at the study site prior to initiation of growth. This sum was reached about 25 days earlier in 1972 than in 1973.

Browse Production-

The amount of browse produced in a given year may be affected by the length of the growing season and by the rate of growth during that season. The length of the growing season, however, appears to be stable in oak brush. Even though the date of growth initiation may have been influenced by snow melt and spring temperatures, the length of the growing season for the last three years has remained relatively constant (Table 3).

Table 3. Growing season of Gambel oak at its upper elevational limits on Missionary Ridge.

	Final Snow Melt	Growth Initiation	End of Growth	Growing Season (days)
1971	5-13	6-9	7-3	24
1972	3-4	5-28	6-24	27
1973	5-5	6-9	7-3	24

Temperature sums during the growing seasons for the last three years are not significantly different, but there has been about a two-fold increase in the amount of precipitation each year with 1.96 cm, 4.32 cm, and 8.20 cm of water being recorded during the 1971, 1972 and 1973 seasons respectively. This increase in moisture, however, did not appear to enhance the grow growth of oak because the amount of browse produced for the three years is not significantly (95% level) different (Table 4). The lack of response in growth to increased precipitation is probably due to the fact that Gambel oak has low moisture requirements and therefore is most often found on soils with low soil water retention characteristics. Any additional water simply drains through the soil. This is the case on the study site. The almost two-fold increase in precipitation in 1973 over 1972 did not increase soil moistures. The water potential of the soil at -50 cm and -90 cm depth was the same for both years throughout each season (between 0 and -5 bars) and was not considered to be limiting to growth of oak (Fig. 8).

Successional Status-

Gambel oak has low moisture requirements and therefore, is found on soils with low soil water retention characteristics. In areas where it is found on soils of higher soil water availability, oak brush will most often be replaced by the more competitive species of aspen or ponderosa pine. Data for determining the successional status of oak brush on Missionary Ridge has been collected, but the analysis is not complete enough to make any conclusions at this time.

4.6.4 Summary

Winter Distribution-

Total precipitation, frequency of storms, cloud cover, and temperature all influence the frequency and rate of baring of the winter range. As a result, down slope migration patterns of elk in the winter vary with severity of the winter. The elevation at which elk occur during winter is related to a snow line of a certain critical depth. A depth of 35 - 40 cm of penetrable snow will cause elk to move to more exposed winter range if available. Areas with 70 cm or more of penetrable snow cover probably represent added winter stress and are usually avoided. Fescue and/or oak habitats on south aspects are used to a higher degree than other habitat types or aspects during the winter period.

Calving-

Spring movements of elk back into the high summering areas are associated more strongly with the greening up of the open fescue parks than directly with a receding snow line. Snow probably does not limit the actual location of calving on Missionary Ridge. For the three calving seasons studied, there appeared to be ample habitat available for calving below the snow line, with the prime calving areas open each spring.

Oak-

The timing of final snow melt may delay the onset of growth in oak by as much as two weeks through the cooling effect of melt water on soil temperatures. A delay in growth initiation, however, does not decrease the length of the growing season which appears relatively constant. The production of browse by oak is not enhanced by increased precipitation because of the low water holding characteristics of the soils on which it is commonly found. As a result, the production of browse has not been significantly different for the three years of study. In areas where an increase in moisture results in an increase in soil water availability, oak may be replaced by the more competitive species such as aspen or ponderosa pine and thereby decrease the overall production of oak browse.

Table 4. Production of Gambel oak browse for the 1971, 1972 and 1973 growing seasons.

Production of Biomass (gms/m³)

	Year 1	Year 2	Year 3
Twigs:			
Stand 1	2.4	6.4	4.8
Stand 2	6.2	6.7	11.1
Leaves:			
Stand 1	24.8	43.0	21.2
Stand 2	40.9	65.5	68.2

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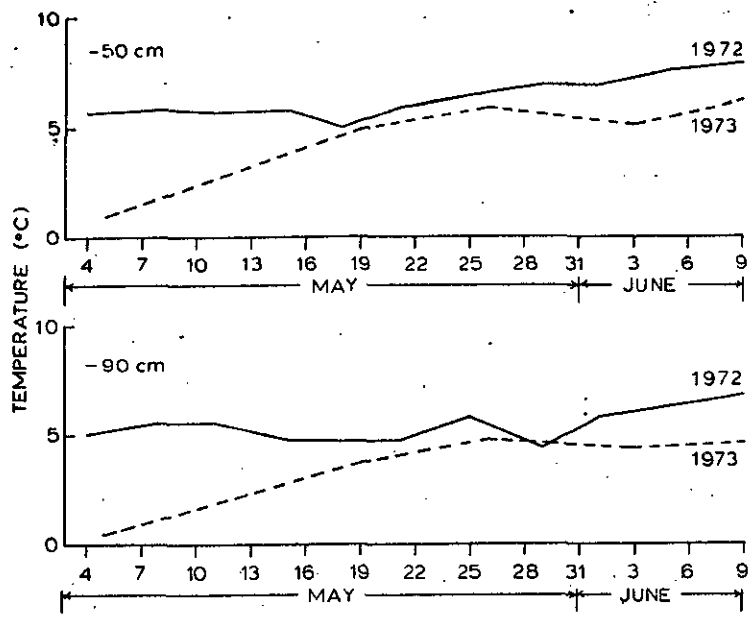

Figure 7. Soil Temperatures in the Zone of Root Growth At The Oak Study Site, Missionary Ridge.

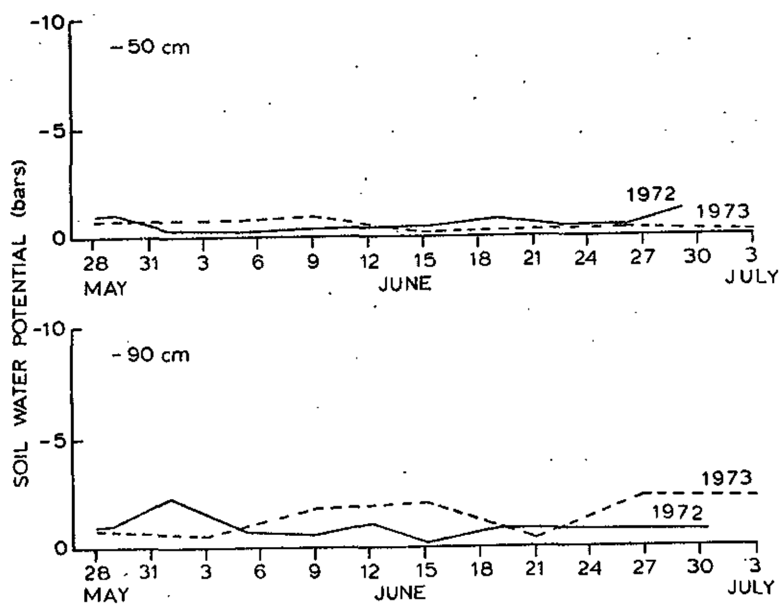

Figure 8. Soil Water Potentials In The Root Growth At The Oak Study Site, Missionary Ridge.

4.7 SMALL MAMMALS (Drs. Albert Spencer & Harold Steinhoff, Roger Sleeper)

4.7.1 Introduction

Small mammals of the forest are seldom seen by the casual visitor so their importance in forest ecosystems is easily overlooked. Their biomass often exceeds that of the larger more obvious mammals. Add to this the faster energy turnover rate characteristic of smaller animals and the consumption of plants by small mammals may greatly exceed consumption by larger ones. The result is competition with larger game and domestic mammals of direct importance to man. Also, small mammals girdle tree seedlings and eat tree seeds, thus interfering with reforestation. This is particularly a problem in the San Juans where spruce must be clear-cut to reduce windthrow and resultant natural regeneration is poor. Forest officers routinely check small mammal populations before reseeding cut-over areas, and spend extra effort on control if populations above about 6 per hundred trap nights.

Thus effects of varying snowfall on small mammal populations is of interest to resource managers of the San Juans regardless of the question of cloud seeding. If increased snow hurts small mammal populations, Project Skywater is of economic aid to the timber industry. Of course, the inverse also is true.

The objective of the small mammal project is to investigate effects of varying snowfall on aspects of the population dynamics which relate to size of small mammal populations. These aspects may show responses which demonstrate not only changes in small mammal populations, but the more basic reasons for those changes. Small mammal populations fluctuate considerably, but there are environmental reasons for these variations. If snow is related (or is not related) to the fluctuations, we expect to find this out. The six Jobs in this project are aimed at sensitive and investigable points of small mammal population dynamics.

4.7.2. Job 1. Litter Size and Survival (Roger Sleeper)

- Objective

To relate snowfall to the timing and survival of litters of small mammals.

- Procedures

Weekly examination of the 196 nest boxes provided information on litter survival. Young were marked with ear tags when about 2 weeks old. Nursing young were aged to the nearest week. Live trapping with Sherman live traps provided information on winter survival.

- Findings

The size of the deer mouse (*Peromyscus maniculatus*) population was very small in the summer of 1973, and thus there were very few observations of deer mice in the nest boxes on the study area. There was only one litter of young found in a nest box during 1973, so it was not possible to compare litter survival for the 3 years. Discussion of litter survival for 1971 and 1972 appears in the previous annual report (Teller, Ives, and Steinhoff, 1973).

Over-winter survival was very low during the winter of 1972-73. Only one deer mouse was captured during the first live-trapping period in June, 1973, and this animal was not previously marked. None of the 108 deer mice marked in the summer of 1972 were recaptured in 1973. The mortality during the winter of 1972-73 was so high, there was a very small probability of any deer mouse surviving. In 1972, seven deer mice recaptured from those marked in 1971 were all born prior to mid-July, 1971. This indicated that there was either preferential survival for older animals or that younger animals had a greater tendency to disperse from the area. Due to the high mortality in the winter of 1972-73, no more information was obtained in 1973 to determine which of these two mechanisms might be operating.

There were some data available to compare the timing of litter production for the 3 years. These data consist of estimates of the birth dates of litters, and dates when females were found pregnant or lactating. The information on lactation and pregnancies is not as good as the data on parturition dates, because some subjectivity is involved during early pregnancies and late in lactation periods. This information was used to compare the breeding seasons, because data on birth dates of litters was not obtained in 1973.

The data on birth dates of litters (Table 1) indicates breeding commenced about the same time in 1971 and 1972, but breeding ended earlier in 1972. The majority of litters were produced in July both years. No information was available for 1973.

Table 1. Number of litters born each week.

	June				July				August				Sept.
Year (Week)	1	2	3	4	1	2	3	4	1	2	3	4	1
1971		2	1	2	2	3	1	3	2	3	2		
1972		2	2	2	2	6	2	1		2			
1973					1								

Observations of pregnant females are presented in Table 2. The number of pregnant females is related to population size, so the relative distribution of pregnancies over the summer was used to compare trends in timing of breeding. Observations were not begun until July in 1971. Pregnant deer mice were found early in June, but not late in the summer during 1972. In 1973, breeding apparently began later and ended later, because the pregnancies are distributed more toward the end of the summer. Breeding in 1971 also continued longer than in 1972, but not as long as in 1973.

Table 2. Percent of females observed pregnant each week of each year.

	June				July				August				Sept.
Year (Week)	1	2	3	4	1	2	3	4	1	2	3	4	1
1971	-	-	-	-	8		8	17		17	25	8	17
1972					2	28	19	7	19	19			6
1973					10	10			10	30			40

The deer mouse breeding season began earlier in 1972 than in 1973. The delay in 1973 was probably due to the prolonged snowpack. Hinckley (1966) found that extracts from germinating seeds enhanced testes development in montane voles (*Microtus montanus*). The snowpack may have restricted deer mouse breeding because of the delay in initiation of plant growth. The breeding season was shifted more towards the end of the summer in 1973 than in 1971 or 1972. The 1972 breeding season ended the earliest of the 3 years, and this was when the highest population densities occurred. Krebs et al. (1973) found that at high population densities, meadow voles (Microtus pennsylvanicus) stopped breeding sooner than at low population densities. This feed-back mechanism apparently also occurs in the deer mouse population. When population densities were low and onset of breeding was delayed by snowpack, the greater proportion of breeding occurred later in the summer.

- Summary

The population density of deer mice was low after the severe winter of 1972-73. Also, breeding was delayed by the prolonged snowpack. The population has adapted somewhat to such environmental stress. Thus, in response to this stress, the breeding season lasted longer in 1973. The majority of breeding occurred later in the summer than in previous years when population densities were higher. However, the extension of the breeding season did not enable the population to recover completely.

4.7.3. Job 2 Population Density (Harold Steinhoff)

- Objectives

The objectives of the population density portion of the small mammal study are to relate varying snowfall to varying population density of small mammals and to associated population parameters such as proportion of young, fertility rates, and litter size. Questions we are asking include: (1) How does population density of small mammals relate to varying snowpack?, (2) How does litter size of small mammals relate to varying snowpack?, and (3) How does age structure of small mammal populations relate to varying snowpack? My hypothesis is that Calhoun population indices of deer mice, red-backed voles, and chipmunks will decrease after a heavy snow year while those of montane voles will not.

- Procedures

Paired Calhoun census lines were run in late summer of 1970, 1971, 1972, and 1973 in each major vegetative type available at each of the three elevational sites in each of the three study areas, Missionary Ridge, Wolf Creek, and Rico.

- Findings

Missionary Ridge -

Most small mammal populations on Missionary Ridge decreased markedly in 1973 after three previous years of quite consistent increase (Table 3).

Table 3. Population indices of small mammals in relation to snow.

	1970	1971	1972	1973
Missionary Ridge				
Snow Course 1/, % of mean	96%	75%	78%	147%
Snow Disappearance Date		5-20	5-16	6-24
Small Mammal Pop. (C/100TN)				
Deermouse 2/	0.6	1.6	1.9	0.4
Colorado Chipmunk	0.9	1.7	2.1	0.8
Red-backed Vole	0.6	0.8	2.2	0.5
Microtus spp.	1.0	1.5	3.3	3.3
Rico				
Snow Course, % of mean	94%	81%	62%	140%
Small Mammal Pop. (C/100TN)				
Deermouse	0.4	0.3	0.6	0.8
Colorado Chipmunk	1.3	1.3	1.5	0.7
Red-backed Vole	0.0	0.8	1.8	0.2
Microtus spp.	0.0	0.2	1.1	0.1
Wolf Creek				
Snow Course, % of mean	96%	76%	78%	128%
Small Mammal Pop. (C/100TN)				
Deermouse		0.6	1.1	0.2
Colorado Chipmunk		3.1	3.4	2.3
Red-backed Vole		0.8	1.2	1.3
Microtus spp.		0.2	3.2	1.5

1/ Mean of SCS Snow Courses maximum depths, as follows:
Missionary Ridge - Cascade, Purgatory, Spud Mountain
Rico - Rico, Lizard Head
Wolf Creek - Upper San Juan, Wolf Creek Summit

2/ Deermouse (Peromyscus maniculatus), Colorado Chipmunk (Eutamias quadrivittatus), Red-backed Vole (Clethrionomys gapperi), Microtus spp (M. montanus and M. longicaudus.

Microtus spp. populations were the exception. They remained at the same high level as 1972. The population changes of deermice (Peromyscus maniculatus), Colorado chipmunks (Eutamias quadrivittatus, and red-backed voles (Clethrionomys gapperi) were strongly inversely correlated with snow depth in these years as can be seen in Table 3. The relation of the deermouse population to snow-free date was tested by analysis of covariance and found significant ($F=2206.0$, $F_{.05}=1.99$). The sample size of 32 will permit a valid estimate within 20% of the true mean with 95% probability. The smallest difference in deermouse populations means of Missionary Ridge is about 42%, so there is sufficient sample size to detect easily and significant differences in population between years. Thus the possibility is strengthened that there is in fact a relationship between snow depth and small mammal populations, at least for deermice. Each additional year of data is increasingly valuable now because only one year of completely reversed results would engender almost overwhelming doubt that the relationship actually exists. A continued strong correlation would greatly increase confidence in the tentative conclusions that the relationship does exist.

Other population parameters associated with population change, and which may help to explain the mechanism are shown in Table 4. The population decline in deermice cannot be explained by reduced natality or by differential mortality of young because number of young per litter, proportion of young, and fertility rate of deermice has remained similar through all four years (Table 4). A marked increase in mortality of all age classes from an unknown source, perhaps the stress of a long winter, is a possible explanation. Patterns of these population parameters for other species on Missionary Ridge are either similar to those of deermice or are not consistent enough to interpret in relation to snow. An exception is the proportion of young *Microtus* sp., which seems directly correlated to snow depth and may mean that adults die more readily from snow stress than do young.

Rico-
Small mammal populations at Rico showed a marked decrease, but not to a lower point than 1970 (Table 3). The populations may have been at such a low point in 1970 and 1973 that they could not be measured precisely enough to show a difference. The deermouse population at Rico increased in 1973. If this pattern continues, either some environmental variable at Rico is very different than on Missionary Ridge or we will have evidence against the snow vs. population hypothesis.

Associated population data (Table 4) at Rico are less complete and do not show an interpretable pattern.

Wolf Creek-
The major decrease in the deermouse population is consistent with Missionary Ridge, but the other small mammal populations show an opposite pattern which is puzzling (Table 3). Another year of data is essential.

Other population parameters (Table 4) likewise give little indication of reasons for the small mammal population fluctuation at Wolf Creek.

- Future Plans

Calhoun census lines will be rerun at the same locations in the same way in future years on the same dates, July 20 to August 12. Consideration will be given to running of extra lines on Missionary Ridge to see if all small mammal populations on the Ridge are varying in synchrony.

Table 4. Population characteristics of small mammals in relation to snow.

	1970	1971	1972	1973
Missionary Ridge				
Number of young per litter				
Deermouse 1/	5.1	5.4	5.4	5.5
Colorado Chipmunk	3.9	4.0	4.5	4.4
Red-backed Vole	6.0	5.8	5.5	5.5
Microtus spp.	6.0	5.5	5.4	5.0
Proportion of young				
Deermouse	0.3	0.2	0.2	0.2
Colorado Chipmunk	-	0.1	0.1	0.04
Red-backed Vole	0.3	0.1	0.4	0.4
Microtus spp.	0.3	0.2	0.1	0.4
Fertility Rate 2/				
Deermouse	1.0	0.8	1.0	1.0
Colorado Chipmunk	0.7	0.8	0.6	0.8
Red-backed Vole	1.0	0.6		
Microtus spp.	1.0	1.0	1.0	1.0
Rico				
Number of young per litter				
Deermouse	-	-	5.0	5.6
Colorado Chipmunk	3.7	4.0	4.0	4.0
Red-backed Vole	-	6.6	5.0	6.5
Microtus spp.	-	5.0	5.4	-
Proportion of young				
Deermouse	0.8	0.4	0.4	0.2
Colorado Chipmunk	0.8	0.2	0.2	0.4
Red-backed Vole	-	0.1	0.4	0.3
Microtus spp.	-	0.5	0.2	-
Fertility Rate				
Deermouse	-	-	1.0	0.7
Colorado Chipmunk	0.5	0.9	0.4	0.7
Red-backed Vole	1.0	0.9	1.0	1.0
Microtus spp.	-	0.7	1.0	-
Wolf Creek				
Number of young per litter				
Deer Mouse		5.5		-
Colorado Chipmunk		4.0	4.1	4.0
Red-backed Vole		7.3	5.6	6.5
Microtus spp.		3.5	4.5	5.7
Proportion of young				
Deermouse		0.2	0.2	0.3
Colorado Chipmunk		0.5	0.4	0.2
Red-backed Vole		-	0.2	0.2
Microtus spp.		-	0.2	0.4
Fertility Rate				
Deermouse		0.8	1.0	-
Colorado Chipmunk		0.9	0.7	0.3
Red-backed Vole		1.0	1.0	1.0
Microtus spp.		0.5	0.9	0.9

1/ Scientific names are given in Table 3.
2/ Fertility rate means the proportion of mature females which give evidence of conception during the current breeding season.

4.7.4. Job 3. Home Range (Roger Sleeper)

- Objectives

Home range data will be used to determine whether size of home range of deer mice varies with snowfall. The trapping procedures used to obtain data on home range will also provide information on population size, longevity and distributional shifts in individual deer mice. These data will also assist in interpretation of Calhoun population index data.

- Procedures

Live trapping was conducted for 6 days each month during the snow free period of the year. Nest boxes, Sherman live traps and pitfall traps were used to capture small mammals. Animals were marked with ear tags and released.

- Findings

The size of home range can change and thus the distance animals may be moving to a trap line will change (Brant, 1962). Determining home range would be a useful technique to estimate the actual area from which animals were captured during a trapping period. Brant (1962) found that average distance between consecutive captures of an individual deer mouse was a good estimate of the distance deer mice move to a trap line.

Average distance, for deer mice in my study area, can vary with population size and time of year (Fig. 1,2). During early and mid-summer, average distance is inversely related to population density. Late in the summer, average distance is low, apparently independent of population density. The low values for average distance late in the summer may be due to an abundance of food or decreased activity at the end of the breeding season.

Population density was calculated from the effective area trapped and the population size. The effective area trapped was determined by extending the perimeter of the trapping grid outward a length of average distance. The population size was determined by the Schnabel index method for mark - recapture studies.

Population density estimates over the snow free periods of the study are presented in Figure 3. Densities were relatively high during the first two years of the study, but there was a marked reduction in numbers sometime during the fall and winter of 1972-73. Deer mice do not undergo cyclic fluctations in numbers as do some microtine rodents (Terman, 1968). Therefore, such a drastic reduction in the population may be related to the weather conditions to which the deer mice were exposed. Controlling factors of natural small mammal populations are difficult to determine, but weather conditions are a possibility (Ehrlich, 1972; Fuller et al., 1969).

Cumulative precipitation for approximately one month prior to the initiation of snowpack are represented by the dashed lines in Figure 3. There were 2.43 decimeters of precipitation in October 1972 versus 0.96 dm in October 1971. Some of this precipitation may have fallen as snow, but snow does not usually begin accumulating before late October. The heavier fall rains in 1972, coupled with cold temperatures during that period of the year could have adversely affected the deer mouse population. Also, the snowpack during the winter of 1972-73 was greater and lasted longer than in the 1971-72 winter. Hansson (1971) theorized that granivorous rodents, such as deer mice, may ap-

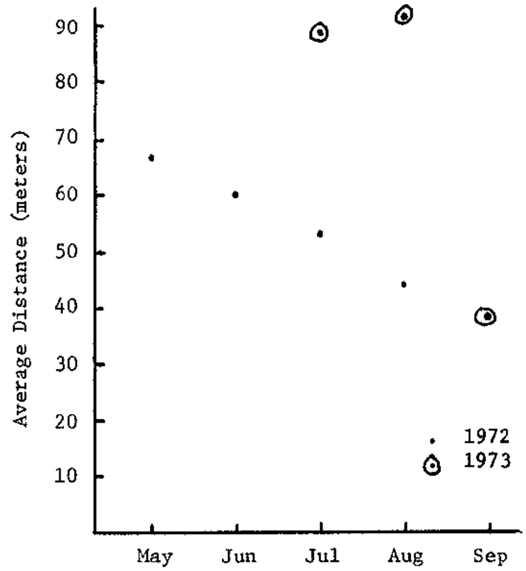

Figure 1. Average distance between consecutive captures of deer mice.

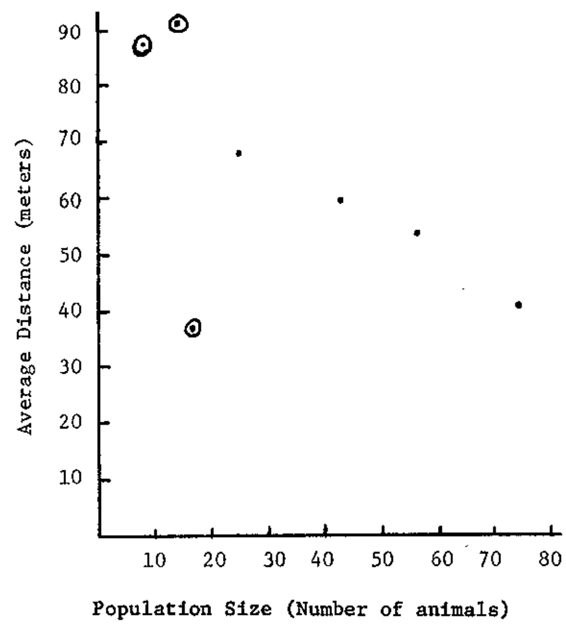

Figure 2. Average distance between consecutive captures of deer mice at different population sizes.

proach a food shortage in late winter or early spring before insects or new seeds are abundant. The prolonged snowpack, with the subsequent delay in plant growth, could have produced such a food shortage. Prolonged snowpack or heavy rains during the early fall may have contributed to the decline of the deer mouse population. However, no conclusions can be made, because there has only been the one heavy snow year during the course of this study.

The monthly population density estimates (Fig. 3) show the population growth rates for 1972 and 1973. The population density increased at a slower rate in 1973, when the density was very low. This may be indicative of a sigmoid growth curve, but also at these low densities, any mortality would substantially decrease

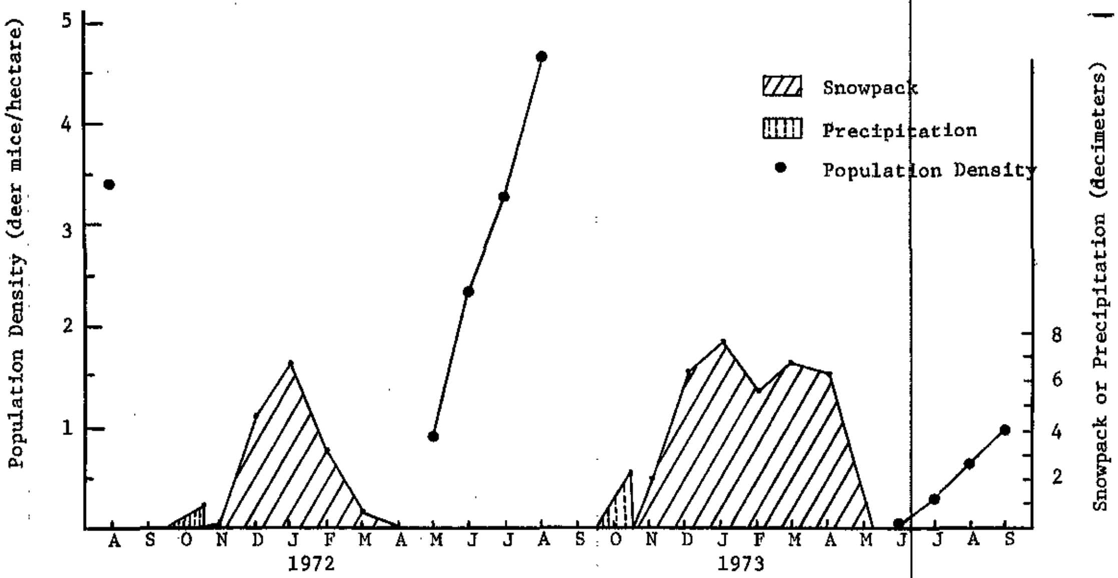

Figure 3. Population density, October precipitation and snowpack for the period of this study.

the breeding portion of the population and thus slow the rate of population growth.

Deer mice generally prefer grasslands with some rocks. In 1972, at the high population densities, some deer mice were found in the spruce-fir forest (Fig. 4), which can be considered marginal habitat. The population density was high enough that some deer mice were forced to use marginal habitats. In 1973, at the low population densities, deer mice were found only in the grasslands, which are the preferred habitat (Fig. 5). When one female was killed by a weasel in August, 1973, the number of breeding females was reduced by 17 percent. There were no deer mice in the marginal habitat that might move into the space in the more preferred habitat. Due to mortality and the small population size in 1973, the population did not grow at as fast a rate as in 1972. Even with the extended breeding season, the population density in September, 1973 was only about as high as the population at the beginning of the breeding season in 1972. After a sharp decline in numbers, the population apparently requires more than one breeding season to recover.

There has been only one heavy snow year during this study. Since there is simultaneous variation in other environmental factors, it is necessary to study the deer mouse population during other heavy snow years to

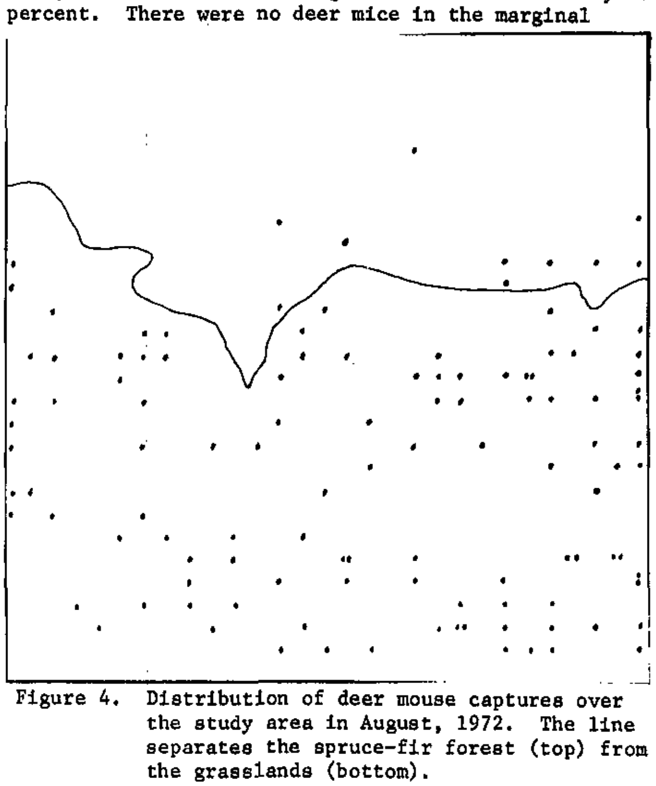

Figure 4. Distribution of deer mouse captures over the study area in August, 1972. The line separates the spruce-fir forest (top) from the grasslands (bottom).

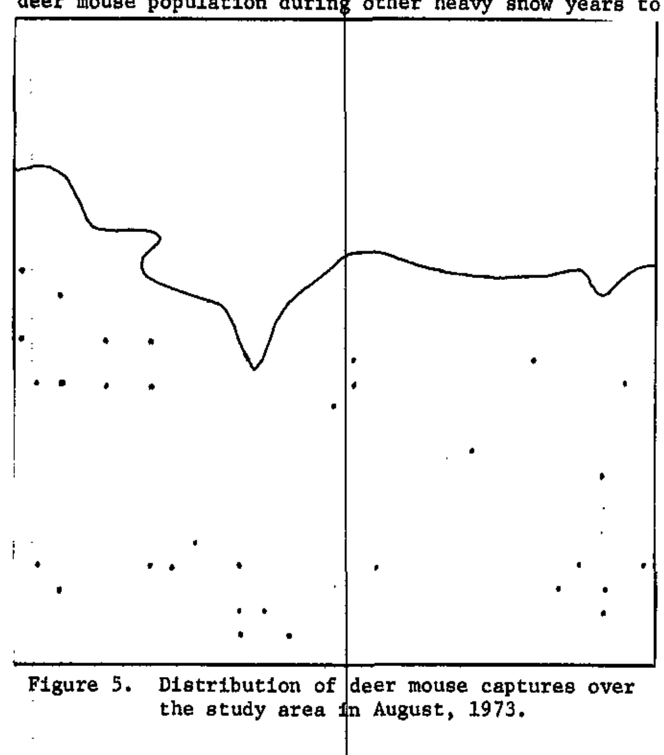

Figure 5. Distribution of deer mouse captures over the study area in August, 1973.

ascertain if heavy snowpack can cause a decline in the population. Further study may also show in what manner the snowpack affects the population. More information is needed to learn how long it will take the population to recover from a population decline.

- Summary

Population density estimates showed the population declined markedly during the winter of 1972-73. This decline was probably related to the heavy autumn rains or the heavy and prolonged snowpack that winter. The deer mouse population was so low that it could not increase at a rate as fast as in the previous year. Even with an extended breeding season to help compensate for the low population density, the population was still relatively low at the end of the summer.

- Future Plans

The same live trapping procedures will be continued next year to learn how home range and other population parameters are changing in relation to snowpack.

4.7.5. Job 4. Food Habits (Albert Spencer)

Tables 5 and 6 summarize our preliminary analysis of stomach contents of M. longicaudus taken during, before, and after the thaw. We had hypothesized that unless snow pack hindered free movement of the animals, their dietary habits would be little affected. The period of thaw seemed a likely point in time on which to center attention as we would be able to compare foods consumed during the period of snow cover with those eaten in the period after its disappearance. It also seemed probable that the period of thaw might be particularly stressful since as the snow lost its structure and collapsed, it should obliterate previously existing burrow systems and restrict the animals' freedom of movement. Lonnie Renner and Eric Rechel prepared the slides, which were then sent to Dr. Richard M. Hansen for analysis by his staff in the Composition Analysis Laboratory at Colorado State University. We wish to acknowledge the assistance given us by Dr. Hansen and his assistant, Mrs. Theresa Foppe, who in addition to carrying out the analysis also trained us in the technique of slide preparation. A sample consists of the combined stomach contents of animals of the same species and sex captured in the same habitat on a given day or adjacent days. In practice, we combined just the contents of one-half of each stomach sectioned longitudinally. The rest of the stomach was saved against the eventuality that we would wish to analyze each animal's consumption individually. Eighty microscope fields from each sample were examined and the materials at chosen sampling points identified and recorded.

Analysis revealed 31 recognizable varieties of material in the stomach contents. Two of these may be partially or entirely contaminants (insects and molds, introduced during preservation of the stomachs. The remainder are definitely species found on the sites where the voles were trapped. One of these may be misidentified. A plant identified as Amelanchier comprises approximately eleven percent of the contents, but Sambucus is not recorded at all. Sambucus grows abundantly in the north-facing clear cuts where the mice containing the plant in question were captured. Amelanchier does not grow on these sites at all. Little of the plant in question was recorded in the stomachs of voles from the south slope where Amelanchier grows most commonly and Sambucus is found also. Rodents rarely attack Amelanchier, but do strip Sambucus severely.

Herbaceous species as expected are the most important species in the food of voles. Festuca alone comprises nearly 29 percent of the total contents and 41 percent of the materials in the stomachs of voles from south aspects. Carex (14%) and Achillea (14%) are also important species. Herbaceous species combined account for almost 72 percent of the materials identified. Berberis (Oregon grape) and moss are included with herbs because of their similar size and comparable growth forms. They make up three percent and four percent of the components, respectively. Shrubs and trees make up most of the remaining 28 percent. Three species are particularly important. Populus constitutes eleven percent, Amelanchier (really Sambucus?) an equal portion, and Picea almost five percent. Thus only ten different kinds of plants (moss being , one) make up more than 95 percent of the materials found.

Despite this deceptively small base, the variation between samples is overwhelming. When considered plant species, there seems to be no apparent pattern to the differences. A partial explanation of this is revealed in Table 7. None of the samples from mice analyzed individually contains significant amounts of more than two kinds of plants. Voles tend, it appears, to feed to repletion on a single kind of food. Lacking samples consisting only of large numbers of stomachs, or better yet, of large numbers of stomachs analyzed individually, I am pessimistic about resolving differences at the species level.

Comparison of the data classified according to the life form, however, does present a consistent pattern (Table 6). Voles living on north aspects in clear cuts utilize shrubs and trees to a greater extent than voles from south aspects. Use of the woody species seems to increase late in the winter and in the year with deeper snow pack. This is consistent with our earlier observations and inferences. Preferred foods (herbs) logically are both more abundant and accessible early in the winter. As these are exhausted or shut away, the animal should turn to shrubs. Shrubs may be more accessible. Their erect stems form a set of passages as the snow settles away from them. Vapor rising from the ground travels upward through the passages and produces a cone of hoar within the bush, which is easily penetrated. Perhaps the layer of hoar does not form as readily or extensively beneath very deep snow. The dense structureless recrystallized snow at the period of thaw possibly presents as much of a problem to the vole in its movements as it does to the researcher attempting to dig down through it. Herbaceous species crushed beneath the heavy layers of collapsing snow would be less accessible. The data indicate males utilize shrubs more intensively and persistently than females do. This may be related to a requirement for higher quality food to support their somewhat earlier sexual development. Table 14 does not seem to support this idea. Male body growth seems to occur largely after the thaw. As snow disappeared in 1972, both sexes turned again to herbaceous species, especially those that are early in appearance.

Several points of interest are not included in the tables. Voles captured in winter invariably have engorged stomachs whereas in summer they are frequently nearly or entirely empty. This probably is related to the lower quality of food utilized in winter. The color of the contents changed strikingly in samples taken from south aspects during the transition from winter to spring. In January and February, 1972, the stomachs were filled with a pasty-white material. But, from March on, the contents were brilliant green

	Males						Females					
	South Slope			North Slope			South Slope			North Slope		
Date	n	Herbs	Shrubs	n	Herbs	Shrubs	n	Herbs	Shrubs	n	Herbs	Shrubs
9 Jan. 72	10	91.56	7.17	-	--	--	14	90.79	8.82	-	--	--
15 Feb. 72	5	98.56	1.16	4	91.51	7.72	2	36.78	62.90	9	91.30	3.42
12 Mar. 72	3	100.00**	--	5	32.15	65.90	6	100.00	--	8	97.59	0.96
26 Mar. 72	8	97.79	2.21	4		41.63	2	98.93	1.07	0	--	--
1 Apr. 72	--	--	--	1	35.2[illegible]	64.32	-	--	--	1	--	100.00
4 Apr. 72	2	88.10	11.90	5	16.59	83.41	1	72.49	27.51	5	94.68	5.32
8 Apr. 72	6	87.32	11.97	-	--	--	2	99.68	0.32	-	--	--
17 Apr. 72	4	98.01	0.39	4	74.04**	20.73	3	98.43	1.26	-	--	--
2-5 May 72	8	90.76	8.87	12	47.83**	49.96	5	71.93	28.07	4	85.06	14.41
16-18 May 72	1	98.82	1.18	7	98.24	0.88	1	100.00	--	4	89.32	5.34
Subtotals	47	850.92	44.85	42	452.55	334.55	36	769.03	129.95	31	457.95	129.45
17-19 Mar. 73	6	57.70	42.30	-	--	--	2	100.00		3	8.41	91.15
1-3 Apr. 73	2	44.62	55.37	-	--	--	5	99.75	0.25	-	--	--
8 Apr. 73	-	--	--	1	--	100.00	1	100.00	--	-	--	--
23-27 Apr. 73	2	85.68	14.32	4	54.41	44.90	3	17.43	82.57	4	14.40	85.60
23-27 Apr. 73	-	--	--		--	--	1	49.05	50.95	-	--	--
	10	188.00 **	111.99	5	54.41 **	144.90	11	366.23	133.77	7	22.81	176.75

** Period of thaw

TABLE 5. Percentage of identified contents of stomachs of long-tailed voles (pooled samples) arranged by vegetative form, habitat, sex of vole and date of capture. Based on 80 field samples.

		Frequency occurrence				Total Percentage Composition				
		Male		Female		Male		Female		Overall Total
Species	n Habitat	(57) South	(47) North	(47) South	(38) North	South	North	South	North	
Carex		12	9	11	5	211.62	168.08	179.53	36.70	595.93
Festuca		12	4	10	5	529.73	7.89	532.75	162.33	1232.72
Achillea		8	7	8	4	181.40	168.86	115.99	139.35	605.62
Erigeron		4	4	2	2	6.01	8.63	.73	2.66	18.03
Lupinus		6	2	3	1	107.00	23.21	15.14	1.43	146.78
Geum		4	3	5	3	12.64	14.83	114.71	92.19	234.37
Oenothera		2	3	2	1	2.98	31.12	3.34	14.40	51.84
Moss		1	5	3	2	1.54	68.79	91.18	2.58	164.09
Berberis		7	2	7	1	69.84	2.90	77.32	5.07	155.13
Picea		5	5	3	4	21.86	203.42	28.98	17.89	272.15
Pinus		1	1	1	1	5.90	--	4.03	0.96	10.89
Populus		3	5	4	4	97.73	125.38	63.85	199.38	486.34
Quercus		3	--	1	--	4.64	--	4.03	--	8.67
Rosa		2	--	1	--	10.02	--	27.51	--	37.53
Amelanchier		1	4	3	2	14.32	148.96	131.48	87.19	381.95
Arthropod Parts		6	6	3	5	4.55	11.63	1.02	13.04	30.24
Fungus		1	1	--	--		1.86	--	--	1.86
# samples		12	10	14	8					
Total Herb						1038.92	507.06	1135.26	480.76	3162.00
Total Shrub						156.53	479.45	263.72	306.20	1205.90
Total Percent		1200	1000	1400	800					4400.00

TABLE 6. Frequency and percentage by species of identified contents of stomachs of long tailed voles based on 80 field samples.

Size of Sample	Frequency	Frequency one food only	Frequency most common food > .9	Mean proportion most common species %	Mean proportion 2 most common species combined %
1	9	3	5	80.4	98.33
2	7	0	1	65.4	92.14
3	4	0	1	81.8	93.00
> 4	25	0	1	63.0	86.76

TABLE 7. Comparison of distribution of composition in samples derived from different numbers of voles.

Class (Percentage of Circumference stripped)	n	Number dead	Percent dead
20-29	1	--	--
30-39	1	--	--
40-49	8	2	25
50-59	18	4	22
60-69	14	6	43
70-79	12	8	67
80-89	11	6	54
90-99	10	3	30
100	81	81	100
TOTAL	156	110	70

Class (Diameter) cm	n	Number dead	Number alive	% dead	X^2 1 d.f.	Associated with difference
1	125	91	34	75		2.24
2	31	18	13	60		$p < .05$
	156					

Treatment	Class (Percentage of Circumference stripped)	Number alive	Number dead	% dead	X^2 1 d.f.	Associated with difference
Exper.	20-59	22	6	21		
Control	20-59	28	1	4	23.0	$p < .001$
Exper.	60-69	24	23	49		
Control	60-69	47	0	0	69.76	$p < .001$
Exper.	100 exp.	0	31	100		
Control	100	77	4	5	95.86	$p < .001$
Exper.	Total	156	110	70		
Control	Total	156	5	3		

TABLE 8. Mortality and survival of oak-brush stems fed upon by voles.

as the voles searched out the new sprigs of *Achillea*, *Festuca*, etc., as they began to grow. North aspect samples continued pasty into May. The pastiness of the south aspect samples in January and February which are made up largely of *Festuca* tissues, indicates the mice are feeding on the dead, bleached stems and leaves and may be able to extract some nutrient value from them. This means that the amount of reserves contained in the winter "home ranges" in sedge (as reported last year) was probably greater than the amount represented by the green portion alone.

- - Effects of winter food habits

The evidence cited above supports the possibility that winter snow conditions do affect small mammals by limiting availability of food. Voles meet the problem by shifting feeding habits. This implies potentially negative consequences for reforestation if increased snow results from attempts to modify the weather by cloud-seeding. In May of 1973, we tagged 168 oak stems that had been partially stripped by voles during the winter. In September, we were able to relocate 156 of these stems. We chose as controls the nearest unchewed stem of comparable diameter and length. Table 8 compares relative survival of mouse gnawed and control stems. After only nine months, probably less, even moderately chewed stems showed a significantly reduced survival. Completely girdled stems were expected to die soon, but note the frequency of mortality in stems which retained the larger part of their girth intact. We will examine these stems again at intervals.

Date	n	Number Active	Percent Active	Corpora Lutea Number With	Corpora Lutea Mean & S.E.	Embryos Number With	Embryos Mean & S.E.	Placental Scar Number With	Placental Scar Mean & S.E.	Corpora Albicantia Number With	Corpora Albicantia Mean & S.E.
Eutamias quadrivittatus											
23-27 April	1	-									
5-13 May	4	-									
22-31 May	19	2	10	2	5.0	2	5.0				
6-8 June	4	1	25	1	5.0	1	5.0				
12-16 June	6	1	17	1	5.0	1	5.0				
22-30 June	14	9	64	6	5.3 0.35	7	5.1 0.15	2	5	1	5.0
21-26 July	7	-	-	-		-		7	4.3 0.89	4	4.2 0.38
21-23 Aug.	17	-	-	-		-		2	5.0	5	5.2 0.20
21 Sept.	4	-	-	-		-					
Microtus longicaudus											
30 Dec. 72	2										
20 Jan. 73	4										
17-18 March	5										
1-3 April	5										
8-9 April	1										
23-27 April	8										
5-13 May	17										
22-31 May	[illegible]	2	50	2	4.5 0.61	2	4.5 0.61				
6 June	3	2	67	2	8.0 0.70	2	5.5 0.61				
12-16 June	7	7	100	7	5.0	7	5.				
22-30 June	8	7	88	7	4.9 0.33	7	4.4 0.93				
21-26 July	13	7	54	7	4.7 0.41	6	4.8 1.07				
21-23 Aug.	4	3	75	3	5.0	2	5				
21 Sept.	9							3	5.7 1.20	3	4.7 1.20
29 Sept.	3							3	4.0 0.57	2	4.0
Microtus montanus											
22-31 May	1	-									
6 June	5	4	80	4	6.0 0.17	4	5.8 .25				
12-16 June	8	6	75	6	6.0 0.26	6	6.0 0.26				
22-30 June	1	-									
21-26 July	19	17	90	17	5.8 0.25	17	5.6 1.26	3	4.7 0.34	3	5.3 0.34
29 Sept.	3	3	100	3	6.0 0.54	2	5.5 0.5	2	2.5 1.5	2	2.5 1.5

Date	n	Number Active	Percent Active	Corpora Lutea Number With	Corpora Lutea Mean & S.E.	Embryos Number With	Embryos Mean & S.E.	Placental Scar Number With	Placental Scar Mean & S.E.	Corpora Albicantia Number With	Corpora Albicantia Mean & S.E.
Clethrionomys gapperi											
30 Dec.	3	-									
18 Feb.	3	-									
17-18 March	3	-									
23-27 April	3	-									
5-13 May	2	-									
22-31 May	1	-									
6-8 June	1	-									
12-16 June	7	6	85	6	4.7 0.48	2	4.0 —				
22-30 June	2	2	100	2	4.5 1.50	2	4.5 1.50				
21-26 July	2	2	100	2	6.0	2	6.0				
21-23 Aug.	1	1	100	1	6.0	1	6.0				
21 Sept.	3	-	-								
Peromyscus maniculatus											
17-18 March	3	-									
5-13 May	1	-	-								
22-31 May	3	2	67	2	5.5 0.5	2	5.0				
6-8 June	1	1	100	1	6.0	1	6.0				
12-15 June	1	1	100	1	7.0	1					
21-26 July	1	1	100	1	6.0	1	6.0				
21-23 Aug.	2	1	50	1	6.0	1	6.0	1	7.0	1	7.0
29 Sept.	2	-	-					2	4.5 0.5	2	5.5 0.5
Sorex vagrans											
23-27 April	1	-									
5-13 May	2	-									
21-23 August	2	1	50			1	6.0			1	4.0

TABLE 9. Reproductive activity in females, Missionary Ridge, 1973.

Date	n	Testis, mm Mean Length	S.E.	Testis, mg Mean Weight	S.E.	Seminal Vesicle, mm Mean Length	S.E.
				Eutamias quadrivittatus			
23-27 April	5	14.8	0.20	396.8	30.05	6.1	1.89
5-13 May	32	13.0	0.17	302.4	33.13	6.2	0.19
22-31 May	20	6.8	0.61	255.5	10.95	12.0	0.41
6-9 June	10	9.4	1.0	180.3	37.32	5.6	0.84
12-16 June	6	11.3	4.19	216.2	13.45	4.3	1.32
22-29 June	6	6.9	1.48	79.7	32.18	4.3	1.76
21-26 July	10	5.9	0.37	18.0	3.47	3	0.29
21-23 August	16	4.2	0.11	14.7	2.42	2.3	0.17
21 September	2	4.5	0.70	15	1.0	2.5	0.70
				Microtus longicaudus			
20 Jan.	6	3.7	0.33	8.8	1.74	2.7	0.17
18 Feb.	1	3.0	--	3.0	--	2.5	--
17-18 March	7	3.4	0.30	10.0	1.53	2.0	--
1-3 April	3	2.7	0.33	11.0	2.64	2.0	--
8-9 April	1	3.0	--	6.5	--	2.0	--
23-27 April	6	5.9	0.37	64.3	11.38	3.2	0.47
5-13 May	27	8.4	0.27	107.0	7.62	6.4	0.47
22-31 May	7	9.3	0.29	161.7	10.89	11.4	0.87
6 June	2	10.0	--	201.0	49.00	9.0	1.0
12-13 June	5	10.6	0.51	242.6	15.20	14.6	0.60
22-30 June	8	10.5	0.38	242.8	10.08	12.8	0.41
21-26 July	4	11.2	0.48	284.0	6.03	12.8	1.25
21-23 Aug.	8	11.1	0.61	257.4	35.82	12.0	2.36
21 Sept.	11	4.3	0.80	26.5	18.61	3.6	1.26
29 Sept.	1	3.0	--	5.0	--	1.5	1.5
				Microtus montanus			
5-13 May	1	11.0	--	172.0	--	16.0	--
22-31 May	3	8.7	0.34	162.3	11.86	11.3	0.67
6-8 June	1	11.0	--	214.0	--	10.0	--
12-16 June	1	9.0	--	151.0	--	13.0	--
22-30 June	1	10.0	--	233.0	--	14.0	--
21-26 July	5	13.0	1.58	347.4	123.28	15.0	1.0
21-23 Aug.	5	10.4	0.4	234.2	33.68	13.0	1.0

Date	n	Testis, mm Mean Length	S.E.	Testis, mg Mean Weight	S.E.	Seminal Vesicle, mm Mean Length	S.E.
				Clethrionomys gapperi			
18 Feb.	2	3.0	--	7.0	0.37	1.5	--
23-27 April	1	5.0	--	30.5	--	3	--
5-13 May	5	6.6	1.70	53.0	11.67	2.2	0.65
22-31 May	5	9.4	0.24	144.0	14.03	7.2	0.37
12-16 June	7	9.6	0.20	204.4	12.00	9.7	0.28
22-30 June	1	9.0	--	158.0	--	4.5	--
21-23 Aug.	2	10.0	--	193.0	16.91	10.0	1.0
21 Sept.	5	3.2	0.37	4.8	0.48	2.0	--
				Peromyscus maniculatus			
18 Feb.	1	2.5	--	4.5	--	2.5	--
17-18 March	2	4.0	--	14.5	1.50	2.5	0.5
23-27 April	2	7.5	0.5	77.0	5.29	5.2	0.11
5-13 May	2	6.0	--	45.0	3.0	4.5	0.70
22-31 May	12	7.9	0.33	88.4	11.99	7.1	0.77
6-8 June	1	8.0	--	16.0	--	10.0	--
12-16 June	1	9.0	--	--	--	9.0	--
22-30 June	1	9.0	--	--	--	10.0	--
21-26 July	3	10.3	1.20	133.3	22.67	9.3	0.67
21-23 Aug.	3	9.3	0.34	142.7	7.06	9.0	1 0
29 Sept.	1 subad.	4.5	--	9.5	--	3.0	--

TABLE 10. Mean weight of testis (mg) and mean length of testis and seminal vesicle (mm) by date and species, 1973.

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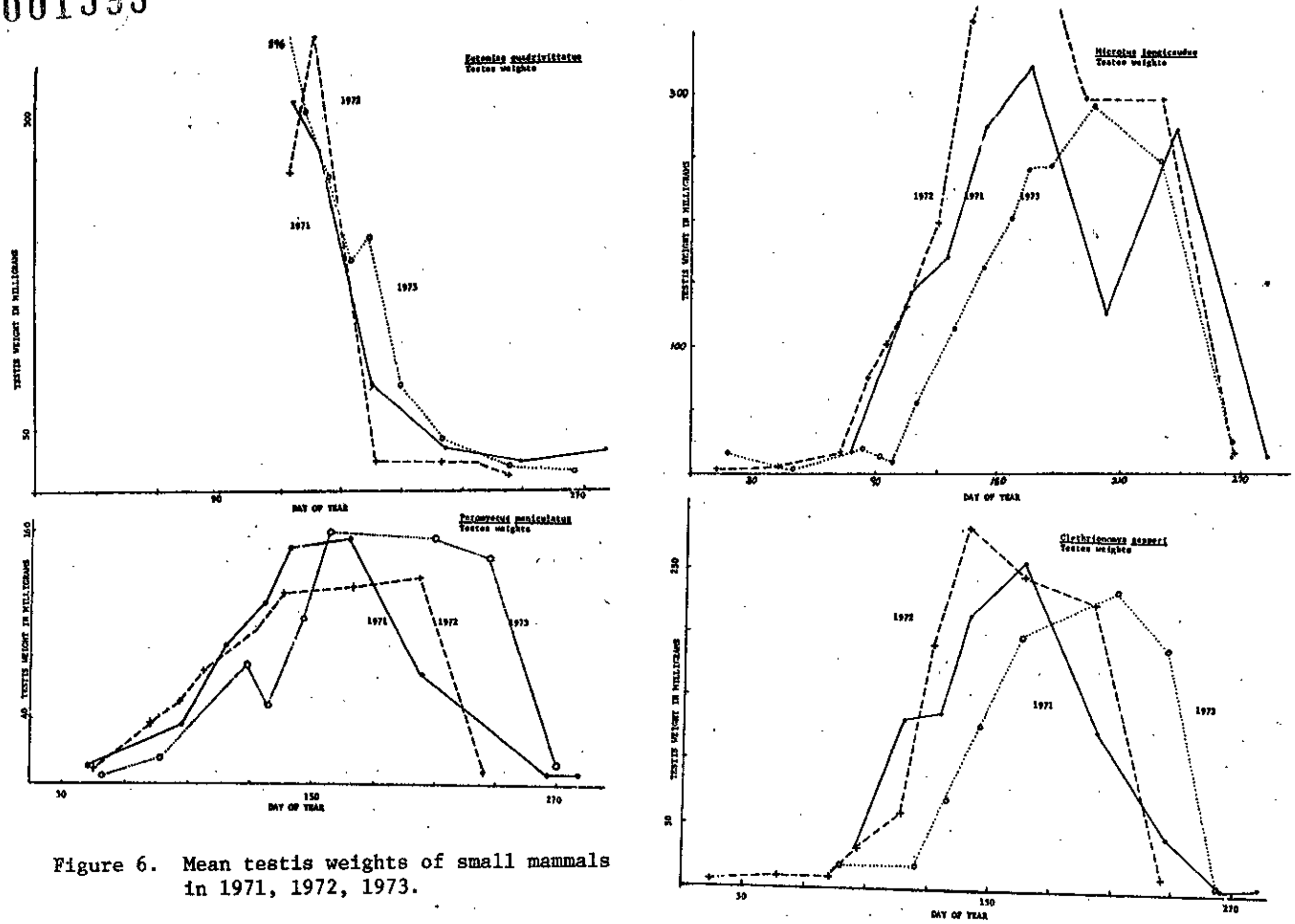

Figure 6. Mean testis weights of small mammals in 1971, 1972, 1973.

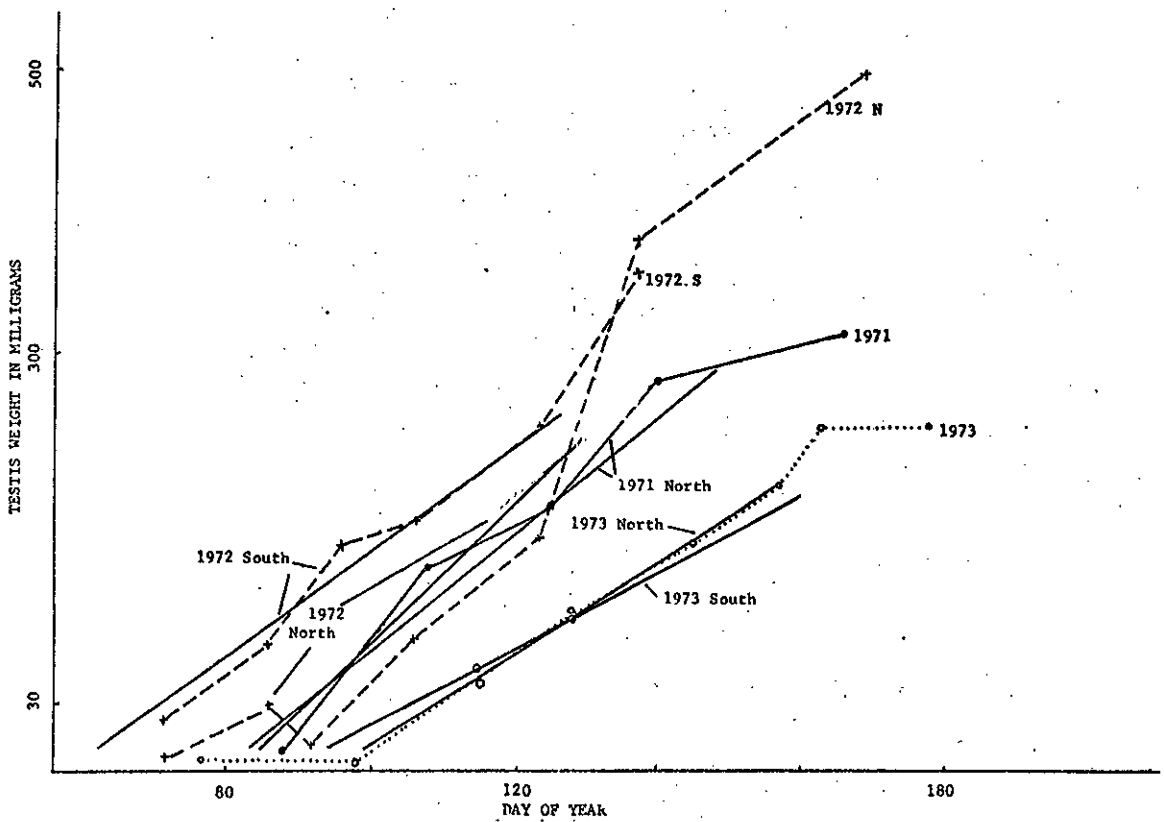

Figure 7. Development of testis weight in voles showing regression of testis weight on day of year.

Eutamias quadrivittatus

	Date late May			Mid to late June			
	1971	1972	1973	1971	1972	1973 (mid)	1973 (late)
Number Pregnant	1	1	2	5	3	1	7
Percent	14	12	10	35	16	17	51
Number Corpora lutea only	1			2	1		
Percent	14			14	5		
Number Parous and/or lactating					12		2
Percent					63		14
Number Inactive	5	7	17	7	3	5	5
Percent	72	88	90	51	16	83	35
TOTAL	7	8	19	14	19	6	14

TABLE 11a. Comparison of reproductive activity of female rodents at comparable periods of 1971, 1972, 1973.

M. longicaudus

	Mid April			Early May			Mid to late May			Mid to late June			
	1971	1972	1973 (late)	1971	1972	1973	1971	1972	1973	1971	1972	1973 (mid)	1973 (late)
Number Pregnant					4		2	4	2	2	2	7	7
Percent							67	67	50	100	25	100	88
Number Corpora lutea only		2			2		1						
Percent		40					33						
Number Parous and/or tactating					1			2			2		
Percent								33			25		
Number Inactive		4	8	6	4	17			2		4		1
Percent		60	100	100		100			50				12
TOTAL		6	8	6	11	17	3	6	4	2	8	7	8

TABLE 11b. Comparison of reproductive female rodents at comparable periods of 1971, 1972, 1973.

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Year	Slope	Regression Equation	Mean Testis wt. mg (Y)	Mean Date (X_1) (day of year)	Mean Body(X_2) Wt. g
1971	North	$Y = -348.2 + 4.29X_1 + 0.17X_2$	153.6	115.9	29.7
1972	South	$Y = -306.1 + 3.50X_1 + 6.81X_2$	186.7	107.2	32.0
1972	North	$Y = -421.3 + 5.0X_1 + 0.38X_2$	136.2	109.2	30.2
1973	South	$Y = -246.9 + 2.70X_1 + 0.34X_2$	110.8	128.9	28.0
1973	North	$Y = -299.4 + 3.14X_1 + 0.21X_2$	133.5	136.0	31.0

Analysis of Variance

1971 North	D.F.	S.S.	M.S.
Total	14	102,223	42,405
Regression	2	84,811	8,706
Dev. from Regression	11		

$F_{2,11} = 4.87 \quad p < .05$

1973 South	D.F.	S.S.	M.S.
Total	23	65,737	
Regression	2	45,093	22,546
Dev. from Regression	20	20,644	1,032

$F_{2,20} = 21.85 \quad p < .01$

1972 See Interim Report, 1972

1973 North	D.F.	S.S.	M.S.
Total	24	140,230	
Regression	2	106,462	53,231
Dev. from Regression	21	33,768	1,608

$F_{2,21} = 33.10 \quad p < .01$

Regression of Testis Wt. on Body Wt.--nonsignificant in all cases, $p > .05$.

TABLE 12. Multivariate analysis of linear regression of testis weight of voles (M. longicaudus) on date and body weight.

Year and Slope (aspect)	Date Testis Wt. = 80 mg. from (Regression Eq.)	*	Date Festuca 50% full height	Date Thlaspi 50% full bloom	Date Mertensia 50% full bloom	**	> 50% Snow cover thawed N Coon C between 3050-3140 m	*	Latest date of Continuous cover Snow Stake Data 3200 m	*
1971 North	99	-1	172	150	168	-11	125	-5		
1972 North	98	+20	157	144	155	+30	120	+35		
1973 North	118		187	174	184		155			
1971 South	--		161	136	148	-7	86[1]	-16		
1972 South	78	+39	154	125	144	+47	70	+65		
1973 South	117		183	174	205		135			

* difference between years
** mean difference (over 3 species) between years
1 several small snows fell subsequent to disappearance of winter pack

TABLE 13. Comparison of phenology of testis development in long-tailed voles with that of 3 selected herbs and spring thaw.

	1972									1973							
	MALE				FEMALE					MALE				FEMALE			
Date	n	Body Length	n	Body Weight	n	Body Length	n	Body Weight	Date	n	Body Length	n	Body Weight	n	Body Length	n	Body Weight
9-16 Jan.	10	112.3	10	28.53	15	109.1	15	26.17	30 Dec. 72	-	--	-	--	2	119.5	2	--
12 Feb.	9	109.6	9	24.19	11	106.9	10	23.93	20 Jan.	6	111.0	6	26.65	4	111.0	3	26.40
12 March	7	107.2	7	25.50	14	107.6	14	22.89	18 Feb.	1	105.0	1	21.3	-	--	-	--
26 March	12	110.8	12	34.92	2	106.0	2	21.20	18 March	6	108.7	6	23.23	5	112.4	5	25.08
1 April	1	109.0	1	23.8	1	115.0	1	26.9	1-3 April	2	107.0	1	23.4	5	108.8	5	22.34
4 April	7	109.6	7	27.03	6	106.8	6	21.93	8-9 April	1	109.0	1	23.9	1	113.0	1	21.80
8 April	6	109.3	6	32.15	2	107.5	2	23.65	15 April	-	--	-	--	-	--	-	--
16-17 April	12	119.9	13	30.98	6	110.2	6	24.43	23-28 April	6	112.7	6	26.57	8	112.6	8	25.85
2-5 May	19	122.9	20	33.94	11	114.7	11	34.08	5-13 May	26	109.5	26	28.46	18	102.6	18	23.51
16-18 May	11	113.5	13	36.53	5	109.0	5	30.14	22-31 May	8	112.0	7	31.94	4	102.2	4	27.12
16-18 June	2	119	2	40.95	--	--	--	--	6-9 June	2	98.50	2	25.70	2	105.5	2	26.65
									12-16 June	5	120.2	5	37.54	7	114.43	7	34.97
									22-31 June	8	118.4	8	38.12	8	110.25	8	28.52

TABLE 14. Body length and weight of body in male and female long-tailed voles (M longicaudus).

1972 July B.W. gm	T.W. mg	1972 August B.W. gm	T.W. mg	1973 July B.W. gm	T.W. mg	1973 August B.W. gm	T.W. mg
19.1	109	21.0	10	18.2	46	17.1	8
16.0	57	19.7	12	16.8	13	16.1	17
16.7	58	11.8	22	16.3	18	13.0	10
16.8	66	10.6	20	15.4	34		
15.6	38			15.3	8		
13.7	42			11.6	32		
12.9	25			11.3	14		
12.5	57			11.0	25		
12.3	40			12.1	34		
11.2	50			10.2	26		

TABLE 15. Testis weight and body weight of juvenile long-tailed voles.

4.7.6. Reproductive Cycle (Albert Spencer)

- Development

Precipitation in the period from August 1972 to May 1973 was exceptionally heavy. The nine months from January 1972 to August 1972 were unusually warm and dry. Snowpack on the trapping transects through April and early May of 1973 averaged 150 to 200 percent of the maximum depth in the same period in the preceeding year. Onset of spring growth of plants was retarded by nearly seven weeks.

Populations of most small mammals trended down during this period. The exceptions were Microtus montanus and, possibly, chipmunks. Trapping success from January 1973 through August 1973 for M. longicaudus averaged less than 40 percent of the same periods a year earlier, for Peromyscus maniculatus, less than 15 percent, and for Clethrionomys gapperi, about 30 percent. Although we set out almost 90 percent more traps than in 1972, we captured only two-thirds as many M. longicaudus, only one quarter as many deermice, and one half the number of red-backed voles. On the other hand, we caught almost one and one half times the number of chipmunks in 1972 and almost three times as many M. montanus. The declines were negatively related to fall precipitation, April snowpack, and an increase in the number of short-tailed weasels, and positively related to precipitation the previous summer. Any one of these factors as well as others unrecognized could have influenced populations of small mammals directly or indirectly through their food supply. I think we can rule out the effects of the heavy late winter snowpack in the case of both deermice and M. longicaudus because their capture rates declined before April, for deermice even before November 1972.

One important effect of the severe winter was to make field work much more laborious. Adequate samples of deermice and red-backed voles were unobtainable and acceptable samples of M. longicaudus were obtained only by more than doubling the time spent in the field.

- Reproductive development and onset of breeding

Previous results made it possible to predict effects on reproductive development of an extended period of snow cover. These predictions can be compared with the observations as a test of our assumptions.

Male chipmunks, Eutamias quadrivittatus, showed little difference between 1971 and 1972 in the timing or trend of reproductive development as measured by testis weight. The inference drawn was that weather conditions have little immediate effect on their reproductive biology. We expected little response to the much prolonged snowpack of 1973 or to the much greater depths of snow present at the onset of breeding in that spring. As Figure 6 indicates, this is borne out by observation. There are, however, significant differences in weights observed in the three years. (Table 10 this report and Table 4, Interim Report 1972 and 1971). The heaviest mean testes weights occurred in 1973, the lightest in 1972, just the opposite of expectations if current snow conditions were inhibiting testis growth. This distribution might be expected if breeding were delayed and more sperm retained in the testes. This suggests that females may be affected more than males. No differences from previous years in the timing of onset of reproductive activity in female chipmunks are discernible in earlier data and none were expected or observed in 1973 (Table 9). There were differences in fertility rates and extent of period of reproductive activity between 1972 and 1971 (Table 11), and in agreement with these trends, differences of the same direction, but greater magnitude were observed between 1972 and 1973. Fewer females achieved pregnancy early in June 1973, and more were pregnant or non-parous in late June. Some females were still lactating in late July. A statistically significant test in this type of comparison could not be achieved with samples of fewer than 100 females each, or approximately ten times the investment. In my judgement, they are biologically significant, but the interpretations must be viewed with caution. It appears that variability in spring snow conditions has little effect on timing of onset of reproductive activity in chipmunks, but does influence its progress.

Our earliest results indicated that the presence of snow cover significantly influences the timing of reproductive development in male M. longicaudus probably through the effect of the snow on new plant growth. Snow cover on both north and south aspects persisted much later into the spring than it had in 1972. We therefore expected the delay in development which is pictured in Figures 6 and 7 and summarized in Table 10. The differences between mean testis weights for equivalent dates in 1972 and 1973 are statistically significant for all dates after early April and before late July. There was no difference between mean testis weights of voles from north and south aspects in 1973, which was to be expected since snow lay deep and unbroken on both aspects into early May. The south aspect means are actually the lower points in Figure 7 in the two samples where they can be compared (April 23-28, May 5-13).

The linear regression of testis weight on date and body weight was calculated for the periods between and including the dates when mean testis weight equalled or exceeded 15mg. and June 6 or the next earlier sample for all three years and for both south and north aspects when available. All voles captured in 1971 were taken on north aspects. The regression of testis weight on date is significant for all the five groups of data. Regression of testis weight body weight is negligible except for the 1972 south aspect sample, in which instance, although the regression coefficient is large, it is not significant. The regression coefficients of testis weight on date vary from 2.70 to 5.00, but the differences are not statistically significant (Table 12). It seems reasonable to conclude that the rate of development in the linear phase of the growth curve is intrinsically controlled and that the observed differences in end points may be attributed to differences in the volume of sperm contained in the testis.

I used the regression equations to calculate the dates of equivalent phenology in testis development. I selected arbitrarily a weight of 80 mg as a point not so far from the mean as to be subject to great uncertainty, but close to the actual point of interest which is the date of initiation of development. The dates obtained were compared with dates of equivalent phenology obtained from Dr. Owen's study of herbaceous phenology and from subjective evaluations of the state of snow cover on the same slopes (North Coon Creek between 3050m and 3140m). The dates are assembled into Table 13. Physical, botanical, and microtine phenology differ in the same direction and to a comparable magnitude.

Correlations between the phenologies are positive and correlation coefficients fairly large, e.g., r(Festuca-south slope aspect - testis weight both aspects) = .66, but with so few data are not significant.

I suggested in last year's report that voles on north aspects were responding to a different stimulus which I think may be photoperiod. Results of 1973 do not conflict with this hypothesis. Testis development began several weeks before the disappearance of snow from either aspect, before herbs or shrubs began growing. I think there was no possibility therefore of new growth acting as a stimulus at that time. The uniformity of conditions reduced the number of stimuli to just one, operating identically on either aspect. The close fit of the calculated regression line to the sample means (1973) may be a consequence of the elimination of all but one significant variable. Conversely the poorer fit of the curves for 1971 and 1972 may be attributed to the lack of homogeneity in those years when some small sites on the north aspects were melted out as early as late March while some large areas of the south aspects were still covered in early April. I had noticed an association between this heterogeneity and the variations in testis weights as early as 26 March 1972, after finding that two of the voles taken in a north-facing clearcut from the same large open area (approximately 12m diameter) possessed larger testes (57 and 88mg) than did voles from solidly covered areas the same day (n = 2 14,20 mg) or nine days later (n = 5,$\bar{x}$ = 15mg range = 14.26 mg). The convergence of regression curves toward their initial ends may be another indication of a common stimulus operating on snow covered slopes. I would not rule out the possibility that there is a synergistic relationship between the different stimuli. Physiological experimentation into this problem will be very helpful in assessing the quantitative relationships between snow cover and reproductive development.

We know less about the cycle of male M. montanus, but our evidence indicates it is similar to that of M. longicaudus, but extends somewhat later into the fall. Negus (1973) believes that M. montanus is more flexible in its response to immediate conditions than M. longicaudus.

Variations from year to year in the reproductive activity of female M. longicaudus differ in the same direction and, as nearly as can be determined, to the same amount of time as the male cycles. Figure 8 illustrates that the first appearance of females with corpora lutea in 1973 was in late May, about five weeks behind their mid-April appearance in 1972. The first appearance of juveniles in 1972 was mid-June whereas in 1973, the first juveniles, generally lighter in weight and presumably younger, appeared in late July, again a difference of about five weeks. This amounts to a difference of about one litter between 1972 and 1973. The effect of such a delay on population recruitment is potentially quite large. If we take, for a simple example $P_t = P_o b^t$ where t equals the interval between litters, as our model of population growth during the reproductive season, shortening the season by one litter reduced P_t by a factor of $\frac{1}{b}$ e.g. $P'_t = P_o b^{t-1}$, $\frac{P'}{P_t} = \frac{P_o b^{t-1}}{P_o b^t} = \frac{1}{b}$. In our sample, b is approximated by b = (1+m) where m is the average number of female offspring per litter; m is approximately 2.5 in long-tailed voles. So, the effect of shortening the season by one litter would be to reduce the potential increase to 2/7 its value allowed the additional litter.

A further reduction in potential increase may be introduced because of an aspect of development in voles. Notice, in Table 14, the step-like increase in body weight in late spring, especially marked in males. Microtus longicaudus on Missionary Ridge appear to display the same delayed growth pattern demonstrated in M. pennsylvanicus by Brown (1973). Females born late in the season delay attainment of reproductive maturity till the following year. Females born earlier attain maturity and reproduce a few weeks after weaning. In 1971, we captured a juvenile female of 16.7gm, just weaning weight, and carrying six embryos. The switching point from the pattern of testis growth in juvenile males peaks then. If on Missionary Ridge, female longtailed voles born after early July do delay their attainment of sexual maturity until the following year as our data suggest, this alone would result in halving the potential cumulative increase otherwise possible in the course of the summer reproductive season. The decreased biotic potential would result from the shift concurrent with the change in developmental path, from an exponential mode of increase to a linear mode (Figure 9). Shortening of the reproductive season by lengthening the duration of snow cover would elicit a reduction in potential recruitment by way of the first type of effect. It would not affect the operation of the second factor. Other factors can not be ignored as illustrated by our observation that despite the apparent temporal advantage, the M. longicaudus population decreased in 1972.

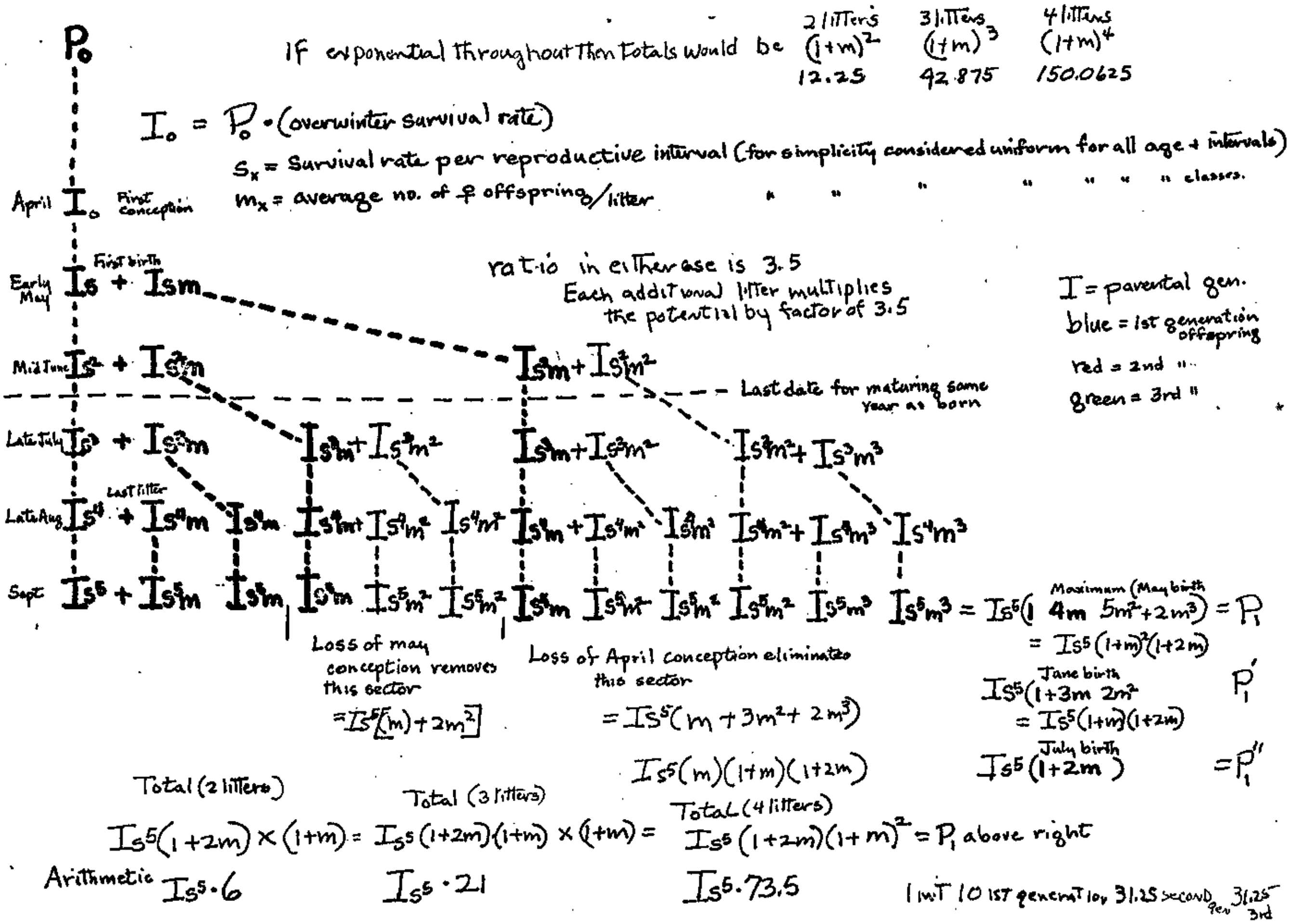
Small samples hampered our efforts to learn more about the reproductive biology of Clethrionomys gapperi and Peromyscus maniculatus. Male C. gapperi (red-backed voles) were delayed in their reproductive development by about the same amount of time as M. longicaudus (Figure 6, Table 9). Although the samples are small, the differences between mean testis weight on comparable dates in the two years is significant. The rate and uniformity of development is almost the same as for M. longicaudus. Clethrionomys inhabit north aspects where the differences in snow duration are least obvious. Their response to 1973 conditions is, therefore, unexpected, and will have to be studied more thoroughly before further conclusions are drawn. Observations of female red-backed voles are limited, but indicate the same retardation.

The difference in testis development for deer mice are not as large as those for microtines, but they are displaced in the same directions. The data for female deer mice parallel the male trends. Sample sizes are small.

The data for all four cricetid species taken together indicates that increased duration of snow and/or depth of snow negatively influences their reproductive activities, particularly time of development. We can extend this to chipmunks and perhaps all small mammals, e.g. snowshoe rabbits (Meslow-Keith 1971).

- Variations in the date of termination of the reproductive period

The decline in testis weight in chipmunks was later than in previous years, but nevertheless was accomplished by mid-July. The differences between mean weights in mid-June differ significantly between 1972 and 1973. The retention of male fertility would obviously be an adaptive response when successful impregnation of females is delayed as it seems to have been in 1973. Verification of the reality of this possibility or understanding its control is



Model for entirely exponential case is $P_{fall} = P_{spring} b^t = I_0(1+m)^t$

" " exponential before early July, linear (or arithmetic?) after is $P'_{fall} = P_{spring}(1+Km)(1+m)^{t-K}$

Effect of delay depends on value of K because $\frac{P'_{fall}}{P_{fall}} = \frac{(1+Km)(1+m)^{t-K}}{(1+m)^t} = \frac{(1+Km)}{(1+m)^K}$

If $K=2$, $m=2.5$ then $\frac{P'_{fall}}{P_{fall}} = \frac{1+5}{12.25} = .49$

If $K=3$, $m=2.5$ " " $= \frac{1+7.5}{42.875} = .20$

Further reduction stems from additional time and attendant mortality before first litter

	2 litters	3 litters	4 litters
If exponential throughout then totals would be	$(1+m)^2$	$(1+m)^3$	$(1+m)^4$
If $m = 2.5$	12.25	42.875	150.0625
If part arithmetic (linear)	$(1+2m)$	$(1+m)(1+2m)$	$(1+m)^2(1+2m)$
	6	21	73.5

Ratios 2 litter/3 litter, 3 litter/4 litter is in either case $3.5 = (1+m)$

Figure 9. Crude model of reproductive potential in relation to varying lenth of season.

probably beyond our capacity in the present study.

Involution of the testes of adult long-tailed voles begins consistently in late August and is accomplished by late September. There are no significant differences between years in respect to this characteristic. The relative flexibility shown with respect to spring conditions contrasts with the apparent invariability of response at the end of the season. In general, their reproductive cycle neatly coincides with the observed pattern of herbaceous phenology. The plants did not grow appreciably in response to either the warm fall temperatures of 1973 or the abundant moisture and moderate temperatures in fall, 1972. In view of the erratic nature of fall weather and the absence of reliable indicators of future conditions in that period, the responses of both voles and plants seem well adapted. They are probably conditioned by the long-term average climatic trends. Indications from the course of development in juvenile voles indicates that they are responding to some cue present in mid-summer. The testes of young voles (defined as less than 20gm body weight) are larger in early summer, June and July, and smaller in August as illustrated in Table 15. I regard this as an indication of the shift in pattern of development (Brown 1973) mentioned above. The stimulus involved in the response of the juveniles may be the same one conditioning the regression of development in adults. A lag in its effect in already mature individuals would be a reasonable expectation. This would account for the difference of about one month in the decline of condition in previously mature animals compared to those recently weaned.

Deer mice continued breeding nearly a month later in 1973 than in previous years. Although the numbers are small, the differences between August testis weights are significant.

	1972	1973	
n (adults)	3	3	
mean testis weight	10.7	142.7	$t_{2d.f.} = 10.36$ P . .01

Two female deer mice caught in August 1973 were pregnant and two caught in September appeared recently parturient. If we accept the hypothesis that the reproductive season was in fact prolonged, then we can ask whether this prolongation was related to the severity of the winter or to other factors. One step in answering this question would be to determine what factors prevailing at the time of prolongation (August) might account for it. Conditions that seem significant to me include the following. A reduced population of deer mice might have relaxed density dependent factors. Spring moisture associated with the severe winter may have resulted in increased density of foods and/or other requirements. One indication of such a possibility is that "Mormon crickets" Anabrus (Tettigoniidae) were exceptionally abundant in late September. I estimated the density of breeding adults in Big Bear Park at more than one per square meter. Their abundance could, of course, be a reflection of the reduced density of *Peromyscus*. Many insect populations respond positively to moist conditions following dry years; cutworm outbreaks occur at such times, for example. Grass and forb seeds and many fruits were abundant also. There have been several reports of anomalously late breeding in deer mice in situations where food was artificially abundant. Until we can assess the importance of or rule out these conditions, it will be unprofitable to seek connections to temporally more distant conditions.

Red-backed voles also appear to have maintained testis weight later into the year than in 1972. In this case, it may be only a false comparison of adults and juveniles. The three males in the August 1972 sample were young of the year ranging from 15.7 to 16.1gm body weight. In 1973, two of the three voles in the sample weighed 17.8 and 20.5gm. Red-backed voles, like *M. longicaudus* and *P. maniculatus* exhibit a delay in attainment of maturity.

In Figure 10, I have superimposed the plots of weekly mean temperature at ground surface on the curves of testis weight. Our small sample of three years includes a remarkable diversity of conditions and has a high probability, in my estimation, of encompassing the major part of the total range of conditions to be expected in the long term. Temperature here is representing several correlated variables, i.e. meteorological variables, photoperiod, primary production, etc. What we see is a remarkable correspondence between mammalian reproductive patterns and the yearly temperature curve. This is not surprising; the animals are reproducing at the time of year when the capacity to sustain the requirements of reproduction exists. It is the period of the year in which the significant portion of primary production takes place; the time when high quality foods are available in quantity, and the time when physical conditions are least stressful. The specific adaptations by which small mammals achieve an accommodation to the variable conditions of early spring have been the subject of much of our attention. In future months, I plan to study the relationships between long-term average climatic conditions and the timing of reproductive activity. It seems to me that the putative photoperiod response, shown so strikingly by the 1973 samples of *M. longicaudus* and *C. gapperi* may be a suitable measure of the adaptation of the population which we can use to compare the "set points" of local populations at selected localities. For example, trapping north aspect samples at 3500 m and 3800 m would establish whether the set points at these elevations were moved back in agreement with the seasonal lag expected. Using these comparisons, we might be able to estimate, acceptably, both the physiological range of tolerance to variability in length of season and the existing limits of genetic adaptation underlying the physiological. Such information would be desirable in predicting changes to be expected from modification of the weather.

Figure 10 illustrates also that we can estimate reasonably closely the current adaptive range of the "3200 meter" populations of several small mammals. It shows us that the populations are currently "adjusted" for a right-hand limit of about 1 June for beginning reproduction. A change in local climate that will increase the frequency of years lying right of that point will require genetic changes in the populations. Smaller shifts can be accommodated by the existing range of physiological mechanisms. (Although genetic change might refine the fit within that range.)

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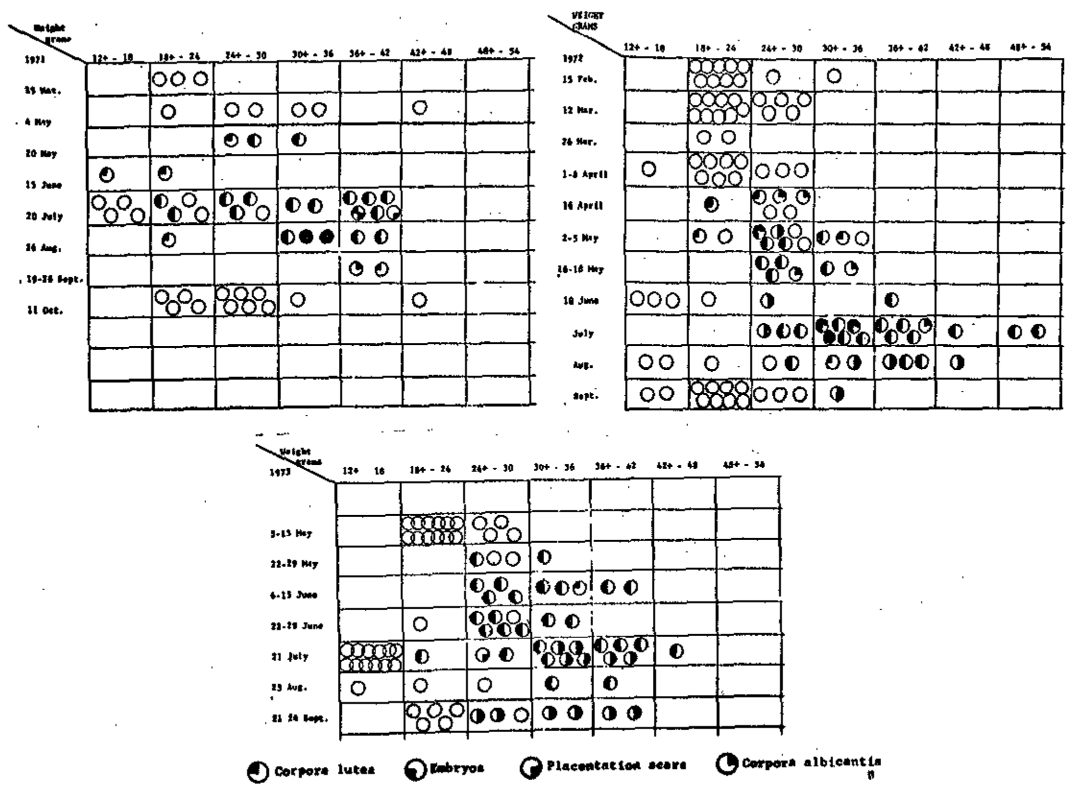

Figure 8. Number of female Microtus longicaudus with corpora lutea, embryos, corpora albicantia, or placentation scars by weight and date.

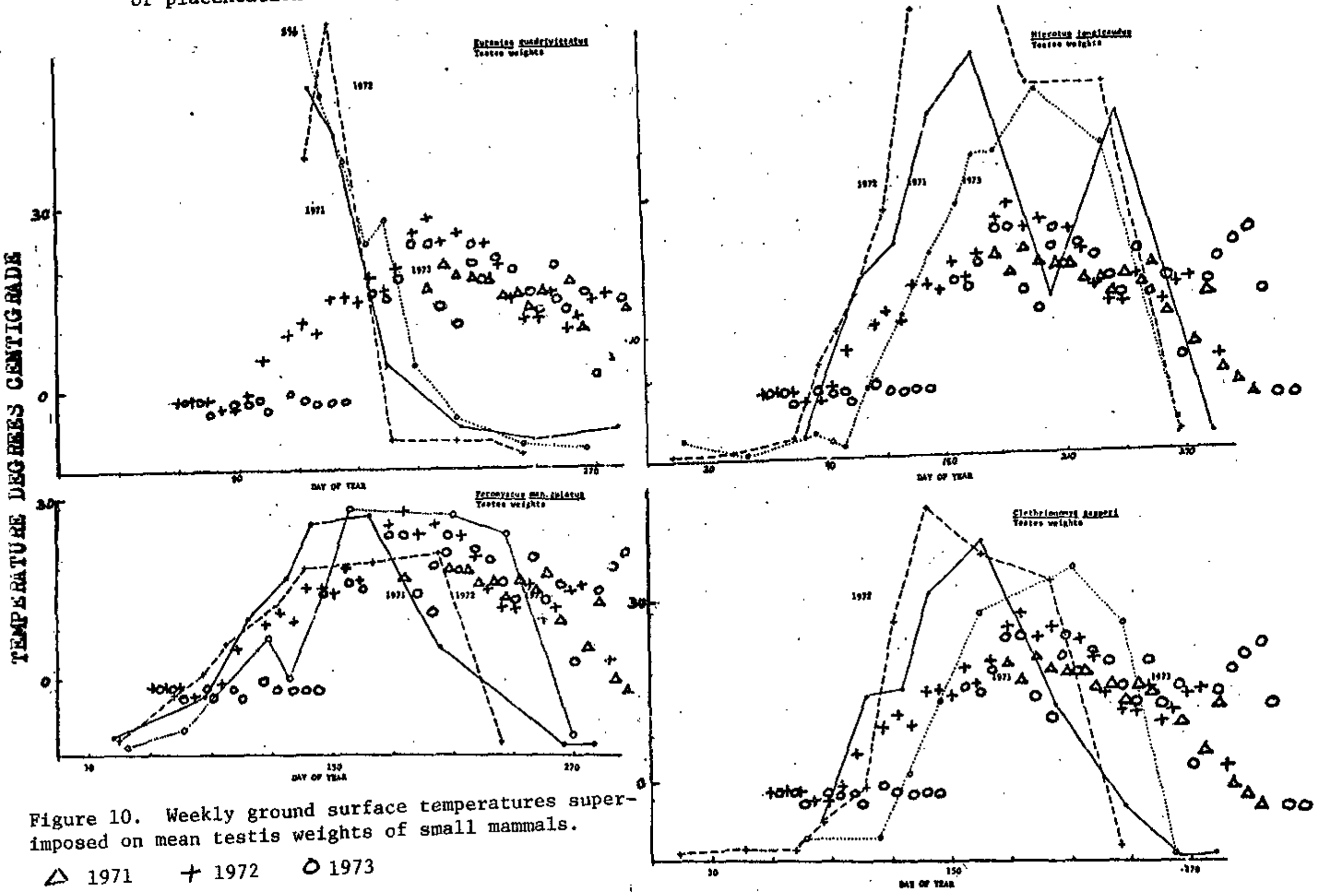

Figure 10. Weekly ground surface temperatures superimposed on mean testis weights of small mammals.

△ 1971 + 1972 O 1973

4.7.7 Job 6. Pocket Gopher Populations
(Harold Steinhoff)

- Objective

To determine relationships of snow depth and persistence to pocket gopher (*Thomomys talpoides*) populations.

- Procedures

The pocket gopher census transects described in the first Interim Report, following the method of Reid *et al.* (1966), were counted again in 1973. In addition, the length of earth cores deposited in snow tunnels in winter were counted in the springs of 1972 and 1973 on the same plots.

- Findings

Table 16 shows results. The locations are arranged in order of the mean year-day of snow disappearance in 1971, 1972, and 1973. No significant pattern is evident of pocket gopher populations in relation to snow persistence. Both the highest (Little Bear North) and lowest (Elk Spur) populations occur in areas where the snow melts neither earliest nor latest. The mean population of all three areas has remained remarkably constant for the three years, although the mean dates of snow disappearance varied as much as 57 days during 1971 to 1973.

Pocket gopher populations as estimated by live trapping were slightly lower than those estimated by mound counts, as shown by a comparison of Tables 16 and 17. However, the relative sizes of the populations among the six areas are the same by either method. A conversion factor of 9.4 instead of 8.2 mounds per pocket gopher per 48 hours would reconcile the two population measurement method. Lengths of winter casts in 1972, as a population index (Table 18), showed the same relative abundance among the six areas as did mound counts and live trapping. However, after a winter of deep snow in 1973, even when adjusted for days of snow cover, seems related to deeper snow that year. Probably this was not because of a higher population in 1973 because neither of the other indices indicate a change in population. Instead, it may be related to increased activity and the need to dig new tunnels in search of food as spring approaches and the winter food supply is exhausted. Then the later-lying snow in a deep snow year would result in a greater length of winter costs per snow cover day, even without a change in population. Thus, the impact of gophers on the grassland in bringing subsoil to the surface and spreading it over a sizable area would be greater in a deep snow year.

- Future Plans

Early spring and late fall censuses will be made as in 1973. Intensive live-trapping in the summer of 1974 will aid in validating the population conversion factor of Reid *et al.* (1966) which has been used to date.

4.7.8 Summary of Small Mammal Studies

Deer mouse populations decreased markedly and chipmunk populations declined significantly in 1973 after a winter of deep snows. Thus the pattern of an inverse relationship between some small mammal populations and snow depth has continued. Whether or not the deeper snow causes the population decrease remains to be seen. At least an additional year of study is needed to either substantiate or refute this hypothesis. The montane and red-backed vole populations failed to follow this pattern.

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Table 16. Pocket gopher populations in relation to snowpack, as estimated from mound counts.

Location	Mean Year-Day Snow Disappeared	Estimated Number of Pocket Gophers Per Hectare 1971	1972	1973	Mean
Top Park	157	28	45	50	41
Little Bear North	147	102	51	74	76
Big Bear Ridge	140	50	--	22	36
Elk Spur	131	30	41	28	33
Big Bear Base	128	59	--	60	60
Little Bear South	116	63	52	50	55
Mean		55	47	47	
Mean Year-Day of Snow Disappearance		129	112	169	

Table 18. Pocket gophers winter cast lengths in 1973 as compared to 1972.

Location	1972 Length of Casts M./0.1ha	M./0.1ha	1973 Length of Casts M/0.1ha	M./0.1ha
Top Park	112	0.61	637	2.64
Little Bear North	471	2.59	894	3.96
Big Bear Ridge	149	0.85	763	3.49
Elk Spur	64	0.43	349	1.60
Big Bear Base	214	1.23	719	3.16
Little Bear South	159	1.08	515	2.35
Mean		1.13		2.87

Table 17. Pocket gopher live-trapping summary, 1973.

Transect	1973 Dates Trapped	Estimated Population Live Total	Per Hectare	Maximum Recapture Distance Meters	Adult	Subadult 95g.	Male	Female
Little Bear North - A	7-24 to 28	19	63	2	0.95	0.05	0.22	0.78
Little Bear North - B	8-20 to 21	12	40	3	0.78	0.22	0.56	0.44
Elk Spur - A	8-18 to 19	6	20	15	0.50	0.50	0.33	0.57
Elk Spur - B	8-19 to 20	7	23	2	0.33	0.67	0.33	0.67
Big Bear Base - A	7- 9 to 14	12	40	10	0.90	0.10	--	--
Big Bear Base - A	8-24 to 25	12	40	10	0.88	0.12	0.33	0.67
Big Bear Base - B	8-23 to 24	15	50	--	0.73	0.27	0.80	0.20
Little Bear South - A	7-24 to 28	17	57	3.5	0.71	0.29	0.60	0.40
Little Bear South - B	8-21 to 22	11	37	5	0.70	0.30	0.80	0.20
Mean		12.3	41		0.74	0.26	0.51	0.49

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5. THE EFFECTS OF WEATHER MODIFICATION ON THE ALPINE ECOSYSTEM

5.1. INTRODUCTION (Jack D. Ives)

During the past year, the Institute of Arctic and Alpine Research (INSTAAR) has continued research aimed at determining the probable effects of an increase in mean snowfall in the San Juan Mountains. The study is centered on the processes acting on the alpine vegetation and geomorphology, considered in both the short and long term. The systems being studied and the reasons for their choice have been presented in earlier San Juan Ecology Project Interim Progress Reports.

Small-scale geomorphic process studies (Section 5.2) are being conducted to define the mechanisms by which snow influences erosion and to assess the significance of this snow-induced effect relative to other causes of alpine erosion. This work has now been expanded to emphasize areas of natural snow accumulation, which earlier work suggested would feel the greatest impact of any increase in snowfall. The broader geomorphic enquiry reported here in Section 5.7 is part of the Ecological Overview project. It is particularly concerned with the recent geologic history of the San Juan region and seeks to define the effects of natural periods of climatic stress.

The effects of snow on the vegetation have also been studied on different local and regional scales. Data on the relationship of snow to the dynamics of tundra plant communities have been collected from situations with experimentally produced snowdrifts and along natural snow gradients (Sections 5.3 and 5.4). Plant productivity, litter decomposition, phenology, and phytosociological relationships are all being monitored in these studies. On a regional scale, the areal distribution of vegetation cover types has been mapped in the target area of snowfall augmentation in the San Juan Mountains (Section 5.6). Dendrochronologic work has also continued in the past year with a view to defining climatic influences on vegetation over a longer period than that available for direct study (Section 5.5).

As in previous years, the detailed studies of environmental processes have been concentrated in the Williams Williams Lakes and Eldorado Lake basins. These study areas have been described in detail in previous Interim Progress Reports. In both basins, permanent camps were maintained as bases of operations during the summer of 1973 and weather records kept during the field season.

The end of the period covered by this report marks a change in INSTAAR's program of work in the San Juan Ecology Project. Rather than extending previous field observations for a further year, the 1974-1975 year will be used to fill gaps in our present knowledge of the alpine system of the San Juan Mountains. To this end, four lines of approach will be pursued. First, we need to know more about the accumulation and melting of alpine snow and this problem will be approached by both empirical observation and theoretical modeling (an initial approach to this problem is given here as Section 5.8). Second is the need to experiment further with the plasticity of tundra species and with the influence of changing snow conditions on the viability of their seeds. In two other areas, we plan to extend the work of integration and modeling. In terms of soil erosion, we need to make compatible the results of small-scale process studies and the broad-scale overview project. The final need is to modify available mathematical models of tundra vegetation to the San Juan situation and to use them in predicting the effects of changes in snowfall on plant productivity.

In view of these plans, this report sees the completion of almost all of the Overview Projects and the Dendrochronology Project. It also comes at a time when our operations in the Williams Lakes basin are to be terminated and any detailed field observations concentrated in the more accessible alpine environments of the Eldorado Lake basin and Niwot Ridge for the summer of 1974.

As in previous Interim Progress Reports, the arrangement of this one begins with detailed tundra process studies and moves from these to the broad-scale considerations of the Overview Projects.

Since the current report covers the period of the final full season of fieldwork, and preparations for the final report are already underway, some aspects of our endeavors have been only covered in outline. In addition several masters and doctoral dissertations based on work in the San Juan Mountains are in the final phases of preparation. I, therefore, feel it is appropriate to incorporate these and other related materials in the final report.

5.2. THE INFLUENCE OF SNOW AND INCREASED SNOWFALL ON CONTEMPORARY GEOMORPHIC PROCESSES IN ALPINE AREAS (Nel Caine)

5.2.1. Introduction

This project seeks to evaluate the physical processes of erosion and sedimentation in the San Juan alpine environment and to estimate the potential for changing either them or their magnitude by manipulating the winter snowpack. Initially, it was suggested that the testing of two hypotheses might achieve this: the first involves the comparison of seasonal erosion rates and the second the modelling of the influence of the snowpack on erosional mechanisms (Caine 1971, p. 243).

Earlier reports have concentrated on the description of two alpine study areas in the San Juan Mountains and preliminary studies of the second approach (Caine 1971) and on an exhaustive examination of the first hypothesis (Caine 1973). Since the seasonal contrast between winter and summer erosion has been clearly demonstrated already, little attention is paid to it in this report. Instead, this paper is concerned primarily with the second hypothesis and with the modelling of the erosional effects of snow. Three separate objectives can be identified:

1. The identification of the influence of the winter snowpack on erosional processes of a quasi-continuous nature;
2. The definition of the magnitude and frequency of episodic events and a similar evaluation of the effect of the snowpack on them;
3. The application of the results of these to predict the effects of an increase in the snowpack due to winter orographic snowpack augmentation (WOSA).

The distinction between the first two of these objectives is necessitated by the difference in approach which the study of frequent and infrequent events requires. The first is amenable to empirical modelling from small plot studies, while the second depends on a more qualitative approach derived from a wider spatial context. Obviously, the last objective depends on the successful attainment of the first two and on an estimate of likely increases in the alpine snowpack due to WOSA.

Within the San Juan Range, the field area used in this study varied with the first two objectives. The study of quasi-continuous processes has been made in the alpine drainages of the Williams Lakes (37° 37' N; 107° 9' W) and Eldorado Lake (37° 42' N; 107° 32' W). These two study areas of about 1 km^2 each have been described previously (Caine 1971) and encompass the variety of lithologic types found in the San Juan alpine environment.

The second objective requires sampling across a wider area to ensure that sufficient occurrences and a wide variety of geological and topographic controls are included. The Silverton - Ouray - Telluride area forms the main base of the study but work has also been conducted in the Williams Lakes and Eldorado Lake basins and in some other parts of the range.

5.2.2. Quasi-continuous processes

For present purposes, quasi-continuous processes of soil movement are defined as those which occur on a small (millimetric)scale. Effectively, these are the processes of soil erosion and waste transport by rain-splash, overland flow, soil creep and solifluction on hillslopes and by below-bank flows in stream channels. Theoretically, each movement should involve no more than one or two soil particles but most observations effectively produce the average rate of many particles. This smooths an episodic, particulate movement through time to make it apparently continuous, or at least not widely variable over the period of a year or two.

Because the movement appears continuous in time it is easily observed and measured. The resulting data are usually of relatively good quality and suited to statistical testing but this convenience should not be allowed to mask the fact that they may refer to only a small part of the geomorphic activity of an alpine area. Early results from this project suggest that episodic events may be more significant in total (Caine 1971; 1973).

5.2.2.1. Hypothesis 1

Hypothesis 1 defines two disjoint erosion sets, only one of which ('winter erosion') is directly influenced by snow on the ground or its melt water. The magnitude of this set is then compared to 'summer erosion' which is not influenced by the snowpack, or by an increase in it, to give a simple test of the relative impact of snow on erosion rates. The hypothesis is stated as:

$$H_1: \quad E_W < E_S \qquad (1)$$

to suggest that the winter period is not one of great erosional activity. The corollary of this is that an increase in the snowpack is unlikely to give, or to have given, a large increase in erosion, at least directly. H_1 was tested statistically by two years of data from the San Juan Mountains and proved acceptable with a high level of confidence on both a local scale (2 m^2) and a mesoscale (1 km^2) (Caine 1973). This was especially true of the most actively eroding parts of the alpine landscape. The additional data collected over the past year verifies this conclusion and need not be considered here.

An extension of Hypothesis 1 to take account of inter-annual variations in snow accumulation is worth noting. It is probably only useful when widely different years of accumulation are available but the 1971-1973 period in the San Juan Mountains seems to meet this requirement. Snow accumulation in the 1971-72 winter was generally about 20% below normal in the range while that in 1972-73 was about 45% above normal. The extension of Equation (1) may be stated as:

$$H_{1a}: \quad E_H < E_N < E_L \qquad (2)$$

where E refers to the annual erosion rate (previously a seasonal rate) and the subscripts refer to years of above normal (H), about normal (N) and below normal (l) snow accumulation. Years of high snowpack should show an extended period of low 'winter' erosion and so a low annual total while years of low snow accumulation have a longer period of 'summer' erosion and a high annual total.

The record of surficial erosion on 52 plots during the 1971-1973 period are available for testing Equation (2). Thirty-eight of the 52 cases confirm the hypothesis, which is a higher proportion than would be expected from random variation around a general equality ($p = 0.01$ on sign test). The mean of the ratios of 1971-72 to 1972-73 is 3.43 with a standard error of 0.7; the expected value of 1.0 for no difference lies beyond the 99% confidence interval around the mean. There seems to be clear corroboration of the earlier analysis of seasonal effects - the protective influence of a long lasting snowpack on the soil under it is indicated.

5.2.2.2. Hypothesis 2

Hypothesis 1 involves only the response part of a process-response model (Caine 1971a) and infers from it a single controlling boundary condition: the snow cover. This is an oversimplification which the second approach seeks to overcome by including other effects, though at the price of complexity in empirical testing. At the same time, since it requires an understanding of the relations between the snowpack and erosional responses, the second approach is more likely to lead to useful predictions of the impact of WOSA. Because of the need for prediction, it is given most weight here.

Procedures: In simple functional terms the model to be evaluated can be stated as:

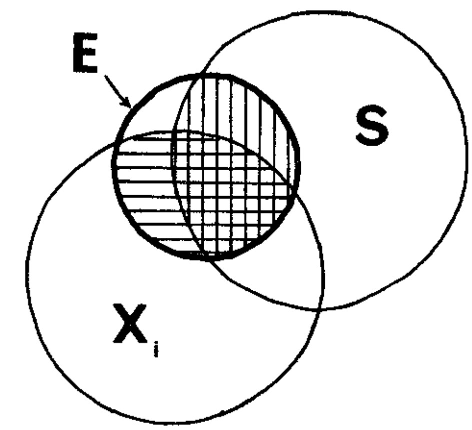
$$E = f(S, X_1, X_2, \ldots, X_n) \qquad (3)$$

where E is the erosion or sedimentation rate, S is one or more snowpack descriptors, and the X_i are the other environmental boundary conditions that are capable of affecting erosion. Ideally, Equation (3) should be in the form:

$$E = f(S), X_1, X_2, \ldots, X_n \qquad (3a)$$

where the effects of the X_i are held constant or otherwise controlled. Such control is not, however, likely to be achieved simply in the study of a natural system since the S and X_i terms will not be mutually independent and may interact in complex fashion. This interaction can be illustrated by a simple Venn diagram (Figure 1) and should be kept in mind in any empirical evaluation of Equation (3).

Five parts of Figure 1 are worth comment. (1) The area $[E \cap S, \tilde{X}_i]$ reflects the interaction of snow and erosion which works independently of other environmental influences. However, if the X_i are defined as observed characteristics (i.e. those of Table 1 in this study), this area may also include effects due to unobserved variables interacting with the snowpack. (2) The equivalent area $[E \cap X_i, \tilde{S}]$ represents the interaction of erosion and the environment independently of the snowpack and is not of immediate concern here. (The 'summer erosion' term used previously is an attempt to estimate the significance of this area.) (3) $[S \cap X_i, \tilde{E}]$ is also not important here since it does not influence Equation (3) directly. The indirect effects which it may represent could be important, however, in the long term. (4) The central area $[E \cap S \cap X_i]$ represents



EROSION CONTROLS

Figure 1. Interactions among erosion controls.
E - the set of erosion responses.
S - the set of snowpack boundary conditions.
X_i - the set of other boundary conditions.
The area of $[E \cap X_i, \tilde{S}]$ is horizontally hatched.
The area of $[E \cap S, \tilde{X}_i]$ is vertically hatched.
The area of $[E \cap S \cap X_i]$ is cross hatched.

the interactions between the snowpack, other plot boundary conditions and soil erosion and is most important in this study. It is the interactions which this area represents that complicate the empirical evaluation of Equation (3). (5) The disjoint area $[E, \tilde{S}, \tilde{X}_i]$ includes the effects of unobserved boundary conditions (either S or X_i) on E as well as the other errors of sampling and measurement that are often assumed random and used as a within-sample variance estimate in testing. Any study attempts to minimize this area but it probably always remains finite.

In the absence of adequate theoretical models of alpine soil erosion, the most efficient evaluation of Equation (3) is made by empirical regression but this should remain subject to constraints of physical reasonableness. In the regression approach used here, E (observed as a number of responses on different plots) is treated as the set of dependent variables whose relationship to S (also a number of variables) is sought. The variables of E and S are identified, with the X_i, in Table 1.

Within the general least squares approach, the four alternatives of Table 2 allow different evaluations of the S - E relationship. They provide for different treatments of the collinear effects due to the interaction of the snowpack and other boundary conditions with erosional responses (area $[E \cap S \cap X_i]$ in Figure 1). In this report, most emphasis will be placed on the simple bivariate model although multivariate approaches have been used in preliminary analysis. The latter allow evaluation of the entire system under consideration and of the relative significance of snow in it. Simple bivariate regression tends to inflate the snowpack effect by including all interactive influences (even those not observed in the X_i) which involve S as due to the snowpack term, whether forced by the snow cover or not. The direction of this error, there-

Table 1. Plot observations

Variable	Identification	Procedure	Units
Soil Texture			
X_1	Graphic Mean Particle Size	Field Measurement, Sieve, Pipette	ϕ (Folk 1961)
X_2	Incl. Graphic Sorting	(As X_1)	ϕ
X_3	Size 16%-ile finer	(As X_1)	ϕ
X_4	Frost Index	Heave Susceptibility of Beskow (1935)	% Wt.
Soil Shearing Resistance			
X_5	Cone Penetrometer Resistance	Mean of 10 Readings	Kg cm $^{-2}$
X_6	Pocket Penetrometer Resistance	(As X_5)	Kg cm $^{-2}$
X_7	Vane Shear Resistance	(As X_5)	Kg cm $^{-2}$
X_8	Internal Friction	Remolded Direct Shear	Degrees
X_9	Cohesion	(As X_8)	TSF
X_{10}	Dry Sliding Angle	Failure in Tilting Box	Degrees
X_{11}	Stability Index	X_{21} - X_{10} Difference	Degrees
Soil Index Properties			
X_{12}	Liquid Limit	ASTM D423-61T	% Wt.
X_{13}	Plasticity Index	ASTM D424-59	% Wt.
X_{14}	Activity Coefficient	Ratio X_{13}/Clay %	Proportion
Vegetation Properties			
X_{15}	Vegetation Cover	2 x 1 m^2 Quadrat Estimates	% Area
X_{16}	Soil Organic Content	Ignition at 550°C	% Wt.
X_{17}	Soil pH	1:10 Slurry	Count
Soil Moisture Characteristics			
X_{18}	Specific Retention	Water Retained Against Gravity	% Wt.
X_{19}	Hygroscopic Moisture	Loss at 105°C, 15 hr.	% Wt.
Topographic Characteristics			
X_{20}	Slope Angle	Mean of 3 Observations	Degrees
X_{21}	Surface Roughness	σ of 3 Slope Angles	Degrees
X_{22}	Distance from hillcrest		Meters
Snow Characteristics			
S_1	Meltdate 1971	Days after March 31	Count
S_2	Meltdate 1972	(As S_1)	Count
S_3	Snow Depth	Probe, at March 1972	cm
Erosion Responses			
E_1	Surficial Movement	Surface Tracer (1 cm ϕ)	cm yr $^{-1}$
E_2	Mass Wasting	Tilt Bars	cm^2 yr $^{-1}$
E_3	Bedrock Weathering	Weight Loss, Andesite	% yr $^{-1}$

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Table 2. Alternative procedures in regression.

Model	Reference to Figure 1	Estimate of f(S)	Comment
1. Simple Bivariate			
$E = a + bS$	$E \cap S$	Maximum	Simple evaluation & predictions; collinear effects included with S.
2. Two-Stage Bivariate			
(a) $E' = a_1 + b_i X_i$	$E \cap S, \tilde{X}_i$	Minimum (?)	Good, if X_i effects are well represented; collinear effects excluded from S.
(b) $(E-E) = a_2 + b_{n+1} S$			
3. Multiple Stepwise Regression			
$E = a + b_i X_i + b_{n+1} S$ (for i=1 to i=n)	$(E \cap S) \cup (E \cap X_n)$	Intermediate	Statistical division of $E \cap S \cap X_n$; predictive use simple; evaluation difficult.
4. Multiple Regression on Component or Factor Scores			
$E = a + b_i Z_i$ (Z_i = surrogate variables)	$(E \cap S) \cup (E \cap X_n)$	Intermediate	Statistical division of $E \cap S \cap X_i$; model evaluation simple but interpretation and prediction difficult.

fore, is known and even the overestimation due to it may be estimated. In impact assessment, this approach gives a safety margin and so its use may be justified in a "consumer's risk" sense (Pittock 1972) even if predictions derived from the regressions are not precise. A simple model is, in any case, most easily evaluated for its physical implications and so the danger of unrealistic predictions from it reduced.

Multivariate models: The 25 independent variables (X_i and S_i) of Table 1 have been measured on 96 2-m^2 plots in the Williams Lakes and Eldorado Lake basins. R-mode and Q-mode analyseses have been performed on the independent variable matrix and on the sub-matrices for each basin separately. The latter separation should allow evaluation of the effect of a change in lithology (volcanics vs quartzite and slates) and elevation (300m).

R-mode analysis: Analysis of the interrelations between the independent variables is especially useful here in indicating other environmental factors that are interactive with the winter snowpack (the area $[S \cap X_1]$ in Figure 1). It also allows definition of the most representative snowpack variable, and the one which minimizes other interactions, for use in bivariate analysis.

For all 96 plots from the two study basins, the results of a correlation clustering are shown diagrammatically in Figure 2. This shows a set of four clusters which include 17 of the 22 variables used (the three penetrometer variables were omitted because they were not available on 10 coarse talus plots). The clusters appear to be distinct and are easily interpreted in physical terms; they seem to represent factors of soil texture (Cluster 1), soil moisture (Cluster 2), snow conditions (Cluster 3) and topography (Cluster 4). Approximately the same clustering of variables emerges from analyses of the two basins separately, although some of the internal links are then defined at levels different to those shown in Figure 2.

In terms of this study, the isolation of the snowpack cluster is especially encouraging; no variable within it is linked to an external one at $/r/ > 0.4$. This suggests that the S X_i area in Figure 1 is relatively small and that collinearity problems should be few.

A factor analysis of the same data (Table 3) confirms the correlation structure of Figure 2. Five factors have associated eigenvalues of more than 1.0 and together account for just over 70% of the variance in the matrix. The clear identification of Factor II with the snowpack characteristics supports the suggestion of their relative independence from the other environmental conditions included in the analysis. Only three variables (other than those involving snow) load on this factor at >0.2 or <-0.2: the Liquid Limit (X_{12}), the vegetation cover (X_{15}) and the soil specific retention (X_{18}). All have negative loadings which suggests a weak inverse correlation between the snowpack and vegetative/soil moisture effects.

It is now possible to identify "best" variables (i.e. those most representative of a cluster or factor) for use in further analysis. Their use in prediction and validation is simpler than that of factor or component scores. The highest intercorrelations in the clusters of Figure 2 and the rank of the factor loadings are sufficient to identify three of four best variables. In the final case, the snowpack cluster, this procedure proves indeterminate; both of the melt date terms are defined and a further criterion for distinguishing between them is required. This has been done on the basis of the lowest summed correlations with the three variables which load on Factor II at <-0.2 (Table 4), i.e. an estimate of least collinearity with those

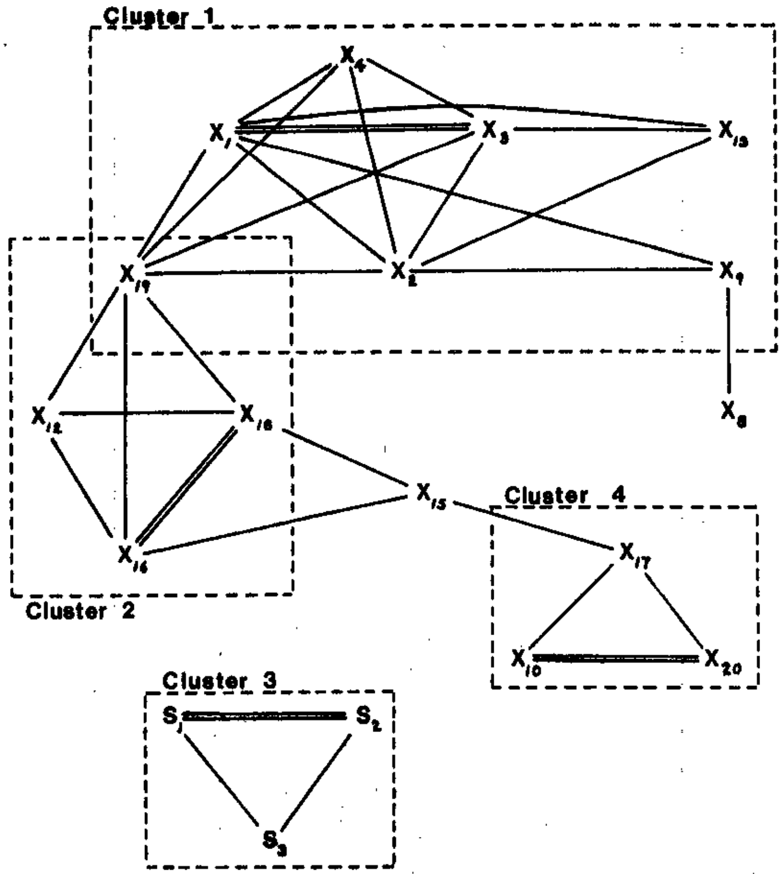

Figure 2. Correlation structure - Williams Lakes and Eldorado Lake basins (N = 96).

Cluster 1 is of soil textural and strength characteristics and includes only links defined by values of $/r/ > 0.75$.

Cluster 2 includes soil moisture variables linked by values of $/r/ > 0.4$.

Cluster 3 includes only snowpack variables which are interlinked by $/r/ > 0.75$.

Cluster 4 is of topographic characteristics and is defined by $/r/ > 0.4$.

All correlations shown are significant with $p < 0.01$ and the highest correlation within each cluster is shown by a double line. Variables are defined in Table 1.

Table 3. Factor analysis: independent variables

Number of cases: 96

Number of Variables: 23

Factor	I	II	III	IV	V
Eigenvalue	7.23	3.54	2.92	1.92	1.61
Variance associated	28%	13.5%	11%	7.5%	6%
	X_3 (0.81)	S_1 (0.88)	X_{11} (0.91)	X_{16} (-0.87)	X_8 (0.72)
Variables & loadings	X_2 (0.78)	S_2 (0.88)	X_{20} (-0.89)	X_{12} (-0.86)	X_9 (0.58)
	X_4 (0.72)	S_3 (0.81)	X_{21} (-0.34)	X_{18} (-0.83)	X_{14} (0.55)
Factor Interpretation	Soil Texture	Snow	Gradient	Soil Moisture	Bulk Strength
'Best' Variable	X_3	S_1	X_{11}	X_{16}	X_8
Cluster (Fig. 2)	1	3	4	2	None,

Table 4. Variables collinear with the snowpack terms.

	S_1	S_2	S_3
X_{12}	-0.25*	-0.36**	-0.33**
X_{15}	-0.11	-0.18	-0.25*
X_{18}	-0.16	-0.28**	-0.31**
Sum	-0.52	-0.82	-0.89

Values are correlation coefficients. N = 96

* $p < 0.05$ ** $p < 0.01$ ($H_0: \rho = 0.0$)

variables. Melt date 1971 (S_1) is now defined as the best of the three snowpack terms for use in further analysis. It is significantly correlated with X_{12} only and has the added advantage of easy application to a snow redistribution model presented elsewhere (Caine 1974).

The correlation of S_1 and X_{12} can also be used as an estimate of the collinear effect, that is, of the error due to $E \cap S \cap X_1$. Assuming the influence to be directed as $X_{12} \rightarrow S_1$, i. e. that the soil liquid limit controls the snow melt date, the explanation of S_1 by X_{12} is only 6% (r^2). Even if X_{15} and X_{18} are included, the same assumption of control direction retained and a further one of independence between X_{12}, X_{15}, X_{18} made, the explanation would only reach 10% (the sum of three r^2 values). Thus, the errors introduced by use of a bivariate model for the direct snow effect are not likely to be great, especially since the relationship between S_1 and the X_1 probably reflects a control made in the opposite direction to that assumed here - a control _by_ the snowpack rather than _of_ it.

Q-mode analysis: Ninety-one of the 96 plots have been grouped on the basis of the independent variables of Table 1 by the algorithm used earlier (Caine 1973, Table 4). This identifies sets of similar plots to which the bivariate model can be applied separately. This procedure should have the effect of reducing the X_1 area in Figure 1, while retaining some of the X_1 influences implicitly as the basis of grouping. The results of the plot grouping are summarized on Table 5. Five plots have not been included either because they are too dissimilar to any other or because no soil movement record is yet available from them. Six of the 8 groups will be used in evaluation of the bivariate model (Groups E and H contain too few plots for meaningful analysis).

The differences between Table 5 in this report and that in Caine (1973) are due to the introduction of 30 additional plots in Groups A and B. This expansion was necessitated by the significance which earlier analysis placed on such unstable, active situations.

Multiple regression analysis: Although difficult to use in prediction, the multiple regression procedures of Table 2 (Numbers 3 and 4) are useful in evaluating

Table 5. Plot classification by similarity clusters.

Group	Number of Plots Williams	Eldorado	Identification
A	8	15	Unstable fine talus at steep angle.
B	14	10	Bare soil at low angle
C	4	3	Snow-free turf at low angle
D	3	13	Close turf cover, varied slope
E	2	0	Partly vegetated, _Geum_ covered talus
F	2	6	Turf upslope of snowdrifts
G	5	3	Stable, low angle talus
H	3	0	Steep willow scrub

the significance of the snowpack on erosion relative to other environmental variables. Only the surficial movement rate (E_1), which is most widely available and most precisely estimated, has been used as a dependent variable in this analysis.

When the data from both study areas are pooled in a stepwise regression procedure, the snowpack tends to be defined as of low importance. No snow-related variable enters the regression until the fourth step; instead a variable from each of the other clusters of Figure 2 is introduced before one from cluster 3. An analysis of the two areas separately shows the reason for this apparent unimportance (Table 6). Now the snowpack enters at the second or third step and adds more than 10% to the cumulative R^2. It has, however, opposite sign in the two basins: a direct influence in the Williams Lakes basin and an inverse one in the Eldorado Lake basin. The inconsistency is unsatisfying but not serious since the correlation between E_1 and S_1 is non-significant in both cases. In summary, the procedure does not identify the snowpack influence sufficiently clearly for predictive purposes, except to suggest that it is of relatively slight magnitude.

Regression model 4 (Table 2) offers an alternative approach, and one which avoids the problems due to changes in the estimates as a stepwise analysis advances. Table 7 shows the correlations of E_1 with the first six components in each of the study areas. Since the components are made orthogonal, a stepwise regression follows the ranking of simple correlation coefficients. In the Eldorado Lake basin, at least, this model gives a better explanation of the erosion term than regression on the original variables. In both cases, the snowpack is defined as of second importance in explaining E_1, following a topographic/shear strength factor, and has a direct effect on E_1.

The positive correlation between E_1 and the snowpack components in Table 7 appears inconsistent with the conclusions reached in testing Hypothesis 1 (above and Caine 1973). This is partly explained by basic differences in the two analyses. The regression analysis is based on a comparison of responses on many different plots with the assumption that these responses reflect

Table 6. Surficial erosion: stepwise multiple regression (Variables)

<u>Williams Lakes Basin</u> N = 20

R = 0.945 (5 steps)

$$E_1 = 0.245 + 4.734X_{20} + 0.006S_1 - 0.031X_{16} - 0.01X_{15}$$

(X_5 omitted with non-significant coefficient)

Step	Variable	Change in R^2	R^2
1	X_5	0.525	0.525
2	S_1	0.106	0.631
3	X_{16}	0.050	0.681
4	X_{20}	0.132	0.813
5	X_{15}	0.080	0.893

<u>Eldorado Lake Basin</u> N = 24

R = 0.671 (3 steps)

$$E_1 = 0.638 + 0.040X_5 - 0.007X_{22} - 0.016S_1$$

Step	Variable	Change in R^2	R^2
1	X_5	0.197	0.197
2	X_{22}	0.165	0.362
3	S_1	0.089	0.451

The stepwise procedure terminated in both cases when the increase in R^2 became less than 0.05.

erosional controls imposed over a long time period. Hypothesis 1, on the other hand, has been tested by comparing responses on the same plot over a short time scale. The first seems to define the effect of the snowpack on erosion which is made through the intermediary of the vegetation cover. This in turn influences the soil strength, moisture characteristics and erodibility and so, eventually, the erosion rate. The tests of Hypothesis 1 show that this erosion is performed under summer conditions and not by the winter snowpack directly.

Apart from indicating a relatively low significance of the snowpack influence, multivariate analysis also offers a scale against which the effectiveness of simpler models can be judged. With about 25% of the variance in E_1 explained by the snowpack in a regression on principal components (for the Eldorado Lake area, only), this may be taken as the limit of acceptability for other models. Thus, a simpler model applied to a small group of plots should give a better than 25% explanation to be useful. In fact, the explanation should be very much higher than this if the model is to be used in prediction with confidence.

<u>Bivariate models</u>: In view of the inconsistency in these results, two hypotheses for the relationship

Table 7. Surficial erosion: stepwise multiple regression (component scores).

<u>Williams Lakes Basin</u> N = 32

R = 0.538 (3 steps)

$$E_1 = 19.793 - 4.511C_I - 6.228C_{II} + 12.612C_{III}$$

Step	Component	Identification	Change in R	R^2
1	C_{III}	Gradient/Surface Strength	0.171	0.171
2	C_{II}	Snow/Vegetation	0.061	0.232
3	C_I	Soil Texture	0.058	0.290

(The influence of snow cover duration on E_1 is <u>positive</u>)

<u>Eldorado Lake Basin</u> N = 41

R = 0.863 (3 steps)

$$E_1 = 9.673 - 2.324C_I + 4.823C_{II} - 2.661C_{III}$$

Step	Component	Identification	Change in R^2	R^2
1	C_{II}	Gradient/Strength/Texture	0.422	0.422
2	C_I	Snow/Soil Moisture	0.249	0.671
3	C_{III}	Surface Strength/Index Properties	0.074	0.745

(The influence of snow cover duration on E_1 is <u>positive</u>)

The stepwise procedure terminated in both cases when the increase in R^2 became less than 0.05.

between erosional activity and the winter snowpack can be suggested. They are distinguished by the direction of the postulated influence (tested by the sign on r) and so can be defined in terms of a linear model as:

$$H_3: \quad E_1 = f(S_1) = a + bS_1 \qquad (4)$$
$$H_4: \quad E_1 = f(1/S_1) = a - bS_1 \qquad (5)$$

where a and b are empirically defined coefficients.

H_3 may be referred to as an erosional hypothesis since it suggests that soil erosion increases with the duration of the snowpack. In view of the tests of Hypothesis 1, this effect is presumable made indirectly through the vegetation and soil characteristics which reflect snow conditions. Direct effects are, however, possible through the downslope component of the snow-
through the vegetation and soil characteristics which
ture. Testing of Hypothesis 1 suggests that the indirect influences are the more important ones but the actual effects have not been examined in detail in

the field.

H_4 is the protective hypothesis which is apparently suggested by the seasonal and inter-annual comparison of erosion rates. Physically, it derives from either a true protection against rain and frost effects or, less likely, from reduced rates (not volumes) of water flux in 'winter situations' of long-lasting snow cover.

The same Null Hypothesis of no relationship between the E_i and S_i is the alternative to both H_3 and H_4. Acceptance of H_0 may, however, mean that the linear model is an inadequate one rather than that there is no relationship. In view of the conclusions drawn from work elsewhere (Caine 1971) and the possibility of both erosion and protective effects on the same site, this should be considered whenever H_0 is accepted.

In testing Equations (4) and (5), three estimates of E_i can be used (Table 1) although they vary in both quality and quantity. The most satisfactory test is that of E_1, the surficial erosion rate, which is most easily measured, least subject to error and available for the greatest number of plots. Observations of E_2 and E_3 are probably more prone to error and are available for fewer plots over a shorter time period. For all three erosion estimates two criteria will be used in testing. In hypothesis testing, the criterion of a non-zero population correlation coefficient is sufficient to define a physical relationship between S_1 and E_1. It does not, however, guarantee precision in predicting the effects of WOSA and so a more stringent criterion is added for that purpose. Empirical regressions will not be used predictively unless they offer more than 50% explanation of the observed variance in E_1 in addition to showing H_3 or H_4 as acceptable.

Surficial erosion (E_1): As in the earlier analysis of seasonal contrasts, surficial erosion is estimated by the rate of movement of tracer particles of 0.8 to 1.0 cm size on each study plot. Comparability between plots is, therefore, reasonably well assured but at the price of representativeness; material of the same caliber as the tracer will not make up the same proportion of the surficial debris found naturally on each plot. This is likely to give overestimates of movement rates for the natural sediment, especially where the plot material is fine enough to allow sliding and rolling of the tracer particles over the ground surface.

At least one year of record is available for 89 plots and gives a non-significant correlation between S_1 and E_1 (r=0.105) even with a log-transformation of E_1. (Without the log-transformation, the correlation is even weaker (r = 0.003) This is true of almost all the cases tested and so only the transformed values are used in this analysis). The analysis of each basin separately gives some improvement in the correlation (Table 8) but still requires the acceptance of H_0. The difference between the two basins is defined by a, the regression constant, rather than by the form of the relationship between S_1 and E_1 and suggests an annual erosion rate in the Williams Lakes basin three times that in the Eldorado Lake basin under similar snow conditions. This seems to be best explained by the lithologic and elevational differences between the two areas, or by some derivative of them, which have been suggested previously to explain similar contrasts (Caine 1973, p. 63).

Table 8. Surficial erosion: regression analysis

Data Set	N	r	Significance	a	b
All Plots	89	0.105	N. S.	1.938	0.005
Williams	40	0.229	N. S.	2.489	0.009
Eldorado	49	0.221	N. S.	0.779	0.009
Group A	20	0.185	N. S.	6.287	0.005
Group B	20	0.168	N. S.	4.201	0.006
Group C	7	0.812	0.05	0.657	0.014
Group D	16	-0.684	0.01	7.295	-0.029
Group F	8	0.559	N. S.	0.006	0.069
Group G	8	0.721	0.05	0.556	0.016

In all cases, the model used is:

$$E_1 = a.e^{b.S_1}$$

Significance is estimated from the test on the correlation coefficient; $H_0: \rho = 0.0$

When groups of similar plots are considered, other contrasts become evident, perhaps as a partial response to the inclusion of other environmental factors which this implies (Table 8). Only three groups (C,D and G) show a significant correlation getween S_1 and E_1, however, and the relationship is not the same in each of the three cases. Groups C (snow free turf at low angle) and G (stable blocky talus) show a direct effect while Group D (relatively similar to Group C except for steeper, more variable slope angle) has an inverse one. The contrast between Groups C and D seems to reflect the difference in average snow conditions and movement rates between the two field areas. This particularly influences the analysis of the Group D plots which occupy different parts of the range in S_1 according to the basin in which they are found (Figure 3). When the Eldorado Lake plots of Group D are treated separately, the correlation reduces to -0.046 (n = 13) and it is clear that the correlation for Group D in Table 8 should be ignored as reflecting only the between-basin contrast. There is more overlap in S_1 between the plots of the two basins in Groups C and G which reduces the between-basin influence and gives greater confidence in the results.

The acceptance of H_0 for the Group A and B plots is especially important since these represent the most actively eroding parts of the alpine environment. It is not produced by either a non-linear response or a change in effect from protection to erosion as S_1 increases, as hypothesised earlier (Caine 1971). While it could be due to a compounding of protective and erosive influence on each plot, this cannot be tested empirically and would be difficult to use predictively. It seems best to accept that there is no response in erosion rates to changes of snow cover

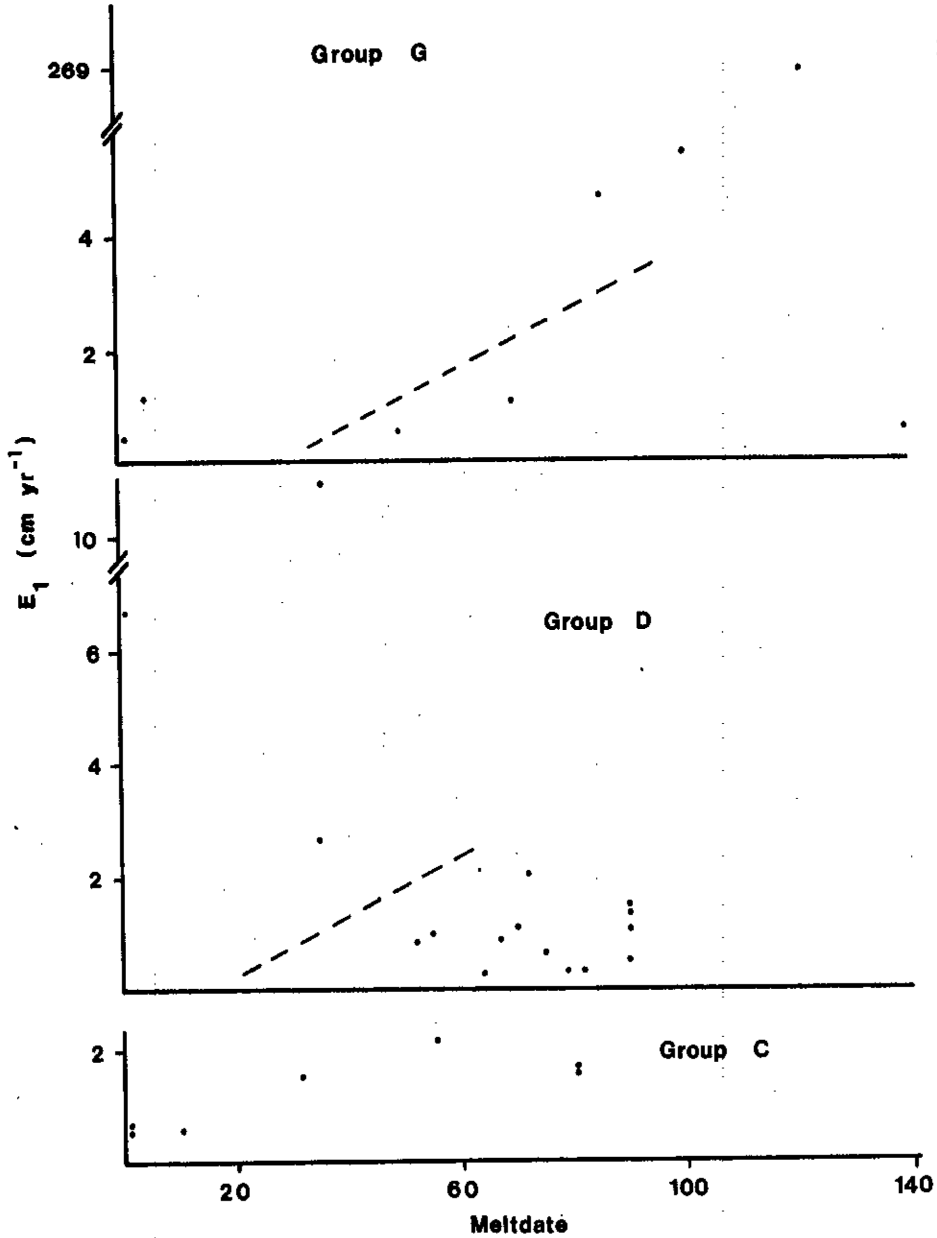

Figure 3. Surficial erosion and snowcover duration.

Snowcover duration is defined by the melt date of each plot in 1971 and is measured as the number of days after March 31. The broken line separates the observations in the Williams Lakes basin (to the left) from those in the Eldorado Lake Basin (to the right).

duration in these situations.

Mass wasting (E_2): Annual rates of mass transfer (below the ground surface) are estimated from the angular deflection of four rigid 'tilt bars' on each plot (Kirkby 1967; Caine 1971). These devices are especially susceptible to disturbance, though this is usually easily detected, so that the results are probably only imprecise estimates of movement in the upper 20 cm of the soil. Nor does the accuracy of the results encourage confidence in tilt bar observations; where tests have been made, they underestimate actual movement by as much as 80% (Kirkby 1967, p. 370). This underestimation should be approximately uniform on all plots and so may not greatly influence correlation analysis. It will, however, give problems in prediction. As with the surficial movement rates, the data have been log-transformed before analysis; this usually has the effect of increasing their correlation with the plot boundary conditions.

Table 9 summarizes the results of regression analysis on the tilt bar observations. Of the 9 cases examined, only that for the Group C plots gives a significant correlation and even this one should not be accepted uncritically because of the small number of plots on which it is based (n = 6). This is, however, one of the two plot groups for which a $S_1 - E_1$ relationship is defined and so the correlation here (with E_2) becomes more important. The results of both process set analyses combine to suggest that low angle, snow free meadow environments are especially responsive to changes in the snow cover duration. The two erosion responses are, of course unlikely to be independent and this is corroborated by a high, if unsignificant, correlation between E_1 and E_2 on the Group C plots ($r = 0.786$; $n = 6$).

Bedrock weathering (E_3): Estimates of ground surface weathering are based on the change in weight of known (approximately constant) volumes of andesite exposed at the surface. The rock has been crushed to a 4 - 8 mm size to increase the surface area exposed to weathering and so amplify changes. Nevertheless, since the experiment was not started at the inception of the project, data are only available for one year of observation and so changes have been slight. The experiment is to be continued.

Table 9. Mass wasting: regression analysis.

Data Set	N	r	Significance	a	b
All Plots	58	-0.107	N. S.	2.253	-0.003
Williams	23	-0.200	N. S.	2.675	-0.008
Eldorado	35	-0.068	N. S.	2.132	-0.002
Group A	12	-0.364	N. S.	9.480	-0.006
Group B	11	0.569	N. S.	0.044	0.035
Group C	6	0.935	0.01	0.171	0.035
Group D	15	-0.128	N. S.	1.923	-0.004
Group F	8	-0.650	N. S.	30.465	-0.045
Group G	4	-0.782	N. S.	2.253	-0.014

In all cases, the model used is:

$$E_2 = a.e^{b.S_1}$$

Significance is estimated from the test on the correlation coefficient;

$$H_o: \rho = 0.0$$

The results of regression analysis are summarized in Table 10 and clearly substantiate an erosional hypothesis for the effect of the snowpack, In all of the cases examined, the correlation between S_1 and E_3 is negative. This is presumably explained by the control of solute removal effected by the water flux across the ground surface. In alpine situations, local variations in water flux will largely reflect the volume of snow accumulated on a site, or immediately upslope of it, hence the influence of snow cover duration.

The positive value of the intercept (a) in all the linear regressions of Table 10 apparently poses a problem for explanation but is nowhere significantly different from 0.0. More important in the present context is the low explanation afforded by the regressions: only the plots of Groups A and C (and the A-B combination) give more than a 50% explanation, with a statistically significant correlation coefficient.

5.2.2.3. Quasi-continuous processes: summary.

Three points of general interest are evident from this analysis of the influence of the snowpack on slow-acting processes of slope development.

First, it appears that the snow cover is not of major importance as a direct control of erosional activity. Its influence is lower than that of topographic, vegetative and soil textural or strength factors. Since soil erosion is a response to mechanical stresses and the forces resisting them, to which the snowpack contributes little directly, this is not surprising. Indirectly, on the other hand, the alpine snowpack may control these other factors and so influence measured erosion rates in the long run but this effect has not been estimated here. It will, however, be taken into account in predicting the effects of WOSA.

On a local scale, there are environments within the alpine area in which the snowpack influence is much more clearly defined. It is apparently greatest in the snow free meadow area of low gradient and on stable talus slopes (Groups C and G in Table 4). Both of these 'susceptible' environments are relatively inactive at the present day whereas the most rapidly eroding situations (Groups A and B) respond less clearly to variations in the snowpack, In terms of geomorphic processes, there is also a clear response in rock weathering rates to local snow conditions which seems to be true of most environments within the alpine. This seems to be no more than a reflection of local water budgets.

Table 10. Bedrock weathering: regression analysis.

Data Set	N	r	Significance	a	b
All Plots	57	-0.556	0.01	0.029	-0.0012
Williams	29	-0.618	0.01	0.015	-0.0011
Eldorado	28	-0.556	0.01	0.057	-0.0015
Group A	9	-0.836	0.01	0.028	-0.0018
Group B	8	-0.577	N. S.	0.135	-0.0028
Group C	7	-0.896	0.01	0.028	-0.0016
Group D	16	-0.371	N. S.	0.024	-0.0010
Group F	7	-0.099	N. S.	0.035	-0.0009
Group G	6	-0.683	N. S.	0.011	-0.0012
Groups A & B	17	-0.748	0.01	0.032	-0.0016

In all cases, the model used is:

$$E_3 = a + b.S_1$$

Significance is estimated from the test on the correlation coefficient;

$$H_o: \rho = 0.0$$

Finally, useful empirical prediction models of the snow-erosion relationship can only be derived for a few situations. These again involve the Group C and G environments and the bedrock weathering process and will be considered in more detail later.

5.2.3. Episodic processes.

The erosion performed by snow avalanches, rockfall and mudflow activity in the alpine environment is, under natural conditions, more irregularly distributed in time and space than that due to slower processes of sediment movement. Thus, it requires a broader scale of enquiry and a greater concern with the work performed by given events and their recurrence intervals than does the study of solifluction and soil creep.

The significance of episodic or catastrophic events has been made clear in earlier reports of the Williams Lakes study, in which they accounted for more than 90% of all the observed geomorphic work in two years (Caine 1973). Of this, 76% was ascribed to a single mudflow event (that of early September 1970) and a further 20% to a series of rockfalls during the 1972 summer. Even in the Eldorado Lake basin, where no movements of such large scale were observed, these two process sets accounted for almost 50% of the recorded sediment movement. They will, therefore, receive most emphasis here.

5.2.3.1. Snow avalanches

The study of avalanches as a geomorphic agent is complicated by the need for post facto evaluation during the spring and summer. Studies in other mountain areas have suggested that avalanches should be important (e.g. Caine 1968; Luckman 1971) but this is not corroborated in the two alpine study areas of the San Juan Mountains. There, the volume of clastic debris identified as avalanche transported in the previous winter is usually less than 0.2 m^3 each spring. From this a work rate of only 0.05 x 10^6 Jkm^{-2} yr^{-1} is derived (Table 11) which is less than half that of any other process set considered. (It would appear off even less significance if the consistent underestimations of mass wasting introduced by tilt bar measurements were taken into account). Such a work rate is less than 1% of the total observed in each basin and so, even if subject to very large errors, is probably not important.

This low significance may be attributed to the relatively low relief and gentle slopes of the two areas studied which inhibit long distances of avalance transport. It may, therefore, not be typical of alpine environments nor of the San Juan Mountains, but no attempt has been made to estimate the geomorphic work of avalanches on a wider scale.

That changes in avalanche activity should be associated with variations in the snowpack seems obvious but the relationship is not estimated simply. Initially, Table II suggests that such changes should have only slight total effect and the observational record tends to support this. The high snowfall winter of 1972-73 was associated with less avalanche induced waste transport than the previous two winters. In the Williams Lakes basin, snow avalanches from the cliffs west of the lake in 1971 transported almost 750 kg of blocks and stones whereas those on the same site in 1973 were practically clean. This seems to be a reflection of the extent of snow cover on the slope across which wet snow avalanches move and suggests a protective influence in years of high snowfall.

Table 11. Geomorphic work in two alpine areas.

Process Set	Williams	Eldorado
Surficial Wasting	4.54	0.46
Mass Wasting	3.39	0.14
Solute Transport	3.24	1.68
Avalanche Activity	0.04	0.06
Rockfall[1)]	4.09	1.86
Mudflows[2)]	11.21	2.80
Total	26.51	7.00
Activity Index[3)]	0.225	0.776

Values are Joules x 10^6

This is a revision of Table 8, Caine (1973); p. 62.

1) The 1972 rockfalls in the Williams Lakes basin are allocated a recurrence interval of 10 years.
2) The 1970 mudflows in the Williams Lakes basin are allocated a recurrence interval of 22 years (see text). The value of 2.8 x 10^6 J for the Eldorado Lake basin is taken from a wider survey of mudflows on quartzitic parent materials (Sharpe 1974).
3) The activity index is the ratio of winter to summer erosion rates.

5.2.3.2. Rockfall

In total, rockfall is a much more significant process of sediment transfer than snow avalanches. The record is, however, greatly influenced by the rockfalls of the 1972 summer in the Williams Lakes basin. When those falls are omitted, the level of summer activity is 2.5 to 3.0 times that of the winter and the total is about equivalent to that in the Eldorado Lake basin. Arbitrary allocation of a 10 year recurrence interval to the 1972 rockfalls reduces their apparent significance to a more realistic level and has been used in Table 11. The lack of fresh scars on the cliffs of both study areas suggests that such rockfalls are less frequent than their appearance in a three year record of observation suggests. This conclusion is supported by the observation of Sharpe (1974, p. 55) that the mean age of the surface layer at the apex of talus cones in the San Juan Mountains is 38 years.

There appears to be no clear relationship between snowdrift situations, or the winter snowfall, and rockfall amounts or frequency. The amount of rockfall in the winter tends to be less than half that of the summer period but it has not been possible to define interannual variations for the winter period.

Other workers (e.g. Gardner 1970) have found a diurnal cycle of rockfall from alpine cliffs with peaks of activity in the morning and around mid-day which are explained as temperature effects. Water, perhaps melt water, may be significant but its effect has not been quantified and seems to be neither simple nor direct.

5.2.3.3. Mudflows

Alpine mudflows, involving the rapid transfer of mixed debris and water across steep slopes, have appeared important in both previous reports of this project. The six mudflows which occurred on the eastern side of the Williams Lakes basin in September 1970 and involved almost 250 m^3 of clastic debris account for that. This single event performed 247 x 10^6 joules of geomorphic work, almost 75% of all the geomorphic work done in the basin during the first two years of study (Caine 1973). Because it so clearly controls general tests of Hypothesis 1, and because similar deposits are comcom in the San Juan Mountains, the study of mudflows has received much attentioniin the last two years. Detailed results are available in the theses of Clark (1974) and Sharpe (1974) from which the following has been abstracted.

This project has three requirements in studying mudflows. a) A good estimate of the frequency with which they occur in the alpine environment of the San Juan Mountains. b) Given a good frequency estimate, the comparison of mudflows to other alpine processes can be made more precise. This has been attempted earlier but was found to be especially sensitive to the mudflow recurrence interval used (Caine 1971, p. 260). c) Assuming that mudflows prove important in sediment transport, there is need to evaluate any snowpack influence on their occurrence. Earlier reports, based on the Williams Lakes basin record, have suggested that mudflow activity is not influenced by snow conditions but other workers (e.g. Sharpe 1938; Rapp 1960; Owens 1973) have suggested a closer control by snow melt water. Since the early conclusion derived from only a single observed case, it needs reconsidering.

Mudflow frequency: With only one occurrence in three years, observations in the two study basins are not very useful in estimating mudflow frequency. Nor are published estimates helpful for the frequency of mudflows of the size considered here (>10 m^3) seems to vary from decades (Broscoe & Thomson 1969) to centuries (Rapp 1960). For smaller mudflows, Owens (1973) has even suggested an annual frequency. To resolve this problem for the San Juan environment, observations have been extended across a wider area and longer time scale than those used in detailed process monitoring.

Sharpe (1974) discusses the means of estimating mudflow frequency in the San Juan Mountains in detail. Using measurements of Rhizocarpon geographicum and the growth curve of Carrara & Andrews (1973) with other observations at each site, he estimates the age of two situations on 25 hillslpoes: (1) that of the mudflow itself, i.e. an underestimate of its age by the time needed for lichen colonization; (2) that of the adjacent talus which predates the mudflow stratigraphically and so gives a maximum age. The true age of the mudflow lies between these two estimates and is taken as their average. For 25 different hillslopes, the mean recurrence interval is estimated as 65 years, with a standard error on the mean of 9 years (Sharpe 1974, p. 53). A number of these 'sites' can be amalgamated into drainage units approximately equivalent to the two alpine basins studied in detail. Since each basin is likely to include more than one 'site', this should give a shorter estimate as the 'basin recurrence interval'; in fact, it should be the quotient of the site frequency and the number of sites in the basin. For stream basins of 1 to 4 km^2 area, the recurrence interval is estimated at 22 years which has been incorporated into the evaluation of Table 11.

Corroboration of these estimates is found in the comparison of photographs of the same hillslopes taken in 1909 and 1973 (R.I. ≅ 64 years) and by dendrochronology (R.I. = 27 to 50 years). The results of ^{14}C dating of a series of mudflows in South Mineral Creek will provide a further test but are not yet available.

The geomorphic work of mudflows: Two topics concerning the estimation of the geomorphic work done by mudflows are worth brief consideration here. One concerns the estimates for the two study basins (Table 11 and the other estimates for the entire San Juan Range, which would give some idea of the representativeness of the two study areas.

In using the 22 year frequency estimate in Table 11 it has been implicitly assumed that the mudflow event in the Williams Lakes basin was of average size. In view of the inverse relationship between magnitude and frequency which has been suggested for other geomorphic processes (Wolman & Miller 1960), a wide departure from mean magnitude might require modification of the frequency estimates. The Williams Lake event (multiple mudflows) performed slightly less work than the average of the mudflows studied by Clark (1974) in the San Juan Mountains (247 x 10^6 J compared to 355 x 10^6 J) but lies well within the two standard error limits on the mean. If anything, the 22 year frequency for the event is overestimated but probably not sufficiently to warrant any attempt at 'improvement' in view of the size of adcumulated errors that this could involve. The significance which Table 11 attaches to mudflows in the alpine geomorphic system can, therefore, be accepted with confidence.

An estimate of work done by mudflows in the entire San Juan Range can be made from air photo surveys although that will be biased toward the larger mudflows. Since small mudflows (i.e. those unlikely to be defected on air photos) contribute little to areal work estimates (Clark 1974), this bias is not serious and the underestimation should not be great. A survey of 1500 km^2 gives an average of 270 x 10^6 J km^{-2} of mudflow work (using the empirical relationship between mudflow surface area and work defined by Clark (1974)). Taking the mean age of the mudflows as 65 years, this gives a mean annual work rate of 4.15 x 10^6 J km^{-2} yr^{-1} which is similar to the values shown in Table 11 (both basins) are of about 1 km^2 area). The higher than average rate of mudflow work in the Williams Lakes basin may reflect the relative susceptibility of volcanic-derived material to mudflowing (Sharpe 1974, Table IV-5).

Clark (1974, Table 6.2) provides a further comparison of mudflow work on a range-wide scale by using observed rates of sediment transport through the rivers draining the San Juan Mountains. This is 4 or 5 orders of magnitude greater than that due to mudflows ($1.86 \times 10^{11} J\ km^{-2}\ yr^{-1}$ for the Animas River at Farmington and $1.95 \times 10^{11} J\ km^{-2}\ yr^{-1}$ for the San Juan River at Archuleta). These estimates are, however, based on an assumed transport of sediment from the median elevation of the two basins which may not be justified in view of the semi-arid nature of their lower drainages and the land use there. Nevertheless, it appears on this scale that mudflow activity, and even alpine erosion in general, is relatively insignificant.

The controls of mudflow activity: Mudflow events seem to occur in response to the interaction of two sets of necessary controls, neither of which is sufficient in itself. These involve the two constituents of the flow: the waste mantle which eventually fails and the water which apparently induces that failure. Many previous studies have emphasised the second of these, usually considered in terms of rainfall intensity, and it is important to the present study since it includes the snow melt term. Before discussing either, however, it is worth pointing to three broader environmental requirements which the work of Sharpe (1974) defines. These are the needs for a mantle of surficial debris, a steep slope (mean angle of 35° in the San Juan Mountains) and a superjacent gully (81% of the mudflows studied started immediately below gullies in cliffs). The significance of the first two of these is obvious, the third less so but gullies are important in channelling water and debris onto areas of potential failure, and so contributing to both sets of necessary conditions.

Waste mantle controls of mudflow activity usually involve the mechanical behavior of the material but are not easily defined. There are apparently two types of nudflow in the San Juan Mountains (Clark 1974). One involves material of a sandy texture with low organic content and associated low index properties for liquid and plastic behavior. The second has a finer texture and is associated with slopes of higher vegetation cover, and perhaps greater age. Empirically, the relationships between soil characteristics and the resulting mudflow work tend to be opposed in the two types, e.g. the correlation with the infiltration capacity of soil is direct in the second case and inverse in the first. This led Clark (1974) to suggest an optimum textural range for mudflow development between 40 and 60% sand content (Figure 4). The result seems to reflect an interaction with soil moisture requirements for failure such that water can be transmitted into the mantle but does not drain rapidly through it. The lithological influence which Sharpe (1974) has defined on a broad scale, seems to point to a similar form of partial control: the areal density of mudflows on the quartzitic rocks of the San Juan Mountains is only half that on the volcanic rocks ($0.51\ km^{-2}$ compared to $1.08\ km^{-2}$).

The influence of variations in the water budget of a slope is even more difficult to define post facto, especially since it is often difficult to estimate precipitation intensities in mountainous terrain away from recording rain gauges. Both mudflow events which have been observed in or near to the two study areas during the present work and highway maintenance records suggest that summer precipitation from high intensity storms is important. The mudflow near Eldorado Lake in August 1973 was, however, produced by the conjunction of rainfall and a melting snowbank. The significance of late-lying snowbanks as a moisture source should not be ignored entirely.

An estimation of the melting snow influence on mudflow activity can only be made indirectly. First, it can be shown that snow melt alone is capable of putting a considerable volume of water into a potential failure zone. Solar radiation on a north-facing slope of 30° at 38° N latitude and 3600 m altitude is capable of producing up to 9.0 cm dy^{-1} of water from snow melt in mid-summer. This is approximately equivalent to the 25 year rainstorm in the Silverton area (Hershfield 1961) and may be sufficient by itself to produce mudflow activity. Given this possibility, it remains to be shown that snow actually has been associated with mudflow activity. Beyond the single case near Eldorado Lake which Sharpe (1974) documents (p. 43), no observational evidence supports the contention for the San Juan Mountains. The observations of Owens (1973), however, offer corroboration from the Canadian Rockies.

Other evidence suggests that snow melt (probably in conjunction with rainfall) could be significant. The apparent need for a gully above a mudflow-prone slope also defines a potential snowdrift site: many of the gullies above mudflows carried snowbanks until late summer in 1973, a year of high snowfall (Sharpe 1974). The orientation of mudflow sites is also suggestive of snowdrift situations (Figure 5) and corresponds to the distribution of perennial snowbanks in the San Juan Mountains (Andrews & Carrara 1973, Figure 2).

There is still no evidence on which to evaluate the relative contributions of snow melt and rainfall where their interaction is involved in mudflow initiation, or even to estimate how important in toto that interaction is, and so it has not been taken into account in the estimates of Table 11. Nevertheless, it now seems reasonable to suggest that snow melt accounts for some of the geomorphic work due to nudflows in the San Juan Mountains even if it was not involved in the 1970 event in the Williams Lakes basin.

5.2.3.4. Episodic processes - summary

Previous reports of this project have suggested that episodic erosional processes are hardly influenced by the winter snowpack. As a general conclusion from observations in the two study areas, this remains reasonable but it now seems to be unduly influenced by a single mudflow event in the Williams Lakes basin. Across the entire range, some of the mudflow work must be ascribed to the melting of a snowpack but how much is not known since it involves an interaction with rainstorms. In prediction, a "worst possible case" approach will be used and all the work due to a snow-rain interaction ascribed to the snowpack.

5.2.4. The geomorphic effects of WOSA

In predicting the geomorphic effects of winter orographic snowfall augmentation, three different evaluations are needed. These involve the effectiveness of,

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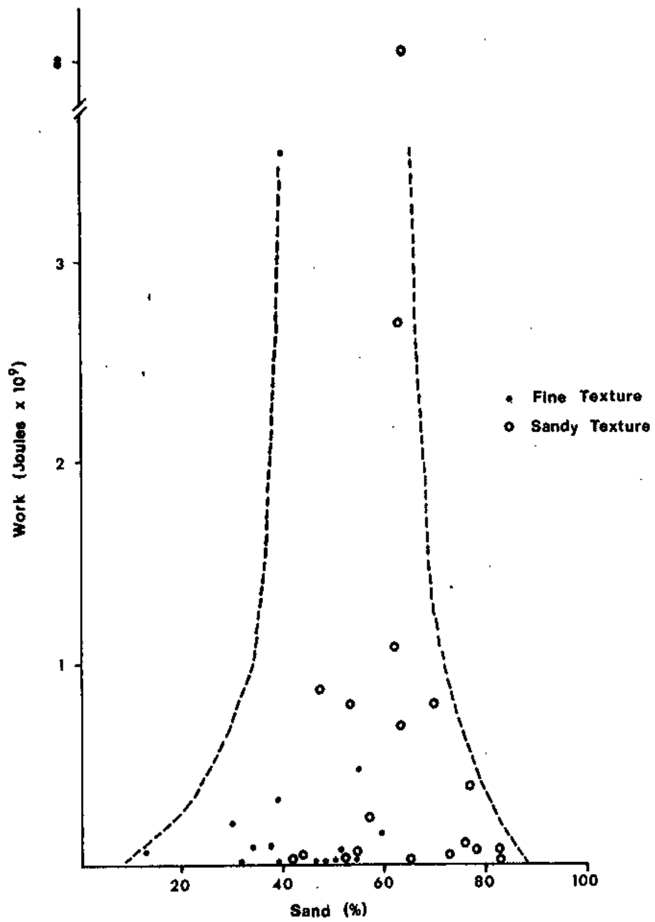

Figure 4. The textural control of mudflow work.

Source: field survey of the size and transport distance of mudflows (Clark 1974).

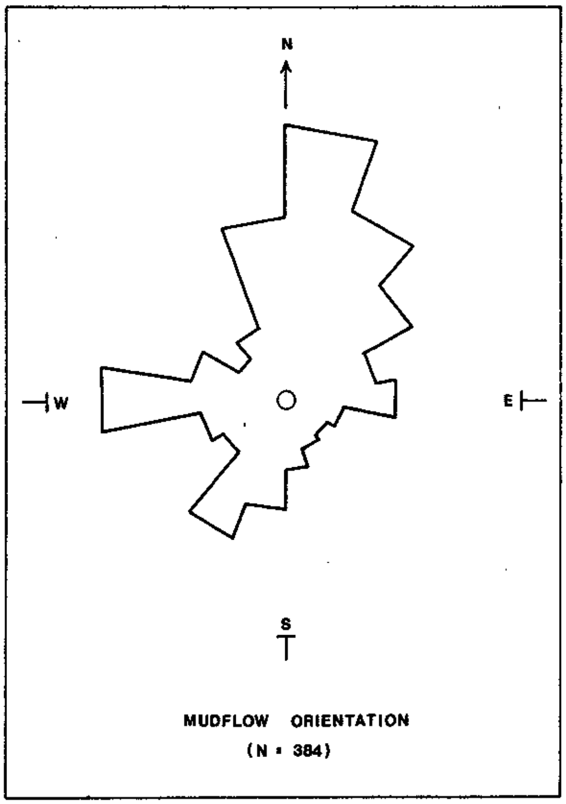

Figure 5. Mudflow orientation.

Source: air photo survey of the alpine areas of the Ironton, Telluride, Snowden Peak and Storm King Peak quadrangles. The histogram is defined in 20° classes with 70 observations in the modal class (0 - 20°) and a vector mean orientation of 28° (Sharpe 1974).

first, the cloud seeding project in producing an increase on the ground; and, third, the relationships between the snowpack and erosional processes and rates. Only the last is of concern here but predictions drawn from it are obviously contigent on the first two. These two contribute to three sets of assumptions on which predictions from the snowpack - erosion relations will be based.

The first assumption is that the period of field study (1970-1973) represents normal conditions in the San Juan Mountains, i.e. conditions prior to WOSA. Since the Pilot Project commenced in 1970 and both study sites are within its target area, this is not strictly true. However, snow course records in the range (Washichek et al. 1973) show that the study period has not been one of higher than normal snow accumulation and so the assumption is probably reasonable. In prediction, the effects of an increase in snowfall will be added to the observed 'normal' conditions.

The second assumption is that the 15% increase in winter snowfall for which the Pilot Project is designed is the one for which predictions of effect are needed. The approach taken here allows the effect of larger or smaller actual increases to be estimated proportionally and will probably give reasonable results for snowfall increases of up to 30% or 40%. With increases of more than 40%, it is likely that some of the assumptions used in the alpine snow redistribution procedure will become invalid.

A third set of assumptions is needed to allow conversion of a 15% increase in snowfall to an increase in the snowpack on the ground, where erosional effects will be felt. A linear model for the redistribution of snow in alpine areas by wind drifting is used for this. The model is based on the snowcover depletion patterns of 1971 in the two study basins and so is easily accomodated to the use of S_1 as an estimate of plot snowpack characteristics. The model itself is discussed in detail elsewhere (Caine 1974).

The two sets of processes distinguished earlier will also be treated separately here. This is convenient although it involves the risk that interactions between them may be ignored, e.g. Sharpe (1974) has suggested that quasi-continuous processes of bedrock weathering may be an important control of mudflow activity in the San Juan Mountains.

5.2.4.1. Quasi-continuous processes

Given a variety of alpine micro-environments (e.g. Table 5), two kinds of change in geomorphic activity may be defined. One involves only a change in erosion rates (either an increase or decrease) within a given environment which remains unchanged except in terms of its snowpack and erosional activity. The other requires a more complex interaction whereby a given site changes between environments, e.g. from that of the Group C to that of the Group B plots in Table 5. This, too, may produce either an increase or decrease in erosion at the site.

These two kinds of change in the quasi-continuous processes of soil erosion are worth treating separately since they should have different impacts on the visible landscape and involve different response times. Changes within environments may not be visibly important whereas changes between environments should be more evident. The first should also be achieved relatively quickly (i.e. in years), since it involves few changes in erosional controls, while the second may require decades before it works through a longer chain of factors, many of which may be only indirectly linked to the snowpack.

The following discussion is based on the data used already in this report and so involves only the environments defined in Table 5. It, therefore, included only about 40% of the two study basins: the stable environments of exposed bedrock and wet sedimentation areas (lakes and swamps) are omitted.

Changes within environments: In regression analysis, only two of the environments of Table 5 give models that offer more than 50% explanation of the observed surficial erosion rates (E_1). These are the gently sloping dry meadow situations and stable taluses of the Group C and G environments which constitute 19% of the total area in the two basins. For the rest; the relationship between S_1 and E_1 is too weak to allow prediction. Table 12 summarizes the predicted increases in E_1, using the regressions of Table 8 and the distributions of S_1 for the plots of Groups C and G. For the Group C situations, the change in the snow cover and the snow melt date is shown to be very slight and, largely because of that, the increase in E_1 should be of less than 5% (0.5 mm yr $^{-1}$). With such slight changes, it is not worth considering the errors in the estimates from the S_1 - E_1 regression. For the stable talus areas typified by Group G, a more significant increase in E_1 is predicted: up to 300% where the talus was snow covered until late September 1971. This is, however, inferred from the tail of a normal distribution defined by only 8 cases; the maximum effect for any actual case is an increase of only 7% (Table 12). In both of these environments, little immediate change in surficial erosion is likely from a 15%, or even a 30% increase in winter snowfall.

A useful prediction model for mass wasting (E_2) is available for only the Group C environment (Table 9) and the results of its application are also summarized in Table 12. Given the importance of soil moisture to soil creep, the impact of WOSA should be expected to be greater in this case than for E_1 and this seems true. An increase of up to 30% in E_2 is predicted for Group C situations which did not melt clear of snow until mid-June, 1971, although the maximum for any study plot is only 6%.

For the bedrock weathering process (E_3), also, there are only two regressions that can be used with confidence in prediction (Table 10). These involve the Group A and C environments and suggest increases in weathering rates on them of 6% and 5% respectively. Again, using the tail of the distribution beyone the 2σ limit suggests a great increase (up to 1000%) but nothing like this is predicted for the actual cases analysed.

The process of solute removal in alpine streams is worth some consideration here although it has not been the subject of detailed work. It should reflect the volume of runoff and so allow two simple estimates

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Table 12. Predicted changes in erosional intensity.

Process	Plot Group	Snow Cover Duration		Meltdate Delay	Increase in Erosion
E_1	C	Mean S_1	Apr 6	<1 day	0.02 cm yr^{-1}
		$+\sigma$	May 11	<1	0.03
		$+2\sigma$	Jun 15	<1	0.04
		W.A.C.	May 19	<1	0.03
E_1	G	Mean S_1	Jun 11	<1 day	0.03 cm yr^{-1}
		$+\sigma$	Aug 1	9	0.62
		$+2\sigma$	Sep 20	>30	5.54
		W.A.C.	Jul 31	9	0.62
E_2	C	Mean S_1	Apr 6	<1 day	0.02 cm^2 yr^{-1}
		$+\sigma$	May 11	<1	0.10
		$+2\sigma$	Jun 15	<1	0.26
		W.A.C.	May 19	<1	0.10
E_3	A	Mean S_1	May 28	<1 day	0.002% yr^{-1}
		$+\sigma$	Jul 16	10	0.016
		$+2\sigma$	Sep 3	>30	0.272
		W.A.C.	Jul 13	2	0.003
	C	Mean S_1	Apr 6	<1	0.001 % yr^{-1}
		$+\sigma$	May 11	<1	0.001
		$+2\sigma$	Jun 15	<1	0.002
		W.A.C.	May 19	<1	0.0015

Processes are identified in Table 1: Plot Groups in Table 5.

Snow cover duration refers to the sample distribution of S_1 for that group of plots - the mean, the mean + 1 standard deviation and the mean + 2 standard deviations are used. W.A.C. refers to the 'worst actual case' i.e. the latest melting plot of the group, not a sample statistic.

Melt date delay is estimated from the nomogram in Caine (1974).

Increases in erosion are estimated from empirical regressions (Tables 8,9, and 10) and the melt date delay term.

of the effect of a snowfall increase to be made. Assuming that all of a 15% increase runs off through the stream channel and the water quality remains the same, an increase of 37.5% in the rate of solute removal from the San Juan alpine area can be predicted. This is based on early estimates of the proportion of precipitation that becomes streamflow from the two study basins (Caine 1971). Alternatively, the increase in snowfall may be distributed among the water budget components of alpine drainage basins in the same proportions as the 'normal'snowfall. This suggests a much lower increase in solute removal (only 12% if it is assumed that 20% of the 'normal' streamflow is due to summer rainfall). Even this is, however, much greater than the effects of other quasi-continuous processes and so streamflow and solute removal from the alpine is being studied in more detail in 1974.

Changes between environments: Predicting changes in the wider characteristics of areas undergoing natural erosion can be approached by using the group of plots of Table 5. Assuming the distributions of these environments in S_1 to be approximately normal, Figure 6 shows much overlap between all six groups. (The number of plots in each group is too small to allow testing for normality). This suggests that snow, by itself, is not clearly diagnostic of alpine geomorphic environments and that the area of overlap between two environments cannot be used as a simple estimate of the probability of a change from one to the other following an increase in snowfall.

The limits of the distributions in Figure 6 are probably more important in defining situations that may respond to a change in snow cover duration and the distinction between environments with a vegetation cover and those without one is especially clear when limiting values of S_1 are considered. This is important since a reduction in the vegetation cover will normally lead to an increase in soil erosion and so the probabilities of areal changes from the C, D and F environments to the A and B environments will be considered here. Since the E and H environments are represented by only a few plots in this study, they will not be considered further. This is particularly unfortunate since the Group E situation appears to be intermediate between those of A and D in terms of both environmental characteristics (Table

Table 13. Plot group erosion rates.

Plot Group	N	Snow Duration Mean	σ	Area (%)	E_1 ($cm\ yr^{-1}$)	E_2 ($cm^2\ yr^{-1}$)	E_3 ($\%\ yr^{-1}$)
A	20	89	49	0.8	9.77	6.31	-0.025
B	20	106	24	1.2	2.27	1.06	-0.093
C	7	37	35	9.2	1.09	0.76	-0.031
D	16	66	25	18.3	1.10	1.52	-0.033
E	2	35	21	0.5	17.30	1.98	-0.012
F	8	72	10	0.8	0.87	1.24	-0.031
G	8	72	51	9.8	1.77	1.00	-0.049
H	3	70	20	12.6	4.82	0.75	-0.022

Plot groups are identified in Table 5.

Snow duration is measured in days after March 31 and refers to 1971.

Values for surficial erosion (E_1) and mass wasting (E_2) are geometric means; for bedrock weathering (E_3) are arithmetic means.

Area is the mean of the two study basins. Other important environments in the two basins are: Exposed bedrock (38.5%); Wet Meadow & Swamp (1.9%); Lakes (5.4%).

5) and erosional responses (Table 13).

June 30, 1971 is taken to be a critical value of S_1. This is defined in Caine (1974) as the threshold at which long term changes in the snow cover duration of more than a day can be expected from a 15% increase in snowfall. If this delay in snow melt is then assumed sufficient to cause normally vegetated sites to take on the bare soil characteristics of the A and B environments, increases in erosion due to this change can be predicted. With removal of the vegetation cover at a point, the change in erosion rate is very great (e.g. from the mean erosion rate of environment D to that of A) (Table 14). However, even with the early threshold of June 30, the areas involved in such changes are very small; they occur only at the limits of the C, D and F distributions in Figure 6. Since only 0.36% of the total alpine area is involved, the overall impact is of an increase of only 2.3% in E_1 and 1.5% in E_2. This is approximately the same as the total within-environment effect (1.7% increase) defined earlier.

In general, there is no reason to expect major increases or decreases in the erosional activity of slow-acting geomorphic processes following a 15% increase in snowfall. In fact, this study suggests that the alpine system is capable of attenuating any such effects; in the cases examined, the predicted changes in erosion are less than those in the snowfall required to produce them. This may not be true of increases of more than 40% in snowfall, however.

5.2.4.2. Episodic processes

As with the quasi-continuous processes, two types of impact on the less frequently acting processes could be defined to include changes in the intensity and area of activity of each process set. The distinction will not, however, be used here because of the lack of estimates of the areas involved and their activity levels. In fact, the prediction of changes in episodic processes is made difficult by the general lack of quantitative estimates of the snowpack - erosion relationships involved. It, therefore, requires a qualitative treatment and many simplifying assumptions.

Snow avalanches: That an increase in the winter snowfall should lead to an increase in the work of sediment transport by avalanches seems intuitively obvious. It is not, however, corroborated by this study; observation does not define a simple relationship between snowfall and the work done by avalanches on an annual basis. Avalanche activity is not a simple function of the volume of winter snowfall and the further relation between avalanche activity and geomorphic effect is also not simple. Instead, it is particularly influenced by surface conditions in the area across which each avalanche moves. Spring wet snow avalanches have been the subject of most study on avalanche

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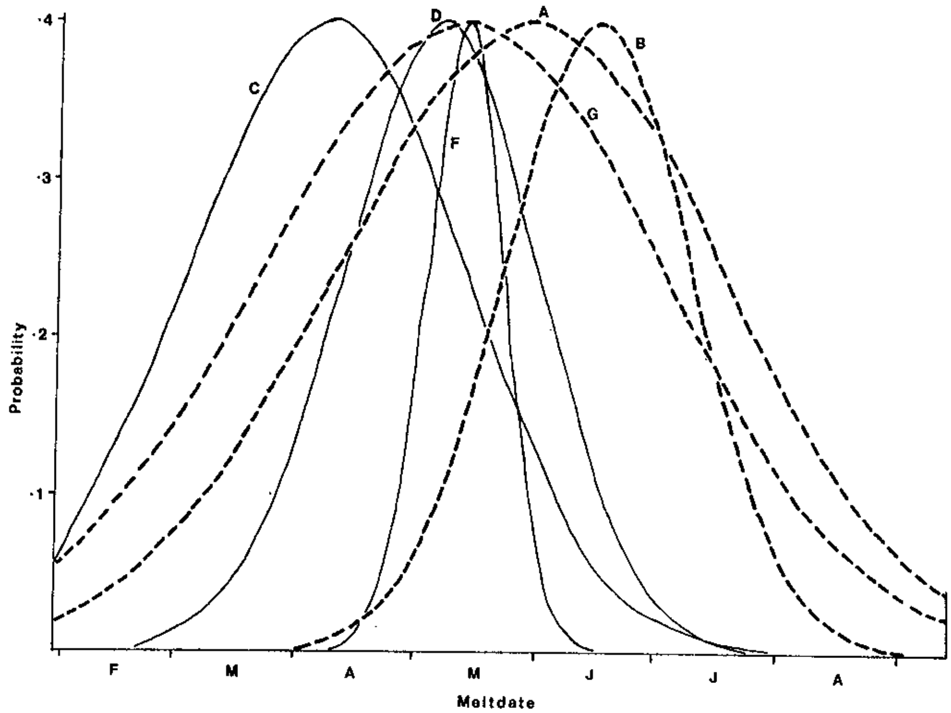

Figure 6. Snow cover duration by plot groups.

The curves are the normal distributions for the mean and standard deviation of the melt dates of each group of plots in 1971. Solid lines show vegetation - covered plots and broken ones, plot groups with little vegetation cover.

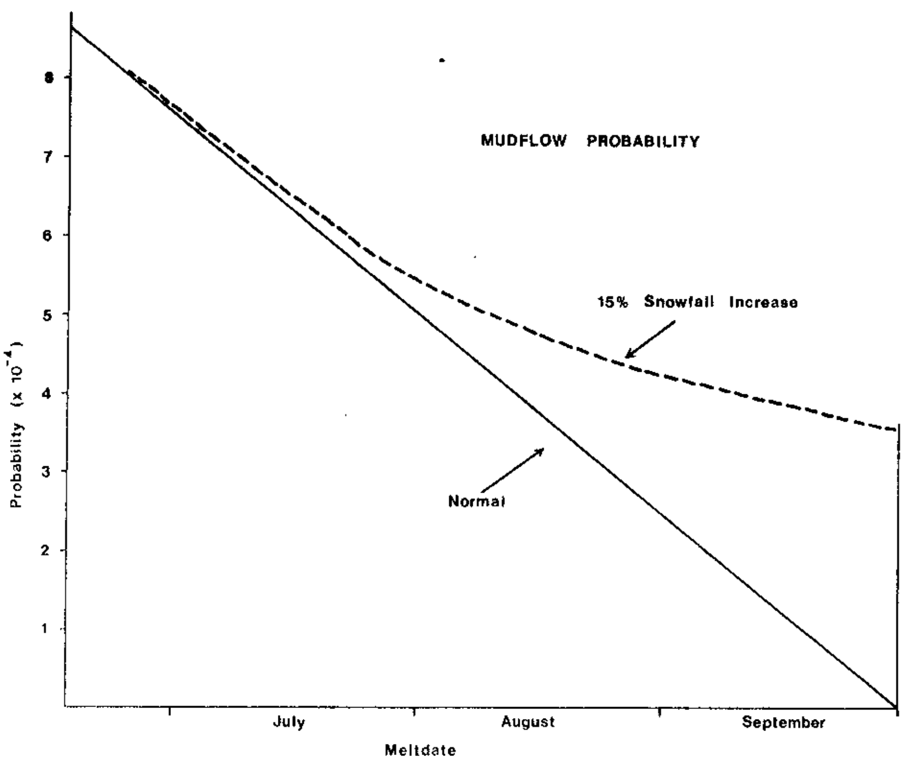

Figure 7. Intra-seasonal mudflow probability.

Defined for a summer season of 105 days from June 17 to September 30 with a normal probability of 0.045. Applicable to areas of from 1 km^2 to 4 km^2 only.

Table 14. Erosion intensity - area responses

Plot Group	Area	June 30 Equivalent	Prob.	Area affected	Changed to Group	Intensity Change E_1	E_2
C	9.2%	Mean+2.43σ	0.0075	0.069%	B	2.08	1.39
D	18.3	+2.24σ	0.0125	0.229	A	8.88	4.15
E	0.5	+4.14σ	0.0	0.0	A	?	?
F	0.8	+5.0σ	0.0	0.0	A	?	?
H	12.6	+2.6σ	0.0047	0.059	A	2.03	8.41
Total	41.4%			0.357%		1.023	1.015

Plot groups are defined in Table 5.

Area is the mean for the two study basins.

The June 30 threshold is defined in terms of the sample distribution for each plot group.

Probability is the proportion of the normal curve for each plot group lying beyond the June 30 threshold.

Area affected is the product of the area in the plot group and the probability; it represents the proportion of the total area in the two basins affected.

Changes in erosional intensity are estimated from the differences in the mean values of Table 13 for the plot group concerned and for plot groups A or B. The total change is weighted by the area affected in each group and expressed as the proportion after : before WOSA.

effects (Caine 1968; Luckman 1971) but, even for them, the relationship between avalanche and erosion remains unclear. No good basis for quantitative prediction is yet available for any class of avalanche.

A qualitative approach which ignores the problem of predicting from cause to effect offers the best evaluation that can be made here. It is only applicable to the field area in the San Juan Mountains and cannot be confidently extended beyond that. Table 11 allocates a low significance to avalanches as geomorphic agents and this would not be greatly increased, in relative terms, were the effect to double in response to a 15% increase in snowfall. Even if it were increased by an order of magnitude the total would only approach that of other process sets under 'normal' conditions. The latter of these is extremely unlikely and the former improbable, so it seems safe to suggest only slight increases in general erosion levels from changes in avalanche activity due to a 15%, or even a 30%, increase in snowfall. This general conclusion is supported by the low proportion of the alpine area influenced by avalanches (under 0.05%: Andrews 1974).

Rockfall: For rockfall too, no satisfactory basis for prediction has been defined by this, or earlier, studies. Since there is no good theoretical or empirical reason to expect a relationship between the snowpack and rockfall intensity or timing, this is not too serious. The observational record suggests that this is largely a summer phenomenon and is not usually influenced by melting snow. It is reasonable to suggest that an increase in winter snowfall of up to 50% will have little influence on its general effect.

Mudflows: Mudflow activity requires the input of water to the waste mantle in potential failure zones. The influence of WOSA on this involves snow melt, either alone or in conjunction with rainfall. Since there is no evidence that snow melt by itself is important to mudflow initiation in the San Juan Mountains, it will be ignored in favor of the rain-on-snow influence. The whole of this influence will be treated as if it were due solely to the snowpack although the result is an overestimation of the effect of WOSA. The further complications due to material constraints on mudflows occurrence will also be omitted from this analysis for the sake of simplicity.

An impact evaluation can be made through the estimated probability of the 'average' mudflow (ignoring questions of a magnitude - frequency interaction) and the predictions of snow melt delay due to a 15% increase in snowfall from Caine (1974). From the 22 year recurrence interval of Sharpe (1974), the annual mudflow probability in a 1 km^2 alpine area of the San Juan Mountains is estimated as 0.045. Assuming it to be the same for both rainfall-induced and rain-on-snow mudflows allows this estimate to be defined as the joint probability of rainfall on melting snow sufficient to give mudflow activity (i.e. $p_{rs} = p_r = 0.045$). Two further assumptions allow this probability to be partitioned through the summer period as in

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Figure 7. These are (a) that all mudflows occur during the summer (i.e. $P_{rs} = P_r$ o.o for the period October 1 - June 16), and (b) that the probability of rain-on-snow mudflows declines in linear fashion to 0.0 during the summer. In view of the observational record, the first of these is probably reasonable but the second may be an oversimplification. It is intended to take account of changes in snow melt rates and snow cover areas for which it suffices as a first approximation. It does not allow for changes in precipitation intensity probabilities during the season. The record from the Williams Lakes basin and the Eldorado Lake basin shows that storm totals are generally higher in late-summer and fall than earlier in the summer (mean of 1.17 cm in September compared to 0.33 cm in June - August), although intensities remain about the same (0.13 - 0.20 cm hr^{-1}). This suggests a higher probability of mudflows in the latter part of the season which is supported by the two observed occurrences in late August and early September.

With a longer lasting snow cover on any site, the probability of its conjunction with a critical rainfall amount or intensity should be increased. This effect has been estimated in Figure 7 by shifting the 'normal' curve to the right by the delay in snow melt predicted for a 15% increase in snowfall. The resulting change in probability levels increases as the season progresses; the wedge shape is largely produced by the snow redistribution model (Caine 1974) but is also influenced by the assumption of $P_{rs} = 0.0$ at September 30.

For present purposes, the total change is probably more important than changes within the season and is estimated by the integration of the area between the two curves of Figure 7. It represents a increase in the annual probability of mudflows in a 1 km^2 area, from 0.045 to 0.056; which corresponds to a reduction in the recurrence interval to 18 years from 22 years on this scale, or from 65 years to 53 years on a 'site' scale.

By extension, this analysis suggests an increase of about 25% in the geomorphic work performed by mudflows that are produced by rain on snow, i.e. one of the greatest impacts predicted by this study. For this reason, the assumptions on which it is based deserve critical evaluation. The errors in the estimation of mudflow probabilities and the assumptions required by the snow redistribution model have been examined elsewhere (Caine 1974; Sharpe 1974) but three further qualifications to the analysis are needed: (1) The analysis does not apply to all the geomorphic work done by mudflows in the San Juan Mountains. In particular, the probability of mudflows for which rainfall is the only source of water (e.g. those in the Williams Lakes basin in 1970) would remain unchanged. The proportion of mudflows which fall into this class, rather than the rain-on-snow class, is unknown but the observation of Sharpe (1974) that 15 of 32 mudflow sites were associated with snow until well into the summer of 1973 can be used as an approximation to it. The approximation is supported by the fact that both classes of mudflow are represented in the two mudflows which occurred in the study areas between 1970 and 1973. Thus, the change in total mudflow work will be less than half of that suggested earlier: a 12% increase rather than a 25% one.
(2) The predicted reduction in mudflow recurrence interval is within two standard errors of the mean. This may be interpreted as showing a non-significant difference from the mean but is probably more important in suggesting that the testing of before and after effects would require a long period of study, even if the predictions made here proved good. A change in mudflow activity of less than 25% would require an even longer period.

(3) The effect of other site constraints, particularly those involving soil characteristics, will probably be to further lower predicted effects. If, as Sharpe (1974) suggests, the rock weathering rate is a basic constraint to mudflow activity, there may be no increase in the work done by mudflows following a snowfall increase. It has not been possible to evaluate this possibility here. Since it has already been shown that an increased snowfall should give some increase in bedrock weathering rates, this may not be a serious lacuna.

5.2.5. Conclusion

This work supports the conclusions drawn from earlier reports that a 15% increase in snowfall should not greatly influence contemporary geomorphic processes. Empirical observations, regression analysis and the comparison of winter and summer erosion rates all combine to suggest that the winter snowpack is not of general, primary importance in accounting for erosional differences within the area above tree line in the San Juan Mountains. (Contrasts in erosion rates between this area and that below tree line have not been considered here and could be very different.) Instead, the snowpack seems to work at a secondary level, below that of the soil strength and topographic controls of stress and strain. This secondary importance is predicated on the indirect nature of many of the links between the snowpack and erosion which also makes an evaluation of the potential impact of an increase in snowfall difficult. The erosional effects, and changes in them, are largely made through a chain of soil and vegetation characteristics rather than by the direct action of the snowpack itself or meltwater derived from it.

On a regional scale, a relative insignificance suggests that the impact of an increase in snowfall on alpine erosion should be slight. Because of the indirect nature of the effect, however, it will be confounded with the influence of other controls and may require a considerable time to become evident. In general, an attenuation of effects, as by negative feedback, is likely in most alpine situations so that an increase in snowfall will be accompanied by a proportionately lower increase in erosion rates. The most important exception to this is found where the effect of wind redistribution leads to a concentration of the added snow in drifts. Such an amplification of impact influences only a small part of the whole alpine area (less than 10%).

For the geomorphic processes considered in the study, separate predictions for a 15% increase in snowfall are summarized in Table 15. The most significant impact is likely through an increase in solute removal by the increased runoff and in mudflow activity, especially that associated with snowdrift situations.

Work continues to refine these two estimates but will probably not change them greatly. Observations of bedrock weathering are also continuing - if for no other reason than to explain the discrepancy between this process and that of solute transport in Table 15. Geomorphic effects other than those involving the stream runoff and mudflows are likely to be so slight as to remain undetected by observational methods presently in general use.

Even the total impact is small for areas of the size considered and is practically negligible when compared to other forms of man induced erosion. These commonly involve increases in erosion by orders of magnitude, overwhelming the natural variability. In contrast, the total predicted effect of Table 15 will probably be masked by 'normal' variations in alpine erosion rates. It is, therefore, unlikely that the impact of a 15% increase in snowfall could be detected by classical before-and-after or paired basin experiments except over a very long time period. The best hope for verifying the predictions made in this paper probably lies in testing of the relationships and assumptions from which they are derived, rather than in the empirical monitoring of alpine erosion rates.

Table 15. The geomorphic effects of a 15% increase in snowfall.

Surficial Erosion	+1.15%	+2.30%	+3.45%
Mass Wasting	+0.55%	+1.50%	+2.05%
Bedrock Weathering	+0.67%	+0.83%[2)]	+1.50%
Solute transport	?	?	.12 to 35%
Avalanches[3)]	+0.05%	0.0%	0.05%
Rockfall	0.0%	0.0%	0.0%
Mudflows	+11.66%	0.0%	+11.66%
Total			+30.71%

1) The changes are estimated for 1 km^2 to 4 km^2 areas of the alpine from the worst actual cases.

2) Only the change from Group C to Group B environments has been used in estimating indirect bedrock weathering effects.

3) Avalanche effects are predicted from an assumed 200% increase in the work performed by avalanches.

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5.3. PREDICTING SOME EFFECTS OF WEATHER MODIFICATION ON ALPINE VEGETATION (P. J. Webber, J. C. Emerick, and Page Spencer)

5.3.1. Project design

Previous reports have described and discussed the objectives and approach used in this study (Webber and Bock, 1970; Webber, 1971; Webber et al., 1973); nevertheless a brief reiteration and updating is appropriate. The overall objective is to predict the effects of weather modification resulting from winter cloud seeding on the alpine vegetation in the San Juan Mountains of southwestern Colorado. Our field studies are concentrated at two locations within the seeded target area. One site is an area of high alpine tundra on acid granitic rocks surrounding Eldorado Lake and the other site is an area of low alpine tundra and subalpine vegetation on basic volcanic rocks surrounding Williams Lakes and Trout Lake. The project has several tasks: to make a floristic survey of each of the two field locations as a baseline prior to weather modification; to construct phytocoenological models of the vegetation in these basins which will predict plant community changes resulting from increased snowfall; to experiment with snow fences and to construct a process model of primary production which will simulate the impact of increased snowpack; to determine the representativeness of the two basins in terms of the entire target area; to document all the methods used to monitor or predict the effects of weather modification; and to make recommendations with regard to future research on the assessment of the effects of weather modification. In this Interim Progress Report only two of these tasks will be discussed in detail; complete documentation of the entire project will be forthcoming in the final San Juan Ecology Project report. These are the phytocoenological studies and the snow fence experiments which are the largest tasks and are also based on the same important initial assumption. The assumption is that it will be impossible to detect vegetation changes in the short time-span of this study especially at the anticipated 15% increase of snowfall from winter cloud seeding. Therefore in the phytocoenological study an analysis of the long-standing vegetation patterns in relation to complex snow gradients is used as the basis of a predictive model and in the snow fence experiments the approach is to greatly increase snowpack to determine the changes in vegetation processes and performance.

5.3.2. Phytocoenology and ordination studies

The following is an abstract from a Master of Arts dissertation which will be submitted to the Graduate School of the University of Colorado (Spencer, 1975). This abstract outlines an important part of these studies, all of which will appear in the final report.

Possible Effects of Winter Weather Modification on Alpine Plant Communities in the San Juan Mountains, Colorado

Abstract

In 1970 the Bureau of Reclamation initiated a pilot project of winter weather modification by cloud seeding in the San Juan Mountains of southwestern Colorado. The following study was conducted from May 1972 to December 1974 to assess the effects of increased snowfall on the composition of alpine plant communities.

Eldorado Lake and Williams/Trout Lake basins were selected as study sites. Over fifty 1 x 10 m plots, distributed along a gradient of snow melt-out date, were established in each basin. These were sampled for species presence and cover, and selected environmental parameters relating to snow and soil characteristics. The vegetation data were analyzed using the Bray and Curtis ordination techniques. Clusters of environmental factors or interdependent complexes which correlated at the P = 0.1 level of significance to the axes of the ordination were identified. In the Eldorado Lake the first ordination axis was correlated with a complex site moisture gradient, the second axis with a soil particle size and stability gradient and the third axis with a complex gradient of snow related factors. In the Williams/Trout lakes area the axes correspond, respectively, to a snow-water complex, a soil particle size and stability-snow complex, and an as yet undefined environmental complex.

For each sampled plot the changes in snow and water regimes which might result from an increase in snowfall were estimated. These evaluations were used to define predicted plot position changes within the vegetational continuum. The result suggests the magnitude and direction of changes which might occur as a result of winter weather modification. Permanent snowbeds may result from increased snowfall, with the resultant loss of the vegetation under them. If the species in these snowbank areas are unable to invade new areas, they will be eliminated from the local flora.

If increased snow makes the environment of the snowfree ridge-tops unfavorable for the species there, then these species will have no area to invade and will be eliminated from the local flora. The magnitude of change would depend upon several factors influencing the vegetation. These include the ecological amplitude of the species present at a site and the competitive ability of potential invader species, as well as the change in snow accumulation patterns and the time of year when cloud seeding occurs.

As indicated in the above abstract, the ecological amplitude or tolerance range of a species at any given site being affected by increased snowfall is a critical factor. Many alpine species have wide tolerances and might either remain established in the vegetation or take many years to decline or increase so that few if any catastrophic changes occur. Nevertheless several alpine species are restricted to sites which have well-defined snow regimes; these species are indicators of specific snow regimes. For example Selaginella densa is restricted to sites with little or no winter snow accumulation while Juncus drummondii is restricted to late snowbeds. Such species with narrow tolerance ranges are perhaps the first candidates for decline in response to a change in the snow regime. The effect of such declines can be debated in terms of loss of vegetation productivity, increased erosion, and perhaps even the loss of a species from the local flora. However, these discussions remain speculative because we do not know how resilient to damage the species really are. In order to answer this question a study involving reciprocal transplanting of wide and narrow ranging alpine species is now in its third year on Niwot Ridge in the Colorado Front Range. Six species have been reciprocally transplanted from and between six major habitat types ranging along gradients of snow, moisture, and stability. Adequate controls have been established for the transplant procedure and detailed environmental measurements have been maintained at each transplant site. The growth and reproductive patterns of plants are being followed to assess the resiliency of each species to environmental change. The results of these experiments are currently being analyzed; these and their significance will appear in the final report.

5.3.3. Snow fence experiments: Primary production modeling

5.3.3.1. The function of primary production in the ecosystem

All animal life depends on the ability of green plants to fix the sun's energy. This primary production becomes the food for consumer organisms (e.g. sheep and coyotes) and is also important in controlling geomorphic processes, soil development, and the hydrological cycle. Thus any changes of plant growth brought about by environmental change will have some impact on the entire ecosystem.

5.3.3.2. Anticipated effects of snow fences on production

Snow cover greatly influences growth and development of tundra vegetation, and changes in distribution or size of snowdrifts may affect the resident plant communities in many ways. Generally, winter snow distribution influences the onset and length of the growing season, and the moisture and temperature regimes of the soil, particularly at the beginning of the growing season. Late-lying snowbanks may either directly or indirectly affect the canopy microclimate.

While some species are able to begin growth when still under snow cover, the majority of the plants must wait until snow release occurs. Therefore, the growing season may begin several weeks sooner on sites blown free of snow than on snow accumulation sites. In some circumstances, unusually high amounts of snow accumulation may be expected to seriously shorten the length of growing season. This could influence the reproductive success of the vegetation (see Bock and Reid, Section 5.4) and also affect seasonal production. Plant response to a shortened growing season may not be restricted to, or manifested by a decrease in aboveground production. Belowground reserves in carbohydrates or other nutrients may be depleted; such reserves are very important in the ability of tundra vegetation to successfully reproduce or withstand poor growing conditions (Mooney and Billings, 1960).

Snowdrifts may contribute considerable amounts of meltwater to the soil. Some of this moisture may be added by early storms in late autumn, when new snow often melts quickly before the soil has become frozen. However, most of the meltwater enters the soil during the spring thaw, and depending on the drainage characteristics of the site, this moisture may be available to the plants for several weeks. Since water is an effective heat sink, soils initially saturated with cold meltwater may maintain lower soil temperatures much longer than on drier sites.

Soil moisture has a direct influence on the internal water status of plants. Low levels of soil moisture result in increased leaf and stem water deficits which, in turn, may impair transpiration and net CO_2 assimilation (Janes, 1973). This partially results from stomatal closure due to increased water stress, and simple dehydration of the photosynthetic system, both contributing to a reduced CO_2 supply (Slatyer, 1967). In addition, water stress in the root systems may inhibit translocation of ions and metabolites, and root development, and may check synthesis of soluble nitrogen and phosphorus into more highly organized compounds needed for growth (Slatyer, 1973).

Aston (1973) has shown that under certain climatic conditions leaf water deficits can occur even when the roots are adequately supplied with moisture. Low soil temperatures can induce water stress in plants by decreasing root permeability and metabolism; this may reduce the rate of photosynthesis, transpiration, and translocation of nutrients. Growth may be decreased without reduction in photosynthesis when leaf and stem water content becomes too low for sufficient turgor for all expansion (Anderson and McNaughton, 1973). Tieszen et al. (1975) have hypothesized that one of the most important limitations to growth and production in tundras is caused by effects of low temperatures on growth and allocation process rather than on the photosynthetic process.

Soil temperature also affects the net radiation profile within the plant canopy inasmuch as the upward infrared emittance is directly related to ground surface temperature. The greatest effect of the infrared component would be during the night when global solar radiation reaches zero. On the other hand, albedo from nearby snowdrifts could contribute substantially to the daytime radiation totals in the canopy. The drifts could also produce local depression in air temperature near the ground surface, particularly in sites shielded from the wind. Surface meltwater and evaporation from prostrate and standing dead vegetation will affect relative humidity in the plant canopy, and this as well as wind and radiation will influence evaporative demand on leaf water content. Net radiation, wind, and vapor density all affect plant temperatures and thus are controlling influences on respiration, photosynthesis, and other plant processes.

5.3.3.3. Methods

-Site selection and plot description

Snow fences were installed on six intensive study sites in each basin; the selection and description of these sites is described by Webber (1971). An experimental and a control plot were located on each site in an area of relatively homogeneous vegetation. Each plot is 1 x 10 m and is permanently delineated by steel stakes. The long axis of each plot is oriented approximately normal to the prevailing wind direction. In most cases, the snow fences are located 5 m to windward and parallel to the experimental plot (Webber et al., 1973). The fences are removed each spring and reinstalled in the fall to minimize summer wind-shielding effects on the experimental plot.

The relative effectiveness of each fence is documented in the 1973 Interim Progress Report (Webber et al., 1973) and will not be discussed here. In general, fences on wind-swept sites were more effective in creating snowdrifts, whereas those located in areas of snow accumulation did not augment snow depths over normal levels. Details of snow fence design are also found in the 1973 report.

Primary production research was concentrated on two sites in each basin, although phenological changes were monitored on the remaining sites (Bock and Reid, Section 5.4). While it was undesirable to discard sites in the production study, manpower limitations made it impossible to sample adequately all original intensive study areas. Sites removed from consideration were those with ineffective snow fences or in areas where vegetation was sparse (e.g., talus slopes). A Geum slope and Kobresia meadow were studied in each basin; this choice facilitated between-basin comparisons since the respective plant communities are similar. These two community types are also characteristic of a large part of the tundra in the San Juan Mountains.

The Kobresia sites are dominated by short grasses and sedges, chiefly Kobresia myosuroides (Vill.) Fiori et Paol, and Festuca brachyphylla Schultes, and short herbs such as Bistorta vivipara (L.), S. Gray, Geum rossii (R. Br.) Ser., and Oreoxis bakeri C. and R. The site in Eldorado basin is better drained and is more poorly vegetated than the Williams site. Both sites are exposed to high winds and are normally blown free of snow during winter.

The Geum sites are characterized by a predominance of low herbs, mainly Geum rossii and Bistorta bistortoides (Pursh) Small. The Eldorado site usually receives more winter snow cover than the Williams site and is not as well drained. Soil characteristics very considerably between sites and this information is summarized in Table 1. Much of the variation between soils can be attributed to differences in parent material; the soils in Williams Basin are derived principally from volcanic rocks, while the Eldorado soils are developing on quartzites and biotite schist.

-Canopy description and biomass estimates

Plant canopy structure has a strong influence on primary production: the spatial arrangement of leaves greatly affects light interception, gas exchange, leaf temperatures, plant water relations, and other factors important to the photosynthetic processes (Monteith, 1965; Baker and Raymond, 1966; Hunt and Cooper, 1967; Pearce et al., 1967; Williams et al., 1968; and others). This study includes techniques for canopy description for two reasons. First, aboveground plant response to increased snow cover may be more subtle than can be measured by standing crop clip-harvests alone. Second, information on canopy architecture is necessary for the modeling objective.

Leaf area index (LAI; ratio of leaf surface area to ground surface area) profiles and leaf angle (LA) profiles are two important canopy descriptors. These were measured using an inclined point quadrat technique (Webber et al., 1973). This technique, modified from Warren Wilson (1959), is nondestructive so the same plots may be sampled repeatedly through the growing season. Therefore, LAI distribution may be monitored as the canopy develops. During the 1973 season, LAI was estimated every two weeks.

All vegetation sampled in 1972 with the point frame was classified according to species. The classification procedure has since been altered to group plants according to their life-form. This has simplified interpretation of the data and facilitated comparisons between basins. The life-form categories are presented in Table 2 and are based on a classification used by Wielgolaski and Webber (1973) in a comparison of tundra vegetation.

Clip-harvesting on each plot during peak season provided estimates of dry-matter production. Five 1 x 10 cm strips were clipped in each plot, and the samples then sorted into (1) live, (2) standing and attached dead, and (3) litter fractions, and oven-dried at 105°C. While LAI has been used to estimate standing crop in the past (Webber et al., 1973), clipped samples provide independent standing crop estimates which also serve as validation points for production modeling.

Weekly phenological measurements were recorded for Geum rossii plants to assess delays in the beginning of growth between experimental and control plots. This was necessary because of occasional logistic problems in making spring observations in the remote study areas while considerable amounts of snow were still present. Fifty plants were marked on each plot, and total plant height, length of the longest leaf, and the number of leaves and inflorescences were recorded.

-Abiotic measurements

A meteorological station is located in each basin and is equipped with a recording rain gauge, hygrothermograph, actinograph, and totalizing anemometer. These instruments provide basic meteorological data for general ecological and geomorphological studies.

Table 1. Analysis of the upper 10 cm of soil on the Geum and Kobresia sites.

Sites	Mechanical Analysis			Available Water	Organic Matter	pH
	64.0 - 4.0 mm	4.0 - 2.0 mm	2.0 mm			
Eldorado Lake Basin						
Geum site						
Experimental plot	29.8	7.3	62.9	10.0	13.4	4.6
Control plot	22.8	7.3	69.9	10.8	11.9	4.5
Kobresia site						
Experimental plot	22.2	13.1	64.7	16.9	10.5	5.2
Control plot	16.8	6.9	76.3	12.4	16.2	5.4
Williams Lake Basin						
Geum site						
Experimental plot	48.8	14.8	36.4	7.5	14.7	5.4
Control plot	31.4	19.8	48.8	6.1	7.5	5.9
Kobresia site						
Experimental plot	30.1	15.5	54.4	11.4	16.8	6.0
Control plot	14.6	17.1	68.3	10.4	13.7	6.2

Mechanical analysis was done by sieving the samples; units expressed are percentages of the total air dried sample weight. Available water was calculated as the difference in moisture retention (percent of oven-dried sample weight) between -1/3 bar and -15 bars moisture potentials, as measured with a pressure membrane apparatus. Organic matter content was determined from weight loss of the sample on ignition at 550°C and is expressed as a percentage of the oven dried (105°C) sample weight. pH was measured with a calomel electrode. All analyses were performed in the INSTAAR sedimentology laboratory.

Table 2. Life-form classification used in the alpine primary production study (from Wielgolaski and Webber, 1973).

Life-form	Code	Example
Shrub		
< 3 cm	S1	Salix nivalis
3-10 cm	S2	S. arctica
10-30 cm	S3	S. planifolia
> 30 cm	S4	S. planifolia
Monocotyledon		
Caespitose, narrow leaved	MT	Deschampsia caespitosa
Single narrow leaved	MS	Carex scopulorum
Broad leaved	MB	Zygadenus elegans
Dicotyledon		
Cushion plants	DC	Silene acaulis
Mat plants	DM	Trifolium nanum
Appressed rosettes	DA	Saxifraga rhomboidea
Upright rosettes	DU	Geum rossii
Erect plants	DE	Castilleja occidentalis
Bryophytes	BM	Polytrichum piliferum
Lichens	LI	Rhizocarpon geographicum

Canopy and soil temperatures are measured on each plot with a multichannel temperature recorder using thermistors as remote sensing elements (Emerick, 1971). One canopy probe (variable height) and three soil probes (1-, 10-, and 30-cm depth) were implanted on each plot and were automatically read every two hours by the recorder.

Weekly soil moisture samples were collected from each plot and analyzed for gravimetric moisture content (ratio of weight of water to the weight of oven-dried soil). These measurements were later converted to soil moisture potentials (expressed in bars) using moisture release curves constructed from water retention data on representative soil samples. These data were obtained by pressure membrane determinations according to Richards (1949). Moisture potential measurements are more meaningful than gravimetric data in the investigation of plant-water relationships and are also required for modeling purposes.

-Modeling

Plants respond to a complex of interacting environmental factors, and as such, it is often difficult to judge in the field specific causes for spatial or temporal changes in the vegetation canopy. For example, the addition of cold meltwater to the soil may either augment or retard growth, depending on the water status of the plants or their tolerance to low soil temperatures. Also, canopy structure may differ between two similar communities; however, it does not necessarily follow that there will be a difference in canopy photosynthesis. Because of these and similar considerations, a modeling approach was used to assess the effects of snow-modified environmental factors on plant processes.

The model used in this study is a mechanistic process model developed by P. C. Miller at San Diego State University and has been extensively modified and refined for application in tundra ecosystems through International Biological Programme (IBP) Tundra Biome research. Because it has been thoroughly described by Miller (1972, 1973), and Miller and Tieszen (1972) a detailed description of the model will not be presented here. The model is based on mean energy budgets for sunlit and shaded leaves at different levels in the canopy and calculates hourly and daily profiles for transpiration, respiration and net photosynthesis. In the present study, the production model has been linked to the Waggoner and Reifsnyder plant canopy environment model (Waggoner and Reifsnyder, 1968; Waggoner et al., 1969). The Waggoner and Reifsnyder model provides temperature, radiation, and vapor density profiles to the production model. Table 3 summarizes the input and output variables for the combined models.

The seasonal course of primary production for a Kobresia meadow was simulated using 1973 data from Eldorado Lake Basin. These data consisted of air and soil temperatures, soil moisture, relative humidity, LAI and LA profiles, and global solar radiation. Other required information such as infrared emittance from the sky and solar diffuse radiation were estimated from 1973 data from Niwot Ridge (Colorado Front Range). Required physiological information on plant water relations was taken from work done by Ehleringer (1973), and various other input values were provided by P. C. Miller (pers. comm., 1974) from model validations done on Niwot Ridge in 1972.

5.3.3.4. Results

Release dates of the experimental plots lagged those recorded for the control plots by at least two weeks on the Kobresia sites (Table 4). The lags were shorter on the Geum sites; between plot differences in snow depths also were less. Prior to 1973, snow release already had occurred on all sites before the first field observers reached the basins (usually in early June). The alpine areas received more snowfall and less wind during 1973 (data from Red Mountain Pass, Ives et al., 1972, 1973) than was recorded in 1972 and snow melt occurred much later. The relatively high amounts of snow on the control plots of the Kobresia sites in 1973 were attributed to low winds and little snow redistribution.

There is little evidence that soil temperatures remained depressed for more than a week after the drift on the experimental plots had melted. Greatest between-plot differences in mean daily soil temperatures were observed on the Eldorado Kobresia site (Figure 1), where differences at the 10 cm depth were more than 3°C for the first six days after snow release. Thereafter, the courses of soil temperatures on both plots were very similar. Spring temperatures under the snowpack usually were nearly 0°C. Upon snow release, soil temperatures began rising rapidly during the first six hours.

Soil moisture data from 1973 show very small differences between the experimental and control plots on both Eldorado Lake basin sites. Differences are much greater on the Williams Lakes basin sites, and the seasonal course of gravimetric soil moisture for both plots on the Kobresia site is shown in Figure 2. The greatest between-plot differences were observed on this site, which is located on a relatively level area, more poorly drained than the other sites. Much higher soil moisture values were recorded during the first week after snow release on the experimental plots of both Eldorado sites, while courses of soil moisture on the control plots were relatively stable.

Leaf area distribution in 1973 did not differ materially between plots in either of the Geum sites, although Eldorado data from all plots were characterized by high variability owing to poor canopy development during this year. Differences in leaf area distribution were apparent between plots in both Kobresia sites during late June and early July. Most of the leaf area was confined to the lower 3 cm of the canopy on the experimental plots. The contrast in canopy development can be seen in Figure 3, which illustrates the distribution of two life-forms on the Williams Kobresia plots. By the end of July distribution of leaf area was essentially the same between experimental and control plots at all sites.

The 1973 seasonal progressions of LAI show little between-plot difference on either of the Geum sites. As with leaf area distribution, the greatest differences between plots were noted on the Kobresia

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Table 3. Summary of input and output variables for the Miller production model.

Input Variables

- Physical parameters
  - Hourly values for:
    - Total incoming solar radiation (cal cm^{-2} min^{-1})
    - Diffuse incoming solar radiation (cal cm^{-2} min^{-1})
    - Infrared emittance from the sky (cal cm^{-2} min^{-1})
    - Wind velocity above the canopy (cm sec^{-1})
    - Air temperatures above the canopy (°C)
    - Vapor density above the canopy (g m^{-3})
    - Ground surface temperature (°C)
- Canopy descriptors
  - Leaf area index profile (cm^2_{leaf} cm^{-2}_{ground})
  - Leaf density profile (mg fresh wt. cm^{-2}_{leaf})
  - Leaf width profile (cm)
  - Leaf angle profile (degrees)
  - Maximum and minimum leaf resistance (min cm^{-1})
  - Parameters defining the leaf resistance-solar radiation and leaf resistance-leaf water deficit relations
  - Parameters defining the light-photosynthesis relation
  - Q_{10} and R_0 defining the respiration temperature relation
  - Extinction coefficient for wind

Output Variables

- Hourly values for:
  - Solar radiation profiles
  - Wind profiles
  - Vapor density profiles
  - Leaf resistance profiles
  - Leaf water deficit profiles
  - Leaf temperature profiles
  - Leaf radiation profiles
  - Transpiration, respiration, and net photosynthesis profiles
- Daily values for:
  - Transpiration
  - Respiration
  - Net photosynthesis profiles

Table 4. Mean snow depths and 1973 snow release dates for the Kobresia and Geum intensive study sites. Snow depth measurements are in centimeters and, except where noted, are averages of ten depths recorded over the 1 x 10 m plot.

	Date	Experimental	Control
Williams Lakes			
Kobresia Site	26 May 71	17.3	None
	14 Oct 71	62.5	None
	28 Mar 72	75.0	6.0
	8 May 73	96.0	51.3
	10 Jun 73		R*
	16 Jun 73	35*	None
	21 Jun 73	R	None
Geum Site	16 Mar 71	24.8	8.1
	14 Oct 71	40*	None
	28 Mar 72	15.5	6.0
	8 May 73	36.0	Trace
	20 May 73		R*
	1 Jun 73	R*	None
Eldorado Lake			
Kobresia Site	16 Mar 72	50*	None
	26 Sept 72	13.1	None
	24 Mar 73	> 1 m	23.4
	5 Jun 73	> 1 m	R*
	8 Jun 73	> 1 m	None
	23 Jun 73	23.0	None
	27 Jun 73	R	None
	29 Mar 74	57.8	None
Geum Site	24 Mar 73	> 1 m	> 1 m
	8 Jun 73	> 1 m	> 1 m
	23 Jun 73	> 1 m	> 1 m
	2 Jul 73	47.3	25.2
	9 Jul 73		R
	16 Jul 73	R	None
	29 Mar 74	90.7	31.5

R Snow release
* Estimated depth of snow release date

sites. Beginning season LAI was substantially lower on the experimental plot than on the control at the Eldorado Kobresia site. There was no "catch up" of the vegetation on the experimental plot with that on the control as had been seen in 1973. A similar trend appeared in the Williams Lake data; however, on this Kobresia site some life forms eventually attained comparable LAIs on both plots. Figures 4 & 5 illustrate the seasonal courses of LAI for two selected life-forms on both Kobresia and Geum sites.

Standing crop data generally reflect LAI between-plot differences at peak season. However, these data also are characterized by high variability and few statistically significant differences between plot means were found. Table 5 shows current-year live standing crop data for 1971, 1972, and 1973. While between-plot means appear to be substantially different in 1971, only two replicates were clipped in each plot and sample standard deviations were large. The number of replicates were increased to five in 1972 and 1973. Few between-year differences were significant except on the Williams Kobresia site where the 1972 standing crop on the control plot was significantly different (95% level) from 1971 and 1973. The 1973 standing crop on the experimental plot was also significantly different from the 1971 estimate.

The seasonal course of net photosynthesis for the upright rossette (DU) life-form on a Kobresia plot as calculated by the production model is shown in

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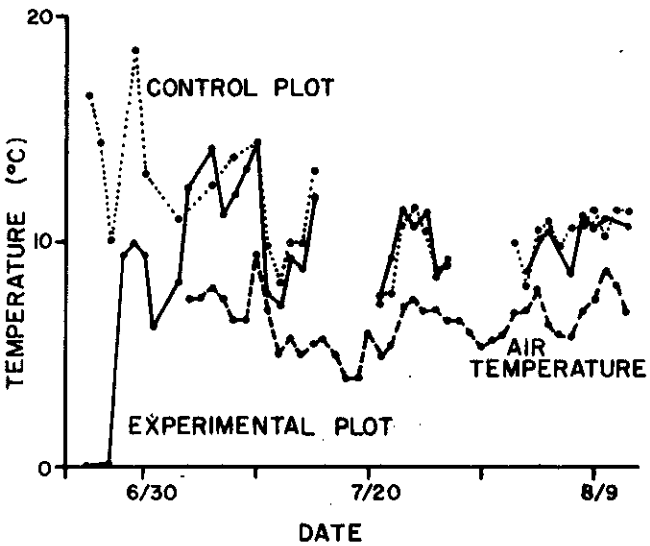

Figure 1. Soil temperature during the summer of 1973 at a depth of 10 cm on the experimental and control plots of the Eldorado Kobresia site. Air temperatures at the Eldorado meteorological station are also shown.

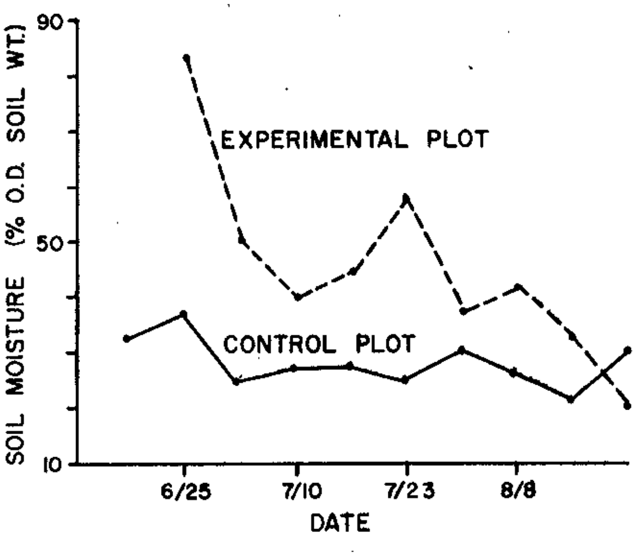

Figure 2. Gravimetric soil moisture on the Williams Lakes Kobresia site during 1973. The moisture retention percentage at -15 bars is 33% on the experimental plot and 26% on the control plot.

Figure 6. Maximum net photosynthesis rates occurred during the beginning of July, when net radiation and soil moisture values were high. Total amounts of organic matter produced during the simulation period for the DU life-form were 41.7 g m^{-2} and 38.9 g m^{-2} for the control and experimental plots, respectively. This amounts to 6.88% less production on the experimental plot. The dry matter portion of the DU life-form amounts to approximately 50% of the standing crop estimates given for the Eldorado Kobresia site in Table 5. Using this percentage, peak season estimates of DU production from clipped samples were 39 g m^{-2} and 37.2 g m^{-2} for the control and experimental plots, respectively, amounting to approximately 4.62% less production observed on the experimental plot. Observed and calculated seasonal production values agree closely as do differences in production between plots.

5.3.3.5. Discussion

There has been some debate over the validity of the snow fence approach in assessing the impact of increased snow cover on a wind-blown tundra ecosystem. It has been argued that drifts caused by the fences are an unrealistic experiment since any snowfall in these areas would normally be removed by the wind. The snowy winter of 1973 was enlightening in this respect; much of the time snow cover of comparable depth to fence-generated drifts was widely distributed over these "snow-free" areas.

Large amounts of the 1973 snowfall occurred as wet spring snow which required relatively high or constant wind for redistribution. Similar situations might be expected in the future if precipitation was substantially augmented during spring storms. In the light of the 1973 snow record, the snow fence approach is believed to be realistic in terms of the plant community types studied and the magnitude of snowdrifts which are produced.

Between-plot differences in most measurements were closely related to snow fence effectiveness, that is, the ability of the fence to generate more snow cover than would normally occur. The most effective fences were on the Kobresia meadows; these are the sites where the greatest contrasts in release dates, soil moisture and temperature, and canopy development were recorded. Striking plant responses in these locations are not unexpected, since Kobresia communities normally occupy drier sites, while Geum communities favor more mesic areas. Therefore, the presence of a snowdrift and shortening of the growing season represents a much greater disruption of natural environmental conditions on the Kobresia meadow.

Local effects of snowdrifts on soil temperature and moisture are limited. Meltwater apparently drains through the coarse-textured soils rapidly as it is released, except for areas having poor drainage, or below large melting snowbanks. As soon as snow release occurs, the soil temperatures rise rapidly and stabilize at surrounding ground temperatures within a few days. A similar trend was observed by Thorn (1974) on Niwot Ridge. He also measured infrared emittance from the ground near melting snowbanks and observed that the banks did not materially influence soil temperatures more than 2 m away, even in wet areas.

The most influential snow-related factor affecting plant production on the San Juan sites appears to be the date of snow release. Later release dates reduce or delay maximum canopy development and lower early

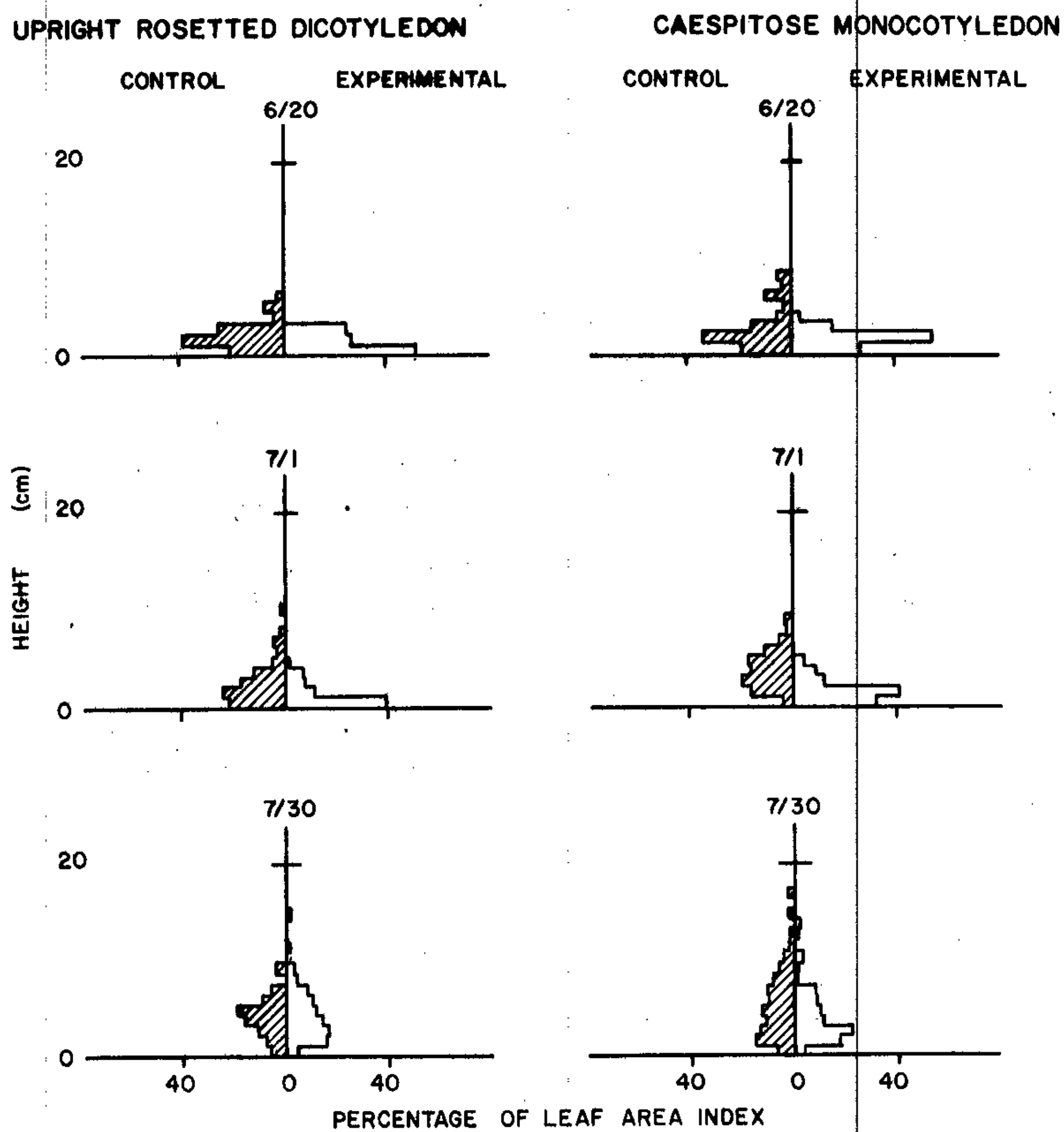

Figure 3. Leaf area index (LAI) profiles for the two dominant life-forms on the Williams Lakes Kobresia site during the summer of 1973. The upright rosetted dicotyledon (DU) life-form is composed mostly of Geum rossii and Oreoxis bakeri on this site, while the caespitose monocotyledon (MT) life-form consists mainly of Kobresia myosuroides. Dissimilarities in LAI distribution between experimental and control plots are much smaller by July 30.

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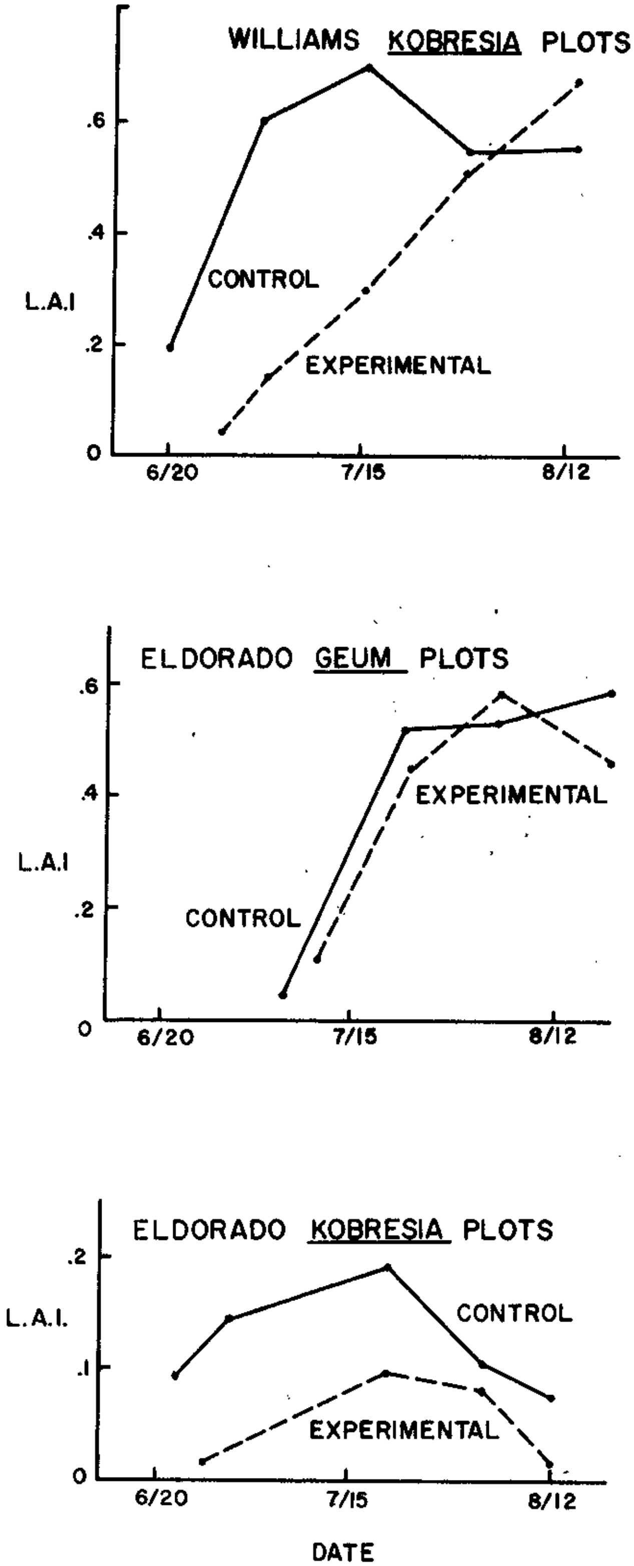

Figure 4. Seasonal course of leaf area index (LAI) for the upright rosetted dicotyledon life-form on selected sites.

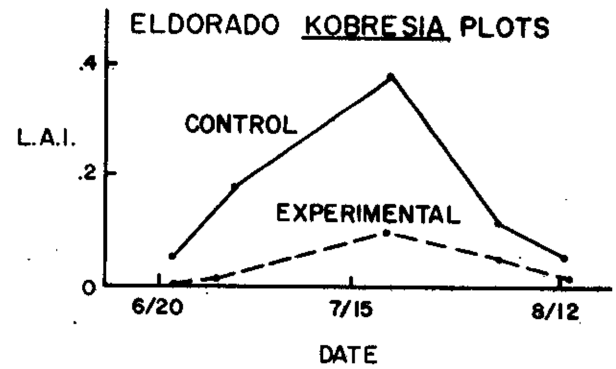

Figure 5. The seasonal course of leaf area index (LAI) for the caespitose monocotyledon life-form on the Eldorado Kobresia site.

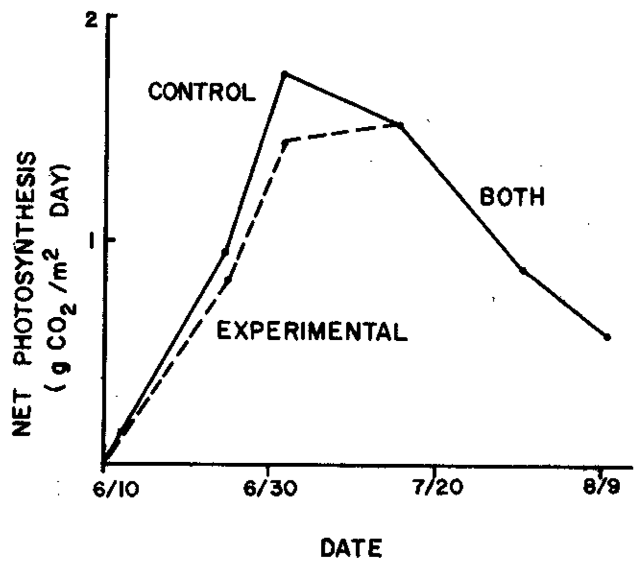

Figure 6. The seasonal course of net primary production on a Kobresia community as calculated by the model. Biological input data were taken from the Eldorado Kobresia plot. In this simulation the onset of growth occurs on the same day for both control and experimental plots, but the latter initially was given lower LAI, 50% higher soil moisture content, and 10°C cooler soil temperatures.

Table 5. Current-year-live standing crop estimates for 1971, 1972, and 1973 on the *Kobresia* and *Geum* plots. Estimates are g m^{-2}.

	1971	1972	1973
Williams Lakes			
Kobresia site:			
Experimental plot	316.7	198.8	213.8
Control plot	359.2	152.0*	283.8*
Geum site:			
Experimental plot	301.1	265.6	289.6
Control plot	196.4	229.2	261.0
Eldorado Lake			
Kobresia site:			
Experimental plot	77.8	n	74.4
Control plot	61.1	n	78.0
Geum site:			
Experimental plot	390.9	n	200.6
Control plot	190.0	n	198.6

n - No samples collected

* - Experimental and control sample means differ significantly at the 95% level.

Note: 1971 and 1973 means on the experimental plot of the Eldorado *Geum* site differ significantly at the 95% level

season light interception efficiency (proportion of total irradiance on green tissue) of the foliage. Restricted canopy development has been shown to strongly limit production in arctic tundra (Tieszen *et al*., 1975).

If the onset of the growing season is delayed until late June, the plants develop when solar radiation is decreasing. While light is not considered limiting in the alpine, a concomitant decrease in air and ground temperatures can lower production rates. Seasonal net production, which includes photosynthate translocated to underground reserves, will be reduced by the shortened growing season as well as by decreased photosynthetic rates. With reduced replenishment of belowground carbohydrate storage, the natural resiliency of the vegetation to sustain poor growing conditions in the future is diminished, and the ability to grow and flower soon after snow release is curtailed.

Many of the trends in canopy development observed in 1972 were not seen in 1973. The midseason catch-up of vegetation on the experimental plots was not as pronounced in 1973, presumably due to the shortened growing season, and possibly due to increasing losses in viability stemming from long-term effects of the snow fences.

Agreement between model results and field observations of seasonal production are quite close. However, these results must be regarded as preliminary, indicating that the model apparently is working well and may be useful in this type of study. Further research in this area is continuing, and it is hoped that additional models of translocation and nutrient uptake can be linked to the production model in the near future.

The snow fences will be maintained as long as possible, although subject to changes in the logistical framework of INSTAAR and compliance by the U.S. Forest Service administration. A limited monitoring program will continue and in this manner the long-term effects of the snowdrifts on plant production and community patterns can be examined.

5.3.4. Snowfence experiments: Decomposition studies

5.3.4.1. The function of decomposition in the ecosystem

All ecosystems are finite; they contain only limited quantities of matter and in order for ecosystems to function their materials must be continually recycled. The productivity of an ecosystem will depend on the rates at which essential nutrients are recycled. This is particularly critical in tundra ecosystems where nutrients are frequently limiting to plant growth (Dadykin, 1954). Any block or change of rate in a matter or nutrient cycle may, because of the holocoenotic nature of the ecosystem, have drastic effects. Nutrient release from biological materials takes place by the process of decomposition. Decomposition is the sum total of a number of subprocesses, for example, bacterial and fungal decay, digestion by soil invertebrates, and chemical and physical leaching.

5.3.4.2. Anticipated effects of increased snow cover on decomposition rates

Until recently, and in fact since this study was initiated, there was only a sketchy understanding of plant and soil decomposition processes. Now there are two edited collections of papers on decomposition, the second of which deals exclusively with tundra (Dickinson and Pugh, 1974, and Holding, et al., 1974). However, nearly all of these papers ignore snow as a factor and we know of only two previous papers which have discussed this (Bleak, 1970; Wood, 1970). Two sets of factors control the decomposition of plant material; so-called external factors such as temperature, available moisture, and soil reaction and nutrient regime, and internal factors such as litter structure and chemical composition.

The effects of increased snowpack on decomposition rates in the lee of the snow fences is likely to be readily measurable. Increased snowfall could decrease decomposition by slowing microbial activity with lower temperatures and less liquid water; also less water might also produce less leaching. However, decomposition proceeds under snowbanks (Bleak, 1970) and as water shortage is frequently a limiting factor to decay it is reasonable to argue that the observed moisture increases resulting from the snow fences will increase decomposition. The different geological and climatic characteristics of the Eldorado Lake area compared to the Williams Lakes area should also affect decomposition rates. The higher soil pH (Heal and French, 1974) and warmer temperatures (Williams and Gray, 1974) should provide higher rates at Williams Lakes than at Eldorado Lake.

5.3.4.3. Methods

Two standard litters of Geum rossii and Salix planifolia were prepared by picking large quantities of green foliage and pressing and drying it between clean herbarium blotters at 105°C. Exactly 2.0 g of standard litter were enclosed in fine nylon mesh 1 x 1 dm envelopes by sewing with nylon thread. Nylon does not decay and was used to keep the litter separate from the soil, natural litter and burrowing invertebrates. These decomposition specimens were placed on each of the six control and six experimental (snow fence) plots in both alpine basins. Specimens were placed at each plot on a clipped and cleared surface and buried at a depth of 30 cm. Both species were installed and each experiment was duplicated. All specimens on a plot were adjacent to one another. The surface specimens were pinned into place and protected from removal by animals and high winds by a 10 cm high cage of galvanized hardware cloth which had a 1/4-inch-square mesh. The buried specimens were installed in soil pits with the original soil and sod carefully replaced. The Williams Lakes specimens were installed in August 1970 and the Eldorado Lake specimens in August 1971. Enough packets were placed in the Williams basin to allow removal after intervals of one, two and four years. In the Eldorado basin only one sampling, after an interval of one year, was planned. Duplicate envelopes of each species and treatment were removed at each sampling period which was was always in late summer or early autumn. The envelopes were cleared of surface debris, opened with scissors, cleaned of any higher plant roots, and oven-dried at 105°C. Results are expressed either as percentage oven-dry weight remaining or its compliment, that is, loss. Careful notes were taken of litter color and state of preservation, also samples were pooled and are currently being analyzed for chemical composition; these results will appear at a later date.

5.3.4.4. Results and discussion

-Williams Lakes Basin

The largest weight losses in green litter occur in the first year, in the second year losses are usually less than 20% of the first year losses, and in subsequent years losses decrease further (Figure 7). Presumably soluble carbohydrate fractions and minerals are readily degraded or removed in the first year but the remaining fractions disintegrate or are degraded less easily. There are essentially no data in the literature to compare with these large initial losses as few studies have used green litter; most studies have used senesced foliage, naturally fallen litter, or pure materials such as cellulose sheets. The present standard litter has a very large cold water-soluble fraction (Geum--49% and Salix--32% on a dry weight basis). The first year weight loss approaches in magnitude this readily soluble fraction. However, decay rates in subsequent years are similar to many published values (Heal and French, 1974) and are similar to some for an alpine site in Norway. The classical decomposition curves follow a negative exponential form (Jenny et al., 1949). In this fashion the loss rate (k) can be expressed as:

$$k = \frac{\text{Log}_e \, (W_o/W_t)}{t}$$

where t is the duration of the decay period in years, and W_o and W_t are the weights at the start and end of the decay period respectively. If k is calculated at the end of the three year period following the large first year losses we find these values: Geum on surface (k = 0.142); Geum at 30 cm (k = 0.110); and Salix on surface (k = 0.019); and Salix at 40 cm (k = 0.052). These compare with the Norwegian alpine values where k ranges from 0.385 in a Birch Forest to 0.031 in a Wet Meadow (Heal and French, 1974).

Geum decomposes more rapidly than Salix (Figures 7 and 8). Geum is a herbaceous soft (sensu Heal and French, 1974) material, probably with lots of carbohydrates, and weight losses equal to or exceeding its weight of water soluble material occur rapidly. Whereas Salix is a hard material, probably with a high proportion of lignins and polyphenols, and thus decays more slowly than Geum. Similar trends are seen in the literature (Heal and French, 1974).

There is a strong correlation between the magnitude of Geum and Salix losses with Geum losing about twice as much weight over the four year period as does Salix (Figure 8). However, belowground the

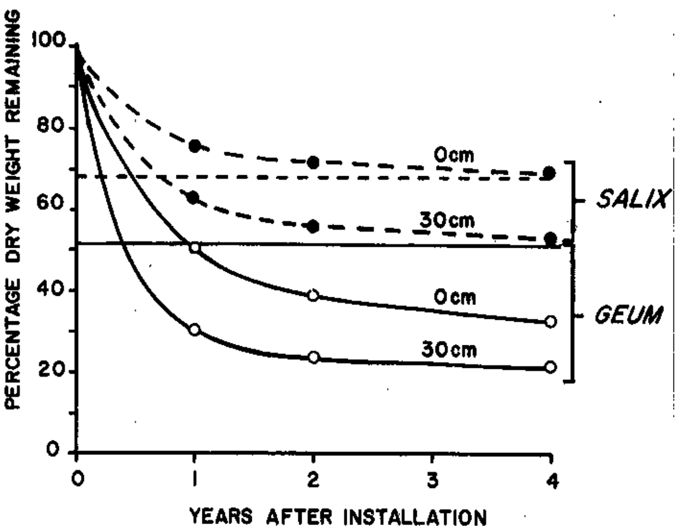

Figure 7. The progression of dry weight loss of green foliage over a four year period from early August, 1970 in the Williams Lakes basin. The percentage weight loss from fine nylon mesh bags containing an initial 2.00 g of oven-dry green litter from two species, Geum rossii and Salix planifolia, installed either on the ground surface (0 cm) or buried in the soil (30 cm), can be compared. Points are means of 24 samples from a total of six sites. The horizontal lines represent the mean weight of non-water-soluble material in the initial oven-dry green foliage of each species.

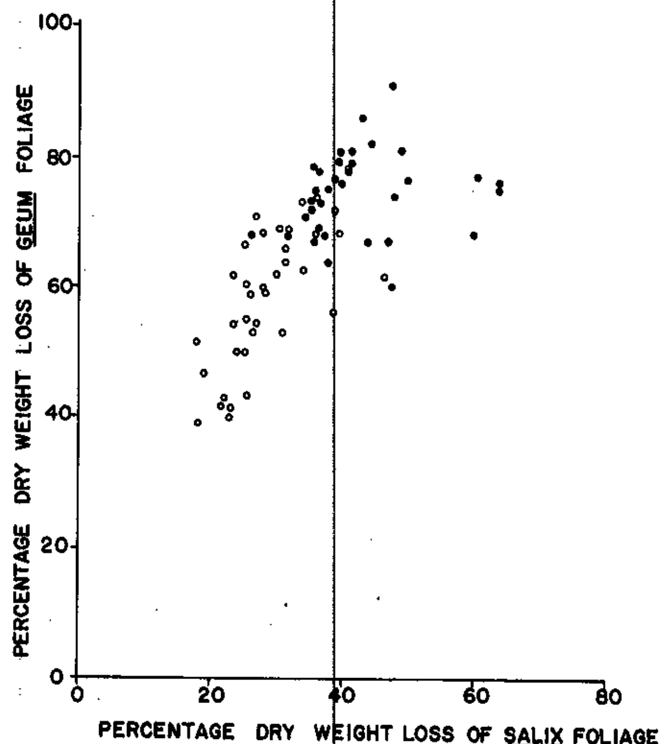

Figure 8. A comparison of rates of decomposition of green foliage of Geum and Salix in the Williams Lakes basin. Surface samples are shown by open circles and buried samples (at 30 cm) by dots. Surface samples of Geum lose weight about twice as fast as surface samples of Salix but the same relationship is not shown belowground. For surface samples $r = +0.57$ ($N = 36$), for buried samples $r = +0.01$ ($N = 36$); and for all samples $r = +0.47$ ($N = 72$). (For $P = 0.001$ and d.f. = 34, $r = 0.52$; for d.f. = 70, $r = 0.38$.)

relationship does not hold in a statistically significant fashion. Presumably the different decompositional environments account for this. The belowground environment is more complex than that aboveground and thus there is a likelihood of greater variations in decay rates. Losses are greater in the soil than on the surface and this is probably a result of greater moisture availability. This point is confirmed by an analysis of decomposition rates as a function of site moisture regime (Figure 9). A clear relationship is seen of increasing decomposition with increasing site moisture for green Geum litter on the surface (Figure 9A). When Geum specimens are buried, however, the trend is different and there is an indication that decay is inhibited by increasing soil moisture possibly as a result of a decreasingly aerobic environment (Figure 9B). The response of Salix is different from that of Geum. Both surface and belowground losses correlate positively with soil moisture and there is no apparent anaerobic inhibition of decay at depth with increasing moisture (Figures C and D). This again demonstrates the complexity of the belowground environment and that different litters do respond differently in similar environments.

-Eldorado Lake Basin

The first year surface losses at Eldorado are identical to those at Williams (Table 6). However, there is a trend of less decay at depth which supports, but does not prove, the hypothesis that the more acid, colder soils of the Eldorado basin are less decomposing than the more basic, warmer soils of the Williams basin. The cause for such regional differences is difficult to assess. A very complete set of decomposition rates for the same standard litters as were used here and other more traditional litters is now available from Niwot Ridge. When analyzed and compared with the present data, these data (which are from 38 different plots spaced along several gradients) may give a better explanation of the causes of regional differences.

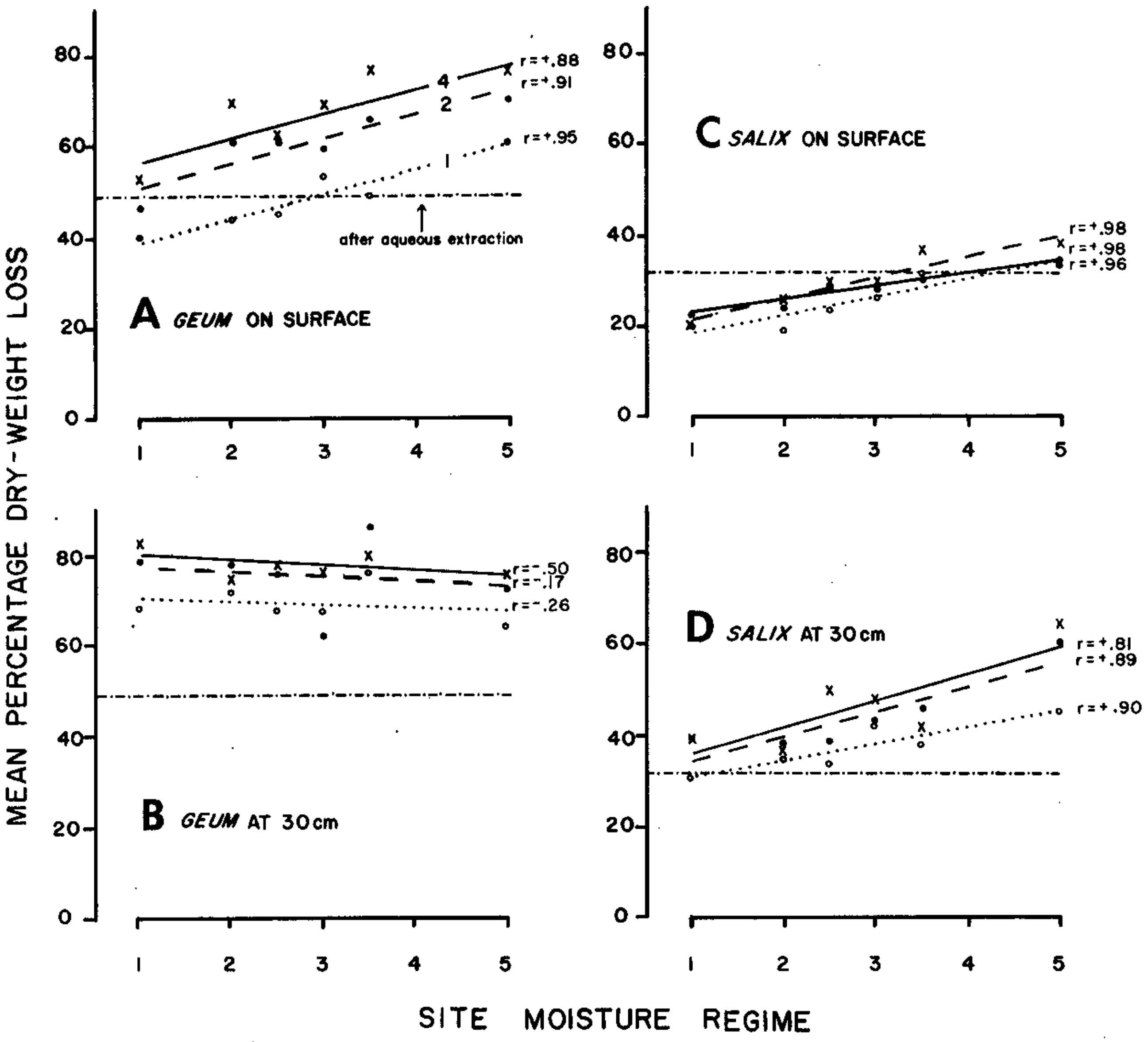

Figure 9. A comparison of the rate of decomposition of green foliage of Geum and Salix along a complex moisture gradient in the Williams Lakes basin. Each point on the graphs represents the mean percentage dry weight loss from the initial oven-dry sample of four samples; two from the snow fence experiment and two from the control at each site. The Site Moisture Regime is a subjective scale; for example a value of 1 would be given to a dry, exposed site and a value of 5 would be given to a site with poor drainage and surface water. Linear regression lines and r-values of decomposition as a function of site moisture are given for each period of decomposition for each species at each depth location (N=6). The symbols (o) and (1) represent losses after one year, (•) and (2) the losses after two years, and (x) and (4) the losses after four years. The horizontal line on each graph represents the mean weight loss of the original green litter after cold water extraction.

Table 6. A comparison of one-year decomposition rates in the two study basins. Values are means ± one standard deviation of percentage dry weight losses of green litter of 24 samples.

Basin	*Geum*		*Salix*	
	0 cm	30 cm	0 cm	30 cm
Williams Lakes 1970-1971	49.0 ± 9.0	69.4 ± 4.2	26.2 ± 6.6	37.7 ± 6.2
Eldorado Lake 1971-1972	48.1 ± 14.9	58.6 ± 10.7	25.2 ± 8.7	33.0 ± 6.2

Snow fence effects.

At first glance the effects of the snow fences on decomposition rates seem mixed (Tables 7 and 8). However, if we look only at surface losses and if each plot with an ineffective snow fence is ignored, it becomes clear that snow fences do have a pronounced positive effect on decomposition rates. For example, on the summit plot (W5-see Table 7) at Williams basin the control occasionally received more snow than the experiment (Webber et al., 1973). In Eldorado basin only plots 5 and 6 have effective snow fences and there is a corresponding increase of decomposition in their lee (Table 8).

The complexity and variability of the belowground decay environment is also shown in Tables 7 and 8 where the increased decomposition resulting from snow fence effects is less belowground than aboveground. A reasonable interpretation of this is that available moisture is the prime limiting factor to decay on the surface and the increased snowpack keeps the foliage wetter for a significantly longer time, whereas belowground the litter has at least some moisture all year. Some sites show increased weight losses where the snow fence was not recorded as effective by Webber et al, (1973). For example, the wet *Carex* meadow (W6 in Table 7) and the moist *Salix* thicket (E3 in Table 8). However, the performance of snow fences in early fall has not been assessed and this could explain the results.

No clear correlation can be seen between measured increase in snow depth and decomposition losses. The length of time that the snowpack is isothermal and melting, and not the quantity of snow is likely to be the controlling factor; but we have no reliable measurements of this. Further evidence for this is suggested by the absence of any clear trends from a correlation analysis of site snow regime with decomposition rate. Snow itself does not promote decomposition; it is liquid water which is important for matter removal by physical or biological agents. The more complete data from Niwot Ridge will be brought to bear on this problem.

No observations were made on how well the litter envelope method represents natural decay. The envelope may stay wetter longer than natural litter or it may repel water from the decaying material. Also this method does not provide a strict analog for the decay of erect dead vegetation which is an important component of the vegetation canopy. Snow may also compact erect dead material into the moister microclimate on the ground surface.

Changes in plant productivity as a result of increased decomposition or nutrient release brought about by increased snowpack would be difficult, if not impossible, to measure. Increased nutrient release might increase production but, if the nutrients are released at snowbank margins before the growing season and are removed from the site during run-off, production might decline. A process model of the type used in this study to simulate primary production combined with a nutrient uptake model might give some clues concerning the long-term effects. Plant canopies on the snow fence plots are more open and do have less erect dead material; this is probably as a result of increased decomposition. This effect can be incorporated into the existing production model but no satisfactory plant nutrient model or soil-decomposition-nutrient models exist at present.

5.3.5. Conclusions from this Interim Progress Report

1. The indirect ordination studies indicate that a change in site snow and moisture patterns will change the vegetation composition. The magnitude of this change will depend on the change of snow accumulation patterns and upon the resiliency of the species in adapting to this change. The nature and extent of this resiliency is being investigated.
2. Snow fences are useful in simulating the impact of increased snowfall. This approach is considered to be realistic in terms of naturally occuring snow cover; however, snow fences are most suitable on sites which do not normally accumulate large amounts of snow.
3. The major influence of increased snow cover on the plant community is to delay onset of the growing season. This is most evident in *Kobresia* communities, which occupy dry, normally snowfree sites. The effect is lessened on *Geum* sites, which usually have moderate snow cover during the winter and favor more mesic locations.
4. The local effects of increased snowpack on soil temperature and moisture are minimal, except in areas below large drifts or having poor drainage.
5. Increased snow cover initially decreases production by reducing leaf area index. A catch up of LAI on the experimental plots to levels on the control plots occurs to some extent, depending on the community type. However, total production for the season is lowered, which may result in substantial depletion of below ground storage over a long-term period. This would seriously

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Table 7. The effect of snowfences on the rate of dry weight loss of green foliage of Geum and Salix in various plots in the Williams Lakes basin. Values are differences (+ or -) as a percentage of the control situations.

Litter type, location, and duration in field	Plots[a]					
	W1	W2	W3	W4	W5	W6
Geum rossii						
on surface (0 cm)						
1970-1971	+5.9	+10.7	+29.9	+3.2	-21.1	+28.3
1970-1972	+15.2	-1.9	+24.2	+16.7	-3.5	+4.4
1970-1974	+5.2	+6.6	+25.4	+1.0	+11.9	+4.6
at depth (30 cm)						
1970-1971	-1.6	+1.1	-0.9	-0.7	+1.3	+9.3
1970-1972	+5.3	-1.3	+10.6	-5.8	+7.3	-12.3
1970-1974	+10.4	-2.1	+2.0	+6.9	+5.8	-1.1
Salix planifolia						
on surface (0 cm)						
1970-1971	+30.3	+6.8	+52.4	+1.9	-9.8	+16.0
1970-1972	+6.7	+8.0	+18.6	+22.9	-6.7	+28.6
1970-1974	+31.8	+6.3	+15.1	+16.2	+19.7	+13.3
at depth (30 cm)						
1970-1971	-28.0	+2.9	-9.0	+25.5	-10.0	-5.4
1970-1972	+1.8	-7.6	+7.2	-25.2	-8.4	-0.5
1970-1974	+20.1	-7.6	+0.2	+2.5	-1.8	-0.6

[a] W1 - dry talus slope, W2 - moist Geum slope, W3 - moist Salix thicket, W4 - dry Kobresia meadow, W5 - dry exposed summit, W6 - wet Carex meadow.

Table 8. The effect of snowfences on the rate of dry weight loss of green foliage of Geum and Salix in various plots in the Eldorado Lake basin. Values are differences (+ or -) as a percentage of the control situations.

Litter type, location, and duration in field	Plots[a]					
	E1	E2	E3	E4	E5	E6
Geum rossii						
on surface (0 cm)						
1971-1972	-28.1	-20.9	+12.2	-12.9	+58.4	+25.2
at depth (30 cm)						
1971-1972	-30.7	+10.9	+5.8	-5.8	-21.4	-26.2
Salix planifolia						
on surface (0 cm)						
1971-1972	-19.3	-38.5	+38.4	-29.3	+45.0	+1.4
at depth (30 cm)						
1971-1972	-1.3	-3.8	+1.5	+12.5	+2.4	+53.9

[a] E1-Dwarf Salix barren, E2-wet Caltha meadow, E3-moist Salix thicket, E4- moist Geum meadow, E5-dry talus slope, E6-dry Kobresia meadow.

reduce the resiliency of the tundra plants under poor growing conditions and to rapidly grow and flower at the onset of growing season.

6. Results of the modeling efforts, although preliminary, show high agreement with observed standing crop estimates. The production model will be a useful tool in assessing the effects of many snow-related factors on primary production processes.
7. Increased snowpack increases the rate of plant decomposition by providing more water to the decaying substrates and perhaps also by compacting standing dead material into a moister microclimate at the soil surface. The effect of this increased decomposition rate on productivity, through plant canopy and nutrient regime changes, are not known.
8. There are still a number of tasks remaining to be completed in this study but substantial progress has been demonstrated. For example, part of the phytocoenological study has been completed and the production model, although more simulations and sensitivity testing are needed, does give plausible output. In the next six months all tasks should be complete.
9. At this time it is possible to make a generalized statement about the effect of cloud seeding on the alpine vegetation of the San Juan Mountains. This statement is based on the intended 15% increase in snowfall and on the assumption that long-standing snow distribution patterns remain essentially unchanged except for perhaps a small increase in the extent of natural snow accumulation areas. Tundra vegetation is so naturally well buffered against year to year environmental change and to short growing seasons that no change will be detected except after decades of operational seeding. If seeding were to stop at any time, the system is unlikely to suffer any irreversible effects. If, however, snow augmentation is increased beyond 15% and especially if the snow were to fall in the spring, the changes would be much greater and would become severe. It is not expected that this statement will alter materially even when all the data are processed and assessed. However, our final statement should be more confident.

5.3.6. Recommendations for Future Studies

1. A soil nutrient monitoring program would greatly complement the existing decomposition study, and should be included in future research. Without more knowledge of the processes involved in nutrient uptake and nutrient cycling, it is doubtful that log-term effects of increased snow cover can be predicted with much certainty.
2. Belowground biomass estimates should be made, since tundra frequently has 90% of its biomass belowground and since tundra plants subjected to poor growing conditions might first exhibit losses underground before appreciable reduction of the canopy is observed.
3. A modeling approach should be strongly considered at the onset of future study. This will greatly contribute to the implementation of an efficient experimental design and also define information deficiencies throughout the study.
4. Intensive study sites should be picked on the basis of a careful analysis of their representativeness of the whole target area and also in areas which offer a high degree of year-around accessibility. The remote nature of the sites used in this study has often made measurements difficult to obtain, particularly during the winter and early spring; the most critical season for this study.

Acknowledgments

Many people have contributed to this plant ecology project and we wish to thank the following people for their help: our faculty, staff and graduate student colleagues at the Institute of Arctic and Alpine Research who have discussed many aspects of this work with us and who have given technical help and advice. In this regard we would like to single out Dr. J.D. Ives, Dr. Nel Caine, Ms Claudia Van Wie, Mr. Rolf Kihl, and Ms. Diane Ebert May. Dr. P.C. Miller and Mr. Wayne Stoner of San Diego State University provided us with a copy of the production model and many hours of their time. This work was performed under Contract Number 14-06-D-6962 from the Bureau of Reclamation, United States Department of the Interior.

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5.4. THE EFFECTS OF INCREASED SNOWPACK ON THE PHENOLOGY OF SELECTED ALPINE SPECIES (Jane H. Bock and William H. Reid)

5.4.1. Introduction

The purpose of our study was to monitor the effects of increased snowpack on the phenology of selected plant species of the Colorado alpine. In two alpine basins in the San Juan Mountains of southwestern Colorado a series of study plots were subdivided into experimental and control areas. Snow fences artificially enhanced snow accumulation in the experimental areas, but did not influence that on the control areas. In other respects, the control areas were comparable to the matched experimental areas. Characteristic plant species were selected on each study plot and phenological measurements were carried out on individuals of these species. These characteristic species were designated "indicator species" for the purposes of this study since they were used to learn if their growth patterns were influenced by increased snow accumulation.

5.4.2. History of the Work

In the summer of 1970, the Williams Lakes basin study plots were selected and the vegetation surveyed. A few preliminary phenological measurements were carried out on the Williams Lakes indicator species. The Eldorado Lake basin study plots were identified, the vegetation surveyed and some indicator species selected. Over the winter, the phenological data were analyzed and selection of the Eldorado Lake indicator species completed.

In the summers of 1971 and 1972, phenological data were collected at Williams Lake and Eldorado Lake. Seeds of indicator species from both experimental and control areas were collected. Over the winter the phenological data were analyzed and germination tests were carried out on the seeds. The earlier work is summarized in Bock (1972, 1973). Indicator species for Williams Lakes and Eldorado Lake are listed in Tables 1 and 3 in Bock (1973). Phenological measurements were recorded on data sheets as given in Bock (1973, Tables 3, 4, and 5).

In the summer of 1973, phenological data and seeds were again collected. Over the winter of 1973, data analyzed, the seeds tested, and the data from 1971, 1972, and 1973 were compared and evaluated.

5.4.3. Summary of the Results

5.4.3.1. Phenology and physical factors

For each of the species studied the relative leaf area of the standing vegetation (Relative Standing Vegetative Area) was computed during the growing season. The expression used was:

$$R_{ij} = \frac{(\bar{N}\cdot\bar{L}\cdot\bar{W})_i}{(\bar{N}\cdot\bar{L}\bar{W})_{max}} \qquad (1)$$

Where

R = the relative standing vegetative area at time i for taxon j;

$\bar{N}$ = the mean number of leaves per plant;
$\bar{L}$ = the mean leaf length;
$\bar{W}$ = the mean leaf width; and
max = maximum observed in each season (1972 & 1973)

Values for each of the indicator species were plotted (Figures 1 to 24) for 1972 and 1973, and these reveal the patterns of growth. In summary, we found that initial vegetative growth of the plants in the experiment plots was retarded by the presence of extra snow. However, both experimental and control plants achieved comparable amounts of vegetative growth and seed set by the end of a growing season. The plants showed considerable phenotypic plasticity in response to the amounts of artificially enhanced snow accumulation in this study. An adaptation to a wide range of snow accumulation is to be expected in alpine plants because of the natural wide range of annual snow accumulation in the alpine.

5.4.3.2. Evaluation of phenological techniques

Several types of phenological measurements were made (Bock, 1973, Tables 3, 4, and 5). The gathering of these data was very time consuming as was the data analysis. In inspecting these data (Figures 1 to 24) we found positive correlations between measurements of leaf lengths and leaf widths and between leaf length and leaf number. In some cases leaf characters, particularly length and width, are highly related. Table 1 provides some examples. It is suggested that in future studies, an intensive determination of these data at the outset will permit a reduction in the field data requirements. For example, it appears that an accurate estimate of vegetative growth in <u>Geum rossii</u> is possible from the measurement of leaf length and number. These computations, using averages for samples of 25, should be supplemented by calculations using the individual measurements. This suggests that few kinds of phenological measurements could be made to obtain the same type of information. Perhaps measurements of total plant height, and leaf length might be as useful for this sort of work as the whole array of phenological measurements. The data will be further analyzed for correlations between measurements and this information will be submitted later.

5.4.3.3. Increased snow accumulation and seed germinability

In the summers of 1972 and 1973, a pilot study was carried out on a comparison of germinability of seeds from indicator species on experimental and control plots. The results of this study are summarized in Tables 2, 3, and 4. They suggest that increased snow accumulation such as that found on our experimental plots is sufficient to inhibit seed germination. This study will be continued on a much larger scale during the 1974 growing season.

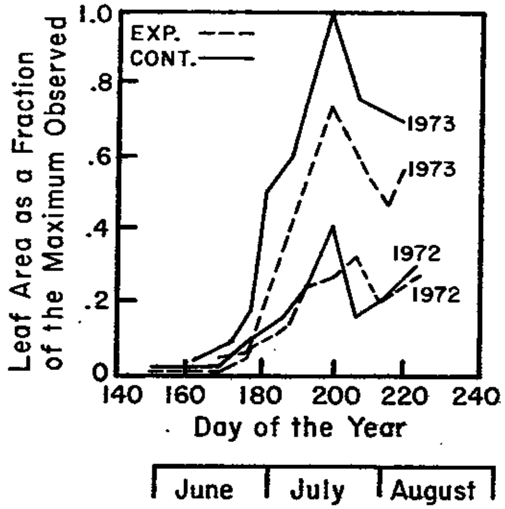


Figure 1. Relative standing vegetative area - Cirsium hesperium (Eastw.) Rydb., Williams, Plot 1.

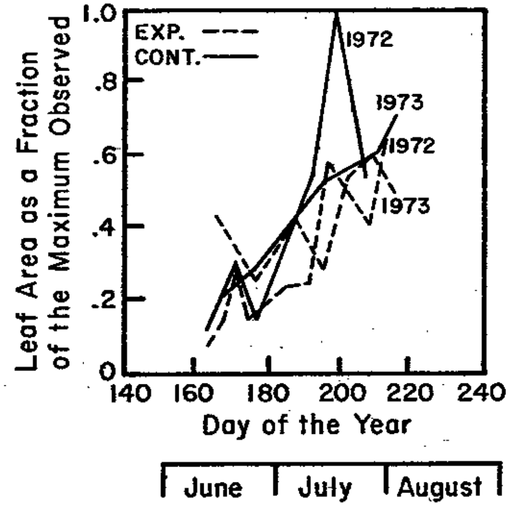


Figure 2. Relative standing vegetative area - Penstemon harbourii Gray, Williams, Plot 1.

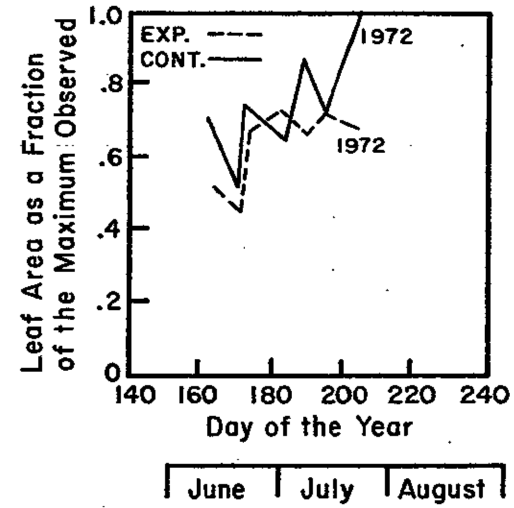


Figure 3. Relative standing vegetative area - Kobresia myosuroides (Vill.) Fiori & Paol., Williams, Plot 2.

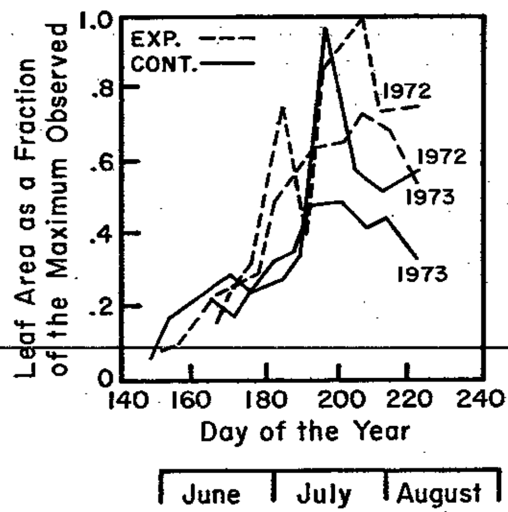


Figure 4. Relative standing vegetative area - Geum rossii (R. Br.) Ser., Williams, Plot 2.

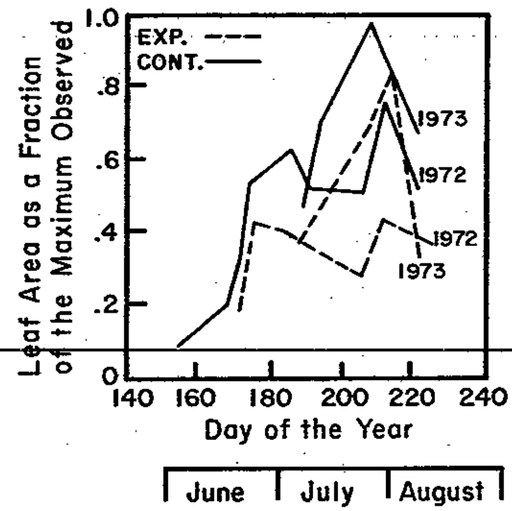


Figure 5. Relative standing vegetative area - Mertensia ciliata (James) G. Don, Williams, Plot 3.

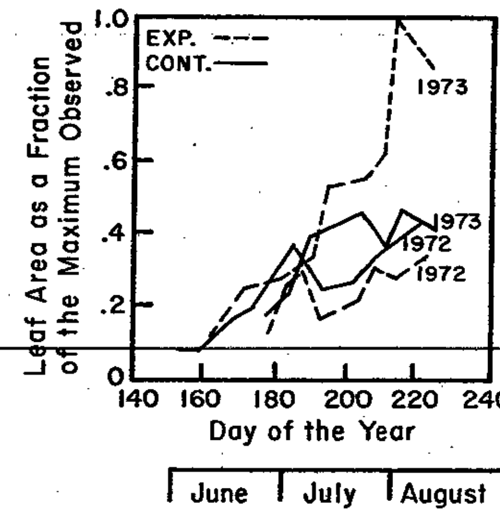


Figure 6. Relative standing vegetative area - Polemonium viscosum Nutt., Williams, Plot 4.

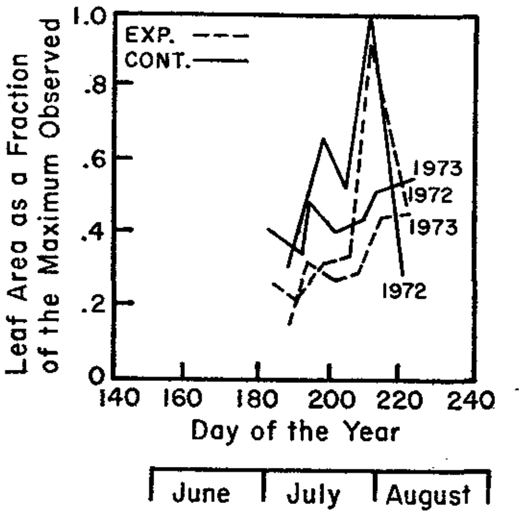


Figure 7. Relative standing vegetative area - Salix brachycarpa Nutt., Williams, Plot 3.

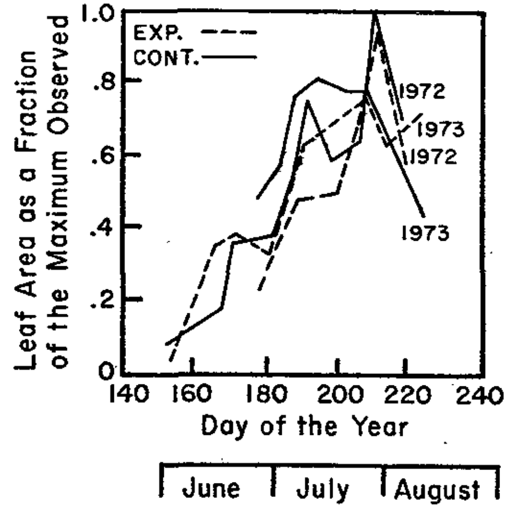


Figure 8. Relative standing vegetative area - Geum rossii (R. Br.) Ser., Williams, Plot 4.

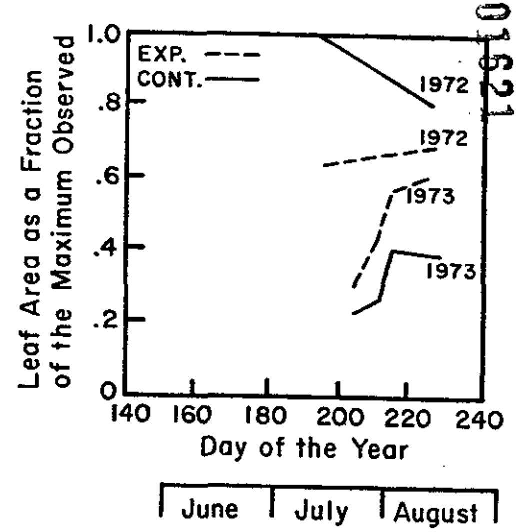


Figure 9. Relative standing vegetative area - Polygonum bistortoides Pursh, Williams, Plot 5.

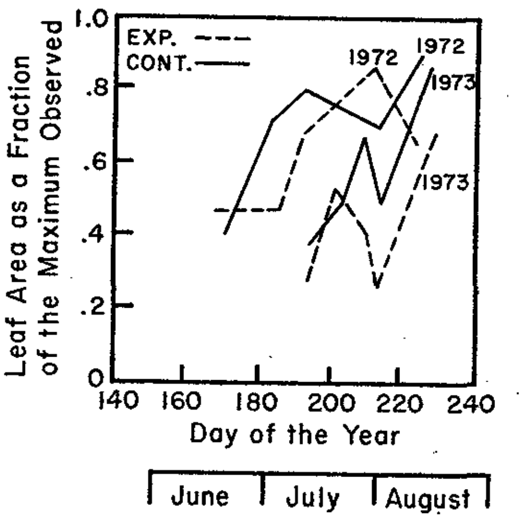


Figure 10. Relative standing vegetative area - Eleocharis macrostachya Britt., Williams, Plot 6.

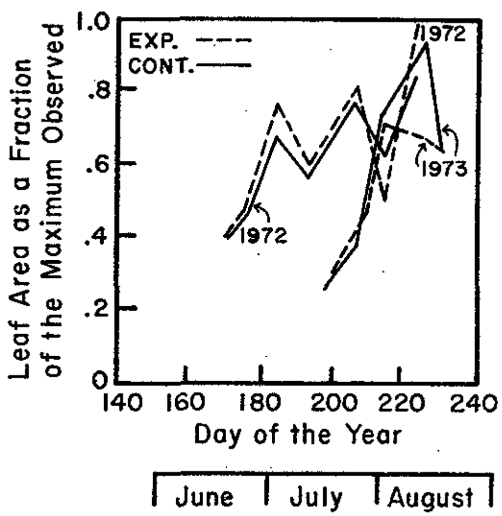


Figure 11. Relative standing vegetative area - Carex scopulorum Holm, Williams, Plot 6.

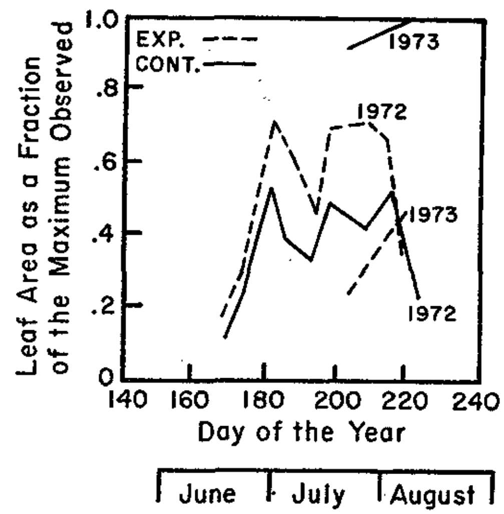


Figure 12. Relative standing vegetative area - Salix arctica Pallas, Eldorado, Plot 1.

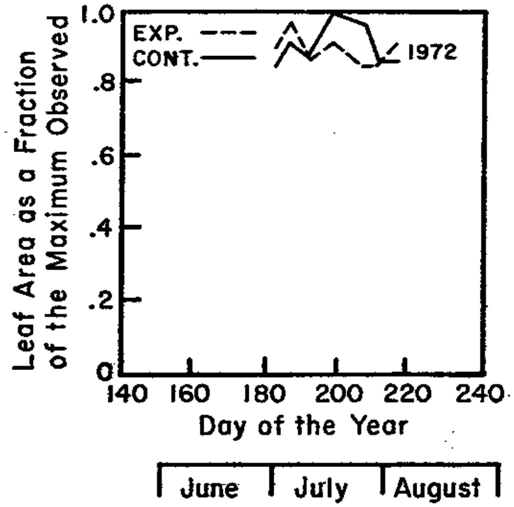


Figure 13. Relative standing vegetative area - Polygonum viviparum L., Eldorado, Plot 1.

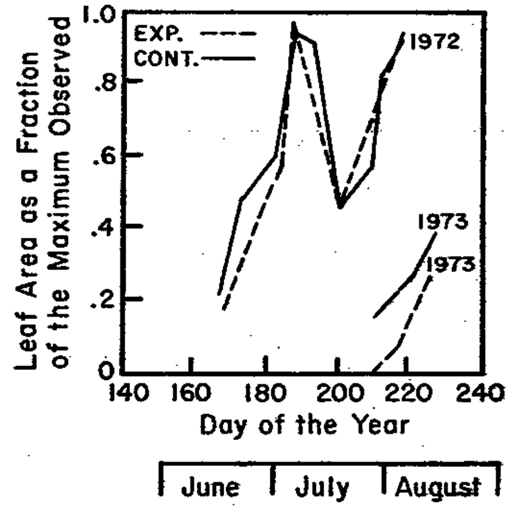


Figure 14. Relative standing vegetative area - Pedicularis groenlandica Retz, Eldorado Plot 2.

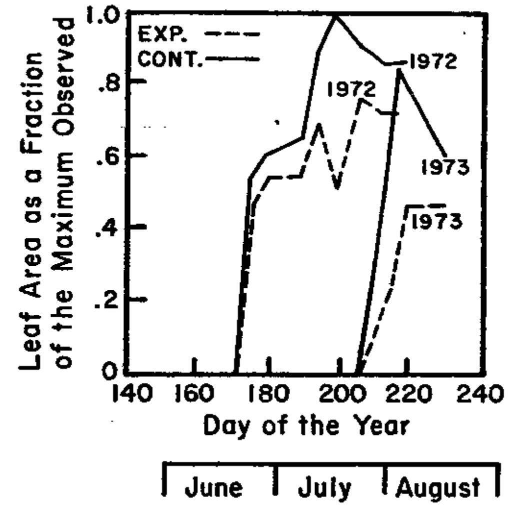


Figure 15. Relative standing vegetative area - Caltha leptosepala DC., Eldorado, Plot 2.

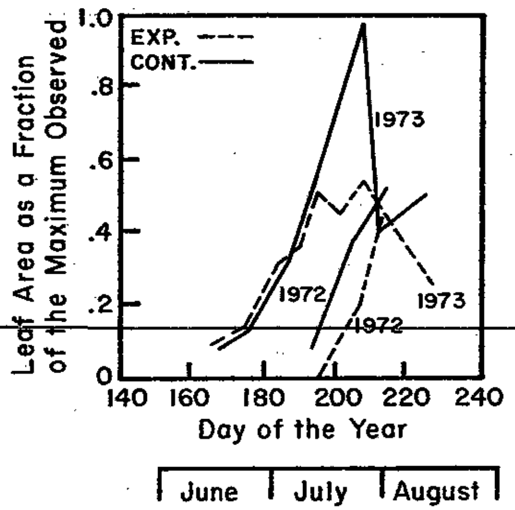


Figure 16. Relative standing vegetative area - Salix psuedolapponum von Seem., Eldorado, Plot 3.

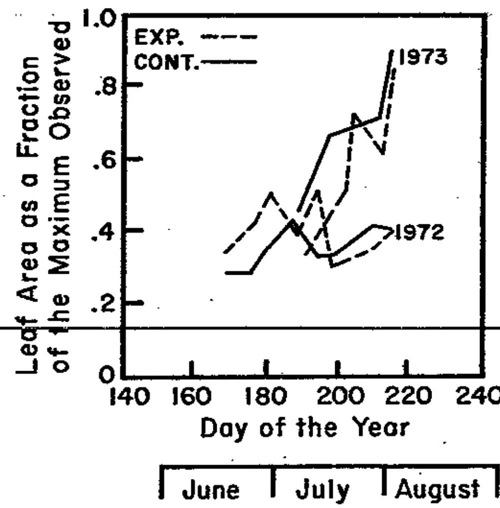
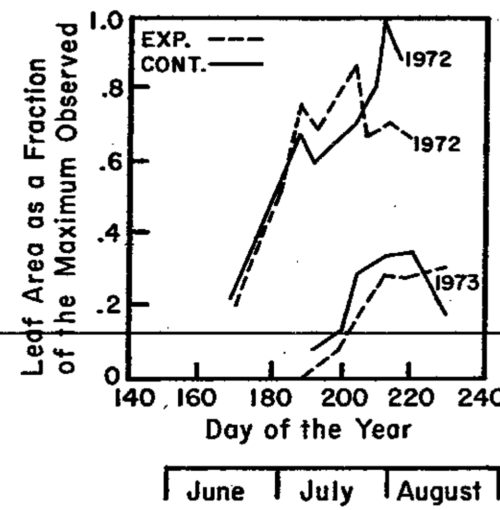


Figure 17. Relative standing vegetative area - Saxifraga rhomboidea Greene, Eldorado, Plot 3.



gure 18. Relative standing vegetative area - Geum rossii (R. Br.) Ser., Eldorado, Plot 4.

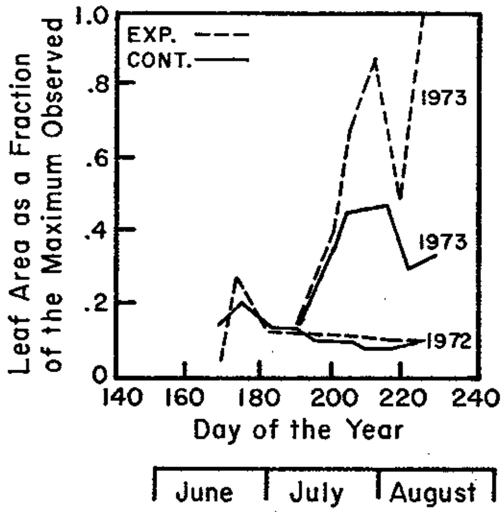


Figure 19. Relative standing vegetative area – Thalspi alpestre L., Eldorado, Plot 4.

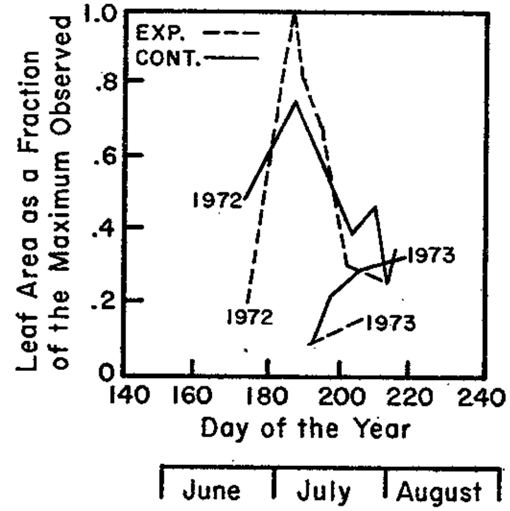


Figure 20. Relative standing vegetative area – Lloydia serotina (L.) Sw., Eldorado, Plot 4.

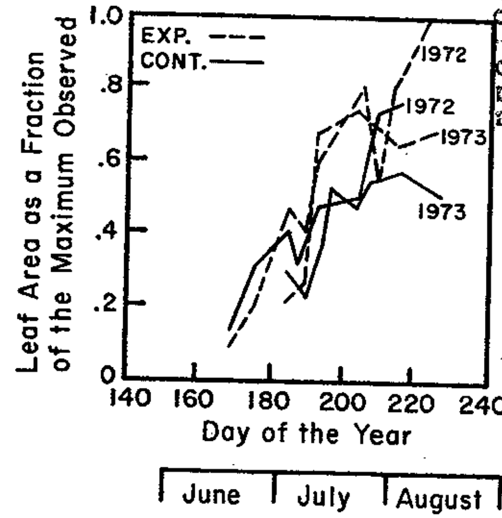


Figure 21. Relative standing vegetative area – Polemonium viscosum Nutt., Eldorado, Plot 5.

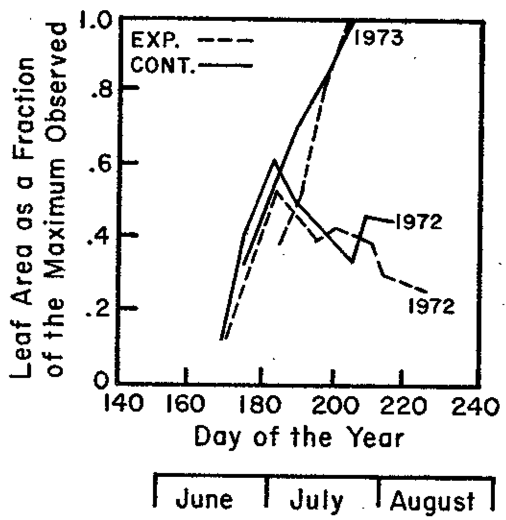


Figure 22. Relative standing vegetative area – Claytonia megarhiza (Gary) Parry, Eldorado, Plot 5.

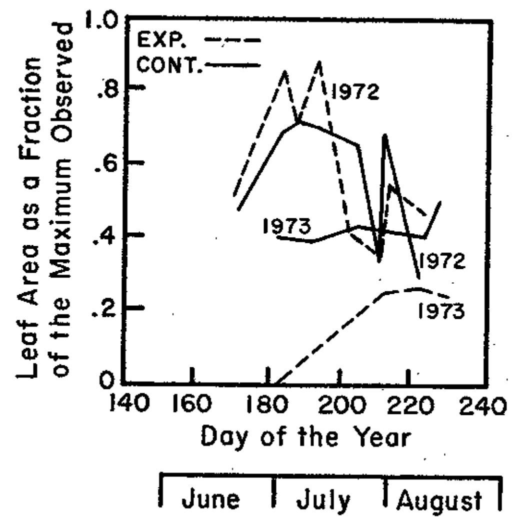


Figure 23. Relative standing, vegetative area – Carex chalciolepis Holm, Eldorado, Plot 6.

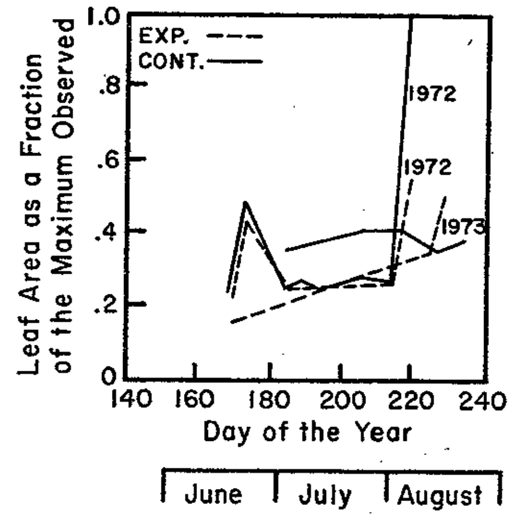


Figure 24. Relative standing vegetative area – Silene acaulis L., Eldorado, Plot 6.

Table 1. Pearson correlation coefficients relating leaf length, width, and number (for all listed values $P < 0.05$).

Species	Year	Plot	Type	Length-Width	Length-Width
Williams Lakes					
Geum rossii	1972	4	E	.981	
			C	.946	
	1973	4	E	.943	
			C		
	1972	2	E	.972	
			C	.986	
	1973	2	E	.854	
			C	.734	
Mertensia ciliata	1972	3	E	.786	.870
			C	.738	.829
	1973	3	E	.863	
			C	.978	
Penstemon harbourii	1972	1	E	.853	
			C	.818	.873
	1973	1	E	.936	
			C	.940	
Eldorado Lake					
Caltha leptosepela	1972	2	E	.938	.783
			C	.958	
Geum rossii	1972	4	E	.911	.815
			C	.899	
	1973	4	E	.955	.964
			C	.897	
Pedicularis groenlandica	1972	2	E		
		2	C	.824	
	1973	2	E	.984	.950
		2	C	.992	.974
Polemonium viscosum	1972	5	E	.882	.930
		5	C	.796	
Salix arctica	1972	1	E	.958	
		1	C	.967	
Salix pseudolapponum	1972	3	E	.998	
		3	C	.898	

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Table 2. Comparative seed germination studies.

		1973			1972			
Species	Plot	Seed[1] Type	% Germ	N	Seed[2] Type	% Germ	N	Summary
A. Eldorado Lake								
Bistorta	1	Ex	80	10	Ex	100	100	Tie
bistortoides		Con	80	10	Con	98	100	
Salix	1	Ex	N.S.[2]	0	Ex	0	50	Control
arctica		Con	84	50	Con	12	50	
Pedicularis	2	Ex	26	100	Ex	0	20	Divided (Ex)
groenlandica		Con	0	100	Con	0	20	
Thlaspi		Ex	7	100	Ex	97	100	Divided
alpestre	4	Con	87	100	Con	33	100	
Claytonia		Ex	3	100	Ex	0	20	Divided
megarhiza	5	Con	0	100	Con	10	20	
Silene		Ex	2.4	100	Ex	64	100	Control
acaulis	6	Con	95	100	Con	97	100	
B. Williams Lakes								
Geum	2	Ex	63	100	Ex	32	100	Divided
rossii		Con	0	100	Con	97	100	
Mertensia	3	Ex	N.S.[2]	0	Ex	N.S.[2]	0	Control
ciliata		Con	0	10	Con	0	4	
Polemonium	4	Ex	0	100	Ex	6	100	Divided (Con)
viscosum		Con	0	100	Con	27	100	
Bistorta		Ex	13	50	Ex	0	100	Divided (Con)
bistortoides	5	Con	50	50	Con	0	100	

[1]Ex = experimental; Con = control

[2]N.S. = No seed set.

Table 3. 1973 germinations without 1972 counterpart

Species	Plot	Seed type[1]	% germ.	N	Summary
Williams Lakes					
Circium hesperium	1	Ex Con	0 0	50 50	Tie
Eldorado Lake					
Caltha leptosepala	2	Ex Con	0 0		Tie
Saxifraga rhomboidea	3	Ex Con	N.S.[2] 12	0 25	Control
Mertensia ciliata	4	Ex Con	0 14	50 50	Control
Polemonium viscosum	5	Ex Con	N.S.[2] 0	0 15	Control

[1]Ex = Experimental; Con = control.

[2]N.S. = No seed set.

5.4.3.4. Relevance of this research to other studies of the effects of artificially enhanced precipitation

Our studies suggest that phenological studies offer considerable promise for the monitoring of the effects of increased precipitation, especially increased snow accumulation. The careful measurement of a few phenological traits may serve as an adequate index of plant growth patterns. Further, we have found that seed germinability may be a very sensitive indicator of increased snow accumulation.

The major flaw in our study is its short duration because changes in vegetation in response to increased snow accumulation are likely to be slow, qualitative changes in the composition of the biotic community. It would be worthwhile to arrange for long-term phenological work in the San Juans where our studies were carried out or in a comparable situation.

Table 4. Evaluation of better germination, total species by year

	1972	1973
Experimental	3	3
Control	10	12
Tie	7	4

LITERATURE CITED

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Bock, J. H. 1973. The effects of increased snowpack on the phenologies of selected alpine species. In Teller, H. L. et al. (eds.) The San Juan Ecology Project. Interim Progress Report for the period November 1971 - December 1972. Colorado State University Report CSU-DWS 7052-2, 104-117.

5.5. DENDROCHRONOLOGY AND DENDROECOLOGY (Paula V. Krebs and Lesley F. Tarleton)

5.5.1. Introduction

Dendrochronologic analysis of ponderosa pine (Pinus ponderosa) offers potential for monitoring the influence of weather modification on tree growth because of known sensitivity of tree growth to climatic change. It has been established by many researchers that tree rings reflect the temperature and precipitation regimes (e.g., Fritts, 1971). The possibility of retrieving climatic information from growth layers depends largely on the site factors which are limiting to tree growth in an area (Fritts, 1971). Fritts has worked largely with trees in the arid Southwest where occurrences of drought are reflected in the growth layers. The effect of limiting climatic factors on tree growth is best observed in years of stress. Trees form thin growth layers when precipitation is low (if precipitation is the main limiting factor), and when temperature is low (if temperature is the limiting factor). Under extremely adverse growing conditions (climatic or otherwise), an annual ring may be microscopic or even missing. At arctic or alpine tree lines, temperature is the limiting factor and growth layers reflect its variation. On dry sites, the growth layer characteristics of P. ponderosa should reflect available soil moisture and so precipitation. Changes in precipitation, such as those due to winter orographic snow augmentation (WOSA), should induce the same response in tree growth as "natural" climatic fluctuations. Our approach, therefore, has been to search for a correlation/regression model for the growth-climate relationship in the years prior to the start of WOSA and to use this in evaluating the growth pattern of the following years.

5.5.2. Coring stations

The growth of trees is assumed to be a response to the amount of available soil water, and so our study sites were selected to represent points along a soil moisture gradient. Station SJS-1 has near-optimum moisture conditions; SJS-2, on a broad ridge crest, is a dry site; and SJS-3 represents the moist end of the continuum. The site characteristics and further details can be found in Glock and Krebs (1971); their locations are shown in Figure 1.

5.5.3. Analysis

Dendrochronologic analysis depends on the recognition of growth layers and the identification of annual increments in growth. It also requires cross-dating between individual cores and the development of a chronology (Figures 2 and 3, Table 1; Glock and Krebs, 1971) if it is to be related to an historical climate record. The smoothing of individual series from separate cores is done by "merging" or averaging them in step-wise fashion.

The skeleton plots of all cores collected from a tree are merged first to form a skeleton plot for the tree which they represent. This is done by averaging the heights of the vertical lines for each of the diagnostically thin growth layers. Diagnostic features of other growth layers are noted if they appear in 50% or more of the core sequences. These derived tree sequences are checked with each other by cross-dating. The tree sequences are then merged to give an area sequence for the stand in which the trees were located.

This merging is the main step in chronology building: the plotting of more and more trees results in a standard master chronology. This emphasizes the diagnostic features common to an area and is a generalized pattern of the growth response of that area. Thus, chronology building includes the merging of skeleton plots into homogeneous units called the tree sequences. Tree sequences are then merged into an area sequence which is the master chronology for the stand. Figure 4 shows the master chronologies for stations SJS-1, SJS-2, and SJS-3.

5.5.4. Trend analysis - a preliminary evaluation

5.5.4.1. Description of the Trend Method

Trend analysis is a method of correlation for continuous time series (Glock, 1942). The trend method has been demonstrated to be a suitable tool for indicating possible relationships between precipitation and tree growth. It requires neither the elimination of secular trends, such as the age curve in trees, nor the estimation of a mean. The analysis gives a measure of the degree of parallel fluctuation between pairs of variables (e.g., tree growth and precipitation; tree growth and temperature) in successive time intervals (Glock, 1950). As in other types of correlation, a high coefficient suggests but does not prove relationship. The trend coefficient is useful for preliminary work involving the comparison of many sets of data.

The trend method yields a coefficient, t, which measures the amount of covariation between two variables. It takes into account not only the number of cases of correspondence in the direction of variation, but also the degree of that correspondence. Values of X and of Y are calculated by taking the successive departures of each year (or whatever interval is used) from the preceding year. If the second of two successive years is the larger, the value of X or Y is positive; if the second of two successive years is the smaller, the value of X or Y is negative. The cross product, XY, for each interval may be calculated and $\Sigma(+XY)$, $\Sigma(-XY)$, $\Sigma(\pm XY)$ (i.e., algebraic sum), and $\Sigma/XY/$ (i.e., absolute values) obtained. The ratio of the algebraic sum $\Sigma(\pm XY)$ to the sum of absolute values $\Sigma/XY/$ gives the trend coefficient (t).

If t = +1.00, the two time series possess perfect parallelism of variation. If t = 0.00, parallel trends equal opposite trends in direction and degree. If t = -1.00, the trends vary in opposite directions in all cases. The range from -1.00 to +1.00 gives a measure of directional variation and degree of variation.

The trend coefficient may be influenced by a few departures of high amplitude whose effect may be detected by a trend index (i). This is the ratio of the average departure of parallel trends to the

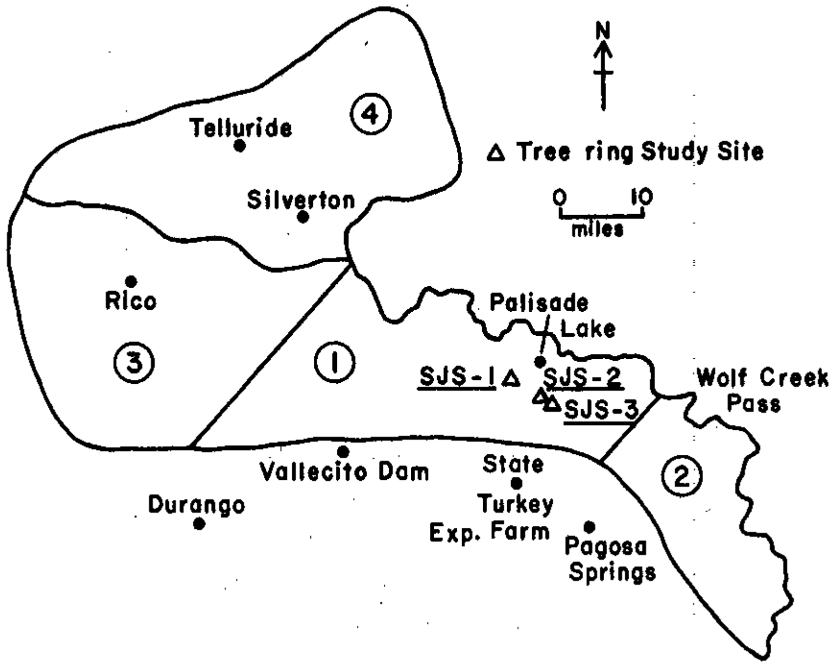

Figure 1. San Juan tree-ring study sites. Map showing locations of sampling sites and weather recording stations: Durango, Pagosa Springs, and Vallecito Dam.

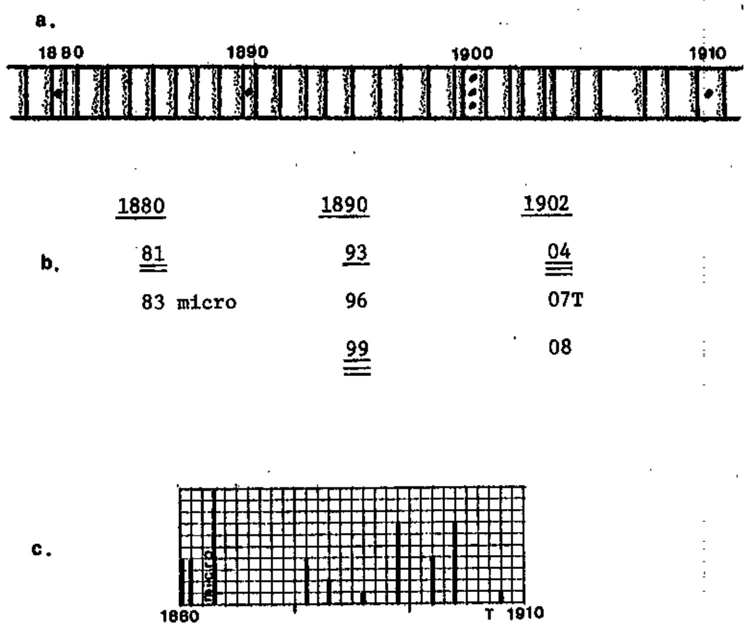

Figure 2. Steps in dendrochronological analysis.
a. surface of core 49-D, 1880-1910.
b. number plot for core 49-D, 1880-1910.
c. skeleton plot for core 49-D, 1880-1910.

average departure of opposite trends.

$$i = \frac{\Sigma(+XY)/n_+}{\Sigma(-XY)/n_-}$$

where $\Sigma(+XY)$ = sum of parallel trends
n_+ = number of cases of parallel trends
$\Sigma(-XY)$ = sum of opposite trend values
n_- = number of cases of opposite trend

If i is greater than 1.00, the amplitudes or departures of parallel trends are greater than those opposite. If i is less than 1.00, the reverse is true. If the value of i departs much from 1.00, then a few departures have an undue influence in determining the value of the trend coefficient, t. Because the trend coefficient may lead to an erroneous conclusion as to the extent of parallel variation throughout a series, the value of i should always be included.

For a time series, the values of t, i, and a ratio of the number of cases of parallel trend to the number of cases of opposite trend yield considerable information on the data sets being correlated. In instances where i is far above or below 1.00 and the ratio n_+/n_- is nearly 1.00, the calculation $T = t/i$ provides a better comparison of the relationship between the variables than does t by itself.

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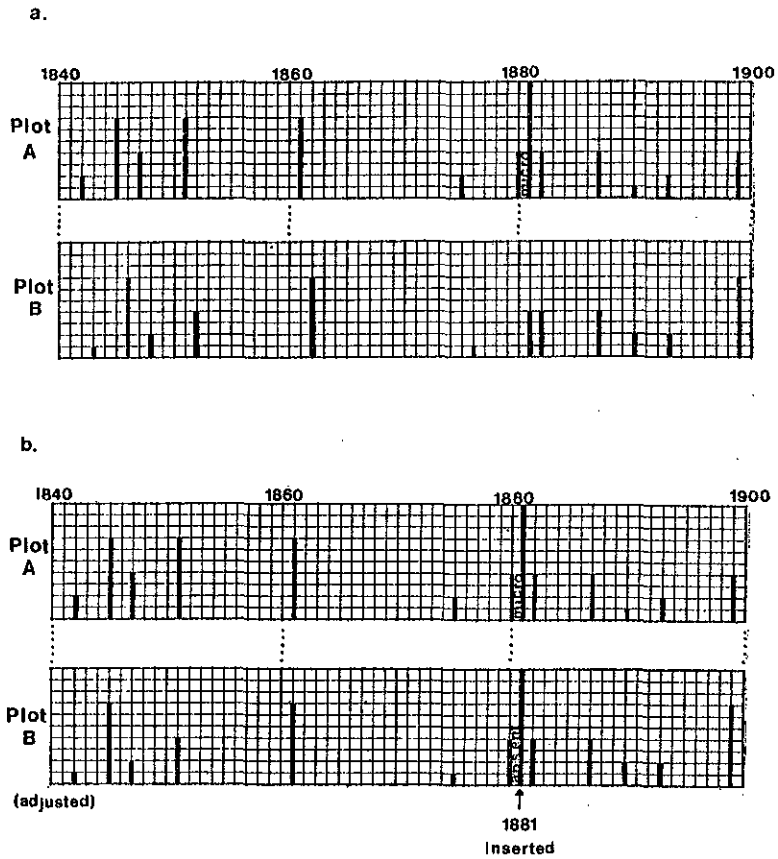

Figure 3. Cross-dating skeleton plots.
a. skeleton plot B matches plot A back to 1881 but plot B is one short of matching to the left of 188.
b. insertion of 1881. The pattern of adjusted plot B now matches all of plot A.

Table 1. Conversion values for core to number plot to skeleton plot.

Core	Number Plot	Skeleton Plot
Recognizably thin	Date notation only	1 unit
Noticeably thin	1 line	2 units
Very thin	2 lines	4 units
Uncommonly thin	3 lines	7 units
Extremely thin	4 lines	10 units
Microscopic	micro	10 units + "micro"
Lens	lens	10 units + "lens"
Not represented	absent	10 units + "absent"

5.5.4.2. Application of trend method

Many sets of climatic data had to be evaluated and compared to make selections for the detailed dendroclimatologic analysis. Weather records for six recording stations were examined for sets of 15 months. These monthly data of precipitation and temperature were in three categories: (1) three months of the preceding growing season for each tree ring, (2) six months of the winter prior to the growing season for each tree ring, and (3) six months during the growing season for each tree ring. The tree ring data represented three coring stations. This meant that there were 270 data set comparisons. The rapidity and ease of direct comparisons using the trend method allowed the grouping of monthly data into meaningful categories for the growth response of trees in the final detailed analyses.

A sample of the results from the trend method is given for monthly precipitation using six recording stations and one coring station for 15 months (Table 2). Only the trend coefficient is included but the preliminary evaluation also considered the index values and ratios. Table 2 is a summary of the results where those values which appeared to be significant are included. From the data sets, the Durango and Pagosa Springs weather records were selected. Pagosa Springs correlations are exceptionally high and relatively consistent. Of particular interest are the trend coefficient values for December (+0.91), January (+0.68), March (+0.62), June (+0.58), and August (-0.72).

The complete trend analysis for monthly precipitation from the Pagosa Springs weather station with tree ring data from Station SJS-1 is given in Table 3. Plots of the trend coefficient (Figure 5), indices (Figure 6), and ratios (Figure 7) aided interpretation. For the previous December precipitation, the variation is mainly parallel and highly correlated. However, the index value is high (4.02), indicating that a few departures have influenced the trend coefficient. Of 28 years of record, 22 show parallel trends. A large number of opposite trends are shown for August precipitation. The amplitude of opposite trends is greater than that of parallel trends. Eighteen of the 28 years of record show opposite trends.

5.5.5. Climatic correlation analysis

The possibility of retrieving climatic information from growth layers depends largely on site factors. Years of greater than normal precipitation are more difficult to evaluate. Growing conditions are not necessarily enhanced with excess precipitation. Thick rings are often noted in a chronology, but not as consistently as thin rings throughout a site or region.

Because of the interrelationships between temperature and precipitation, their effects are not always clear cut and easily separable. In the San Juan area, a comparison of temperature and precipitation records of several weather stations indicates an

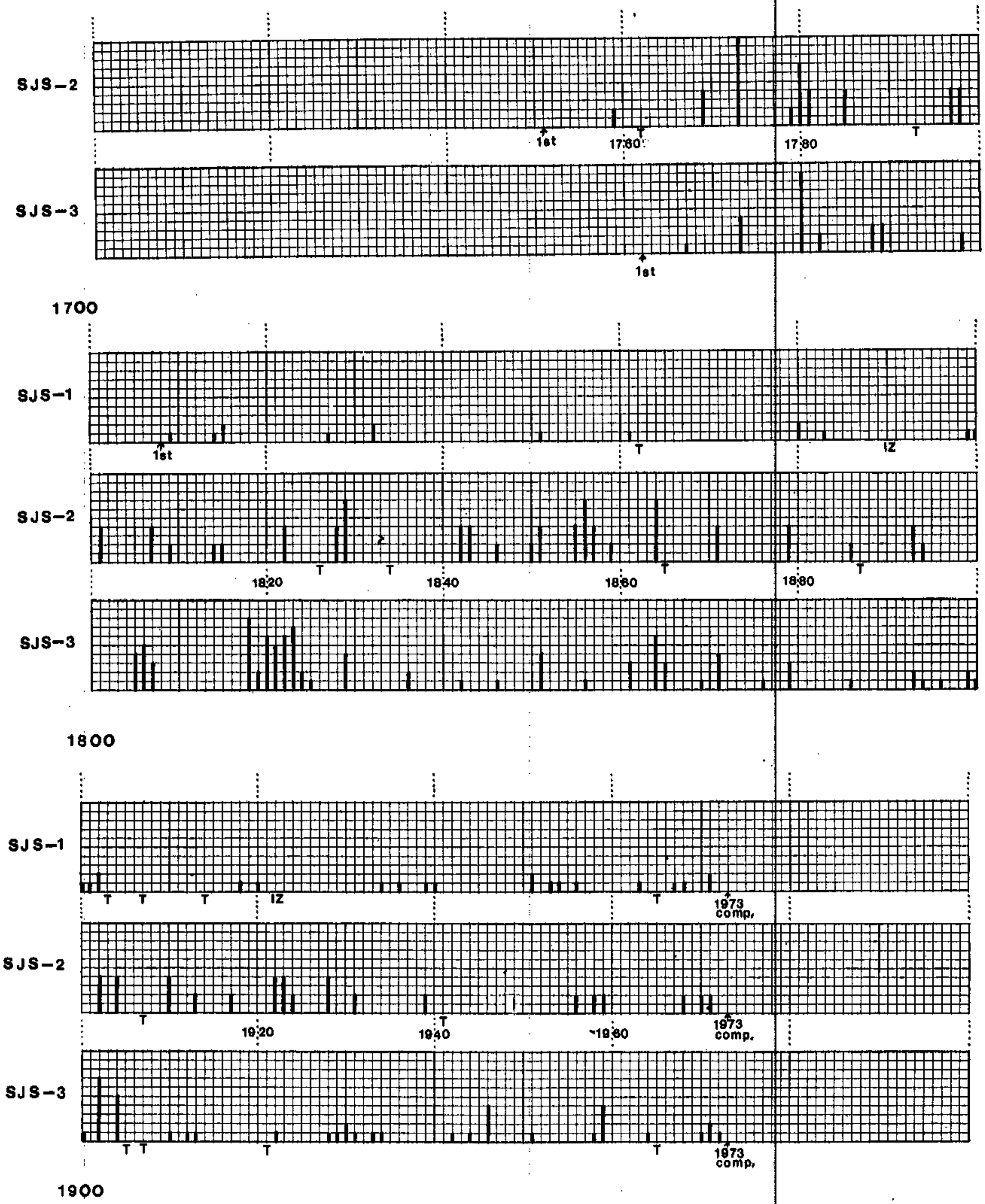

Figure 4. Master chronologies for stations SJS-1, SJS-2, and SJS-3.

Table 2. Summary (trend coefficient) of preliminary analyses using the trend method for precipitation with tree growth of station SJS-1.

Preceding Growing Season

	July	Aug.	Sept.
Ouray	0	+	0
Lake City	-	0	+
Telluride	0	0	0
Durango	-	-	0
Pagosa Springs	+(.51)	+	-
Silverton	-	-	0

Winter Prior to Growing Season

	Oct.	Nov.	Dec.	Jan.	Feb.	March
Ouray	0	+(.53)	+(.49)	-	+(.89)	-
Lake City	+(.61)	+	+(.46)	+.49)	+(.65)	-
Telluride	0	+	+(.57)	+	+	+
Durango	0	+	+(.53)	+.59)	0	+
Pagosa Springs	0	+	+(.91)	+(.68)	+	+(.62)
Silverton	-	+	+(.48)	+(.61)	+	0

During Growing Season

	April	May	June	July	Aug.	Sept.
Ouray	+	0	0	0	-(.64)	+
Lake City	0	+(.54)	0	0	0	0
Telluride	0	0	0	0	+	0
Durango	+	+	+(.66)	+	0	0
Pagosa Springs	-	0	+(.58)	0	-(.73)	+
Silverton	0	+	+	0	+	+

0 = </.25/

± = >/.25/ < /.50/

Value when >/.50/

Length of record used (years): Ouray 23 (1943-1966); Lake City 61 (1905-1966); Telluride 55 (1911-1966); Durango 72 (1894-1966); Pagosa Springs 27 (1939-1966); Silverton 60 (1906-1966).

Table 3. Trend analysis for monthly precipitation data from Pagosa Springs (1939-1966) with tree growth data from station SJS-1 for 1939-1970.

Month	Trend Coeff.	Index	Par[a]	Opp[b]	Ratio	Total N	Missing
July (P)	.51	1.38	18	8	2.25	28	1
Aug (P)	.25	.62	19	7	2.71	28	1
Sept (P)	-.37	.46	12	12	1.00	28	3
Oct (P)	.17	.58	17	7	2.43	28	3
Nov (P)	.41	1.49	16	10	1.60	28	1
Dec (P)	.91	4.02	22	4	5.50	28	1
January	.68	2.03	18	7	2.57	28	1
February	.41	2.05	14	12	1.17	28	1
March	.62	2.02	17	8	2.13	28	1
April	-.38	1.02	8	18	.44	28	0
May	-.07	.95	11	12	.92	28	4
June	.58	2.00	17	9	1.89	28	0
July	.06	1.55	11	15	.73	28	1
August	-.73	.36	8	18	.44	28	1
September	.30	3.12	9	15	.60	28	3

[a]Parallel trend.

[b]Opposite trend.

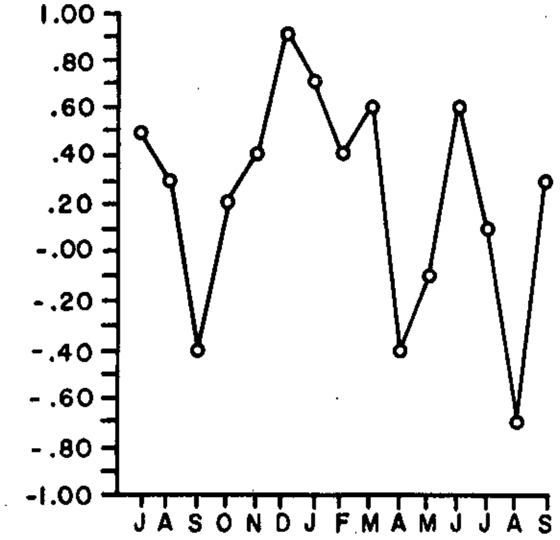

Figure 5. Plot of trend coefficients for precipitation data from Pagosa Springs and tree growth data from station SJS-1.

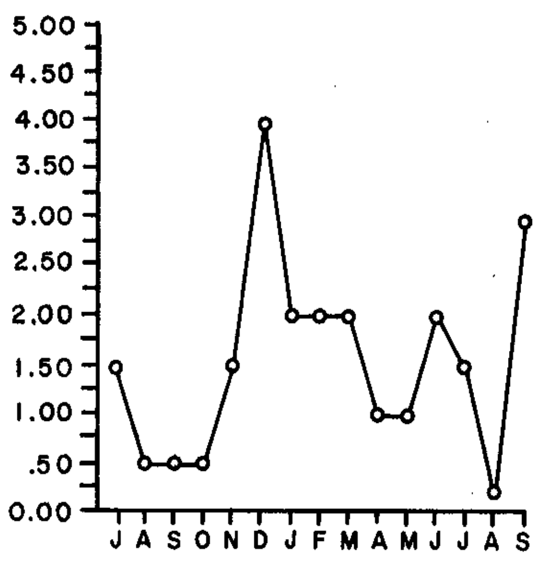

Figure 6. Plot of indices for precipitation data from Pagosa Springs and tree growth data from Station SJS-1.

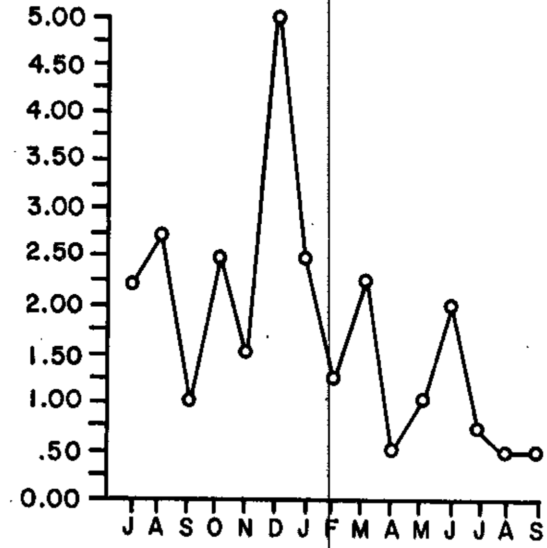

Figure 7. Plot of ratio of parallel trends to opposite trends for precipitation data from Pagosa Springs and tree growth data from station SJS-1.

inverse relationship: warmer periods are associated with low precipitation, colder periods with high precipitation (Barry and Bradley, 1971). Knowledge of tree biology is necessary to determine a tree's response to either or both precipitation or temperature. The relative importance of the factors varies at different times of the year. In the Southwest, where moisture is the limiting factor (except at the upper timberline), the tree ring growth is generally inverse to temperature variation (Fritts, 1972).

The problem of detecting increase in precipitation above normal requirements for the life processes of trees is more difficult. In the San Juan Mountains, thick rings represent an abundance of precipitation rather than a limit for ponderosa pine. Nonetheless, if the climatic regime is reflected in sample tree-ring data prior to cloud seeding, the altered climatic regime due to cloud seeding should be reflected in the rings formed during the seeded years. Preliminary evaluation of the regional growth response indicates that the annual increment of wood should be greater with increased precipitation. Thus, the mean annual tree ring width should increase with an increase in annual available moisture. But such a rise cannot be reliably detected on the small sample of three seeded years. A period comparable in length to that prior to seeding that was used to calculate the mean is necessary. Nevertheless, an attempt was made to predict the ring widths during the seeded years 1971, 1972, and 1973. Prediction formulas are based on the relationships of precipitation and temperature to tree ring widths for the years of climatic record at Durango prior to cloud seeding.

5.5.5.1 Data Evaluation

Approximately 40 cores from 10 trees were composited into each site chronology (Figure 4). Only the last 30 years to 70 years of record from trees of more than 100 years was used so that problems due to the variation of ring width with age in young trees can be ignored. This permits the use of simple averages of annual increments rather than the more complicated standardization procedures of Fritts (1966) and Fritts et al. (1969).

Temperature and precipitation data from weather stations at Durango, Pagosa Springs, and Vallecito Dam (Figure 1) were used, primarily because they are the three closest to the sampling sites. Preliminary evaluation shows them to be usable data sets. Pagosa Springs and Vallecito Dam are about 245 m lower in elevation than the tree-ring sites; Durango is about 490 m lower. Additional information is given in Table 4.

Table 4. Data on weather stations used in this study.

Weather Station	Elevation	Approximate Distance from Tree-ring Sites	Record Period
Durango	1996 m	92 km	1985-1974
Pagosa Springs	2205 m	42 km	1941-1974
Vallecito Dam	2331 m	29 km	1943-1974

Although the distances from stations to tree-ring sites vary from 29 to 92 km, it is assumed that the trees and observations were in the same climatic regime prior to seeding. According to Bradley and Barry (1973), "the San Juan area responds fairly uniformly as a region to seasonal variations in precipitation." Vallecito Dam and Pagosa Springs records are for nearly the same period of about 30 years and the changes from month to month, although slightly different in magnitude, are always in the same direction. The Durango record also follows the same directional changes, but not as closely as the other two. Whether the differences between Durango and the other two are due to the much longer period of record at Durango or to spatial differences is undetermined, but probably both explanations apply.

Durango, although farthest from the tree-ring sites, has the longest record and was included for this reason. To establish a meaningful growth function from climatic data, Fritts believes that at least 60 years of data are needed (personal communication).

Tests for homogeneity of precipitation records by season have been carried out by R. Bradley for Rocky Mountain weather stations with records of more than 60 years for Durango. He finds that the late summer, fall, and winter precipitation data are apparently acceptable, but spring and summer (early) records are suspect (Bradley, 1974).

All three climatic stations are outside the seeded area. Although they reflect the regional climate of the area, effects of cloud seeding should not be expected in their weather records.

Weather observations at the Turkey Experimental Station were discontinued in 1960; Palisade Lake, within the seeded area, data are sporadic, especially in recent years. Although both were considered in the previous report, they were not usable for the analyses described herein.

5.5.5.2. Data analysis

Two statistical approaches were used: step-wise multiple regression and the calculation of serial regression coefficients, monthly and seasonally. Nine step-wise multiple regressions were applied using each combination of the three tree-ring sites and the three climatic stations. The bivariate correlations are in general agreement with Fritts' results for ponderosa pine (Fritts, 1966). The tree-ring growth is best correlated with precipitation and temperature in winter (November-February) and late spring (especially June in the San Juans). In the San Juans, precipitation-tree ring correlation coefficients are nearly all positive; temperature-tree ring correlation coefficients are generally negative (Figures 8, 9, 10, and 11).

Because of instability in relationships between monthly climate data and tree-ring widths, the data were grouped by seasons for statistical treatment. The seasons were chosen for coherence with regard to the biological processes of the tree growth in this area. They are

Season	Month	Season
Summer (prior)	July	
	August	
	September	Fall (prior)
	October	
Winter (prior)	November	
	December	
	January	Winter-Spring
	February	
Spring	March	
	April	
	May	Spring-Summer
	June	
Summer	July	
	August	
	September	
	October	

Stepwise regressions were run with three sets of seasons using Durango temperature and precipitation data. The composition of the sets is as follows: Set 1: (four seasons) summer prior, winter prior, spring, summer; Set 2: (three seasons) fall prior, winter-spring, spring-summer; Set 3: (seven overlapping seasons) set 1 plus set 2.

Winter or winter-spring precipitation was the first variable pulled in five of the six stepwise regressions using SJS-1 or SJS-2. Spring precipitation came first in the sixth case. This is in line with the preliminary work in the San Juans and with

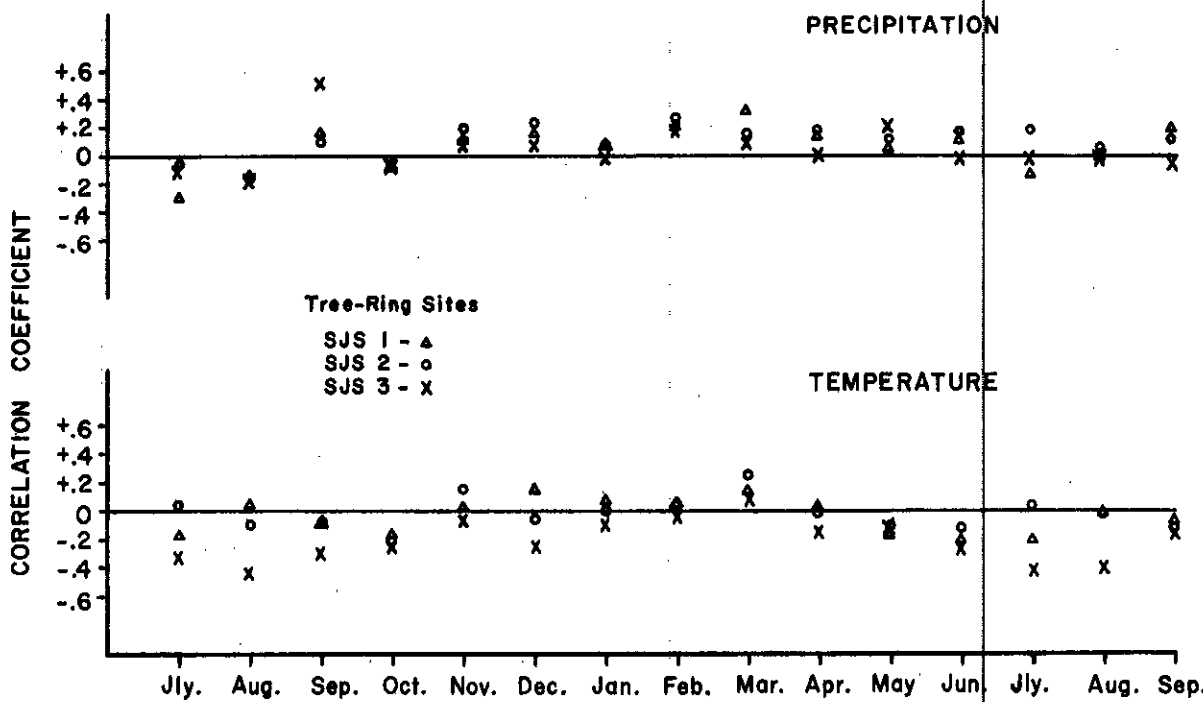

Figure 8. Monthly correlation coefficients of Durango precipitation and temperature with San Juan study tree-ring sites (SJS): SJS-1, SJS-2, and SJS-3.

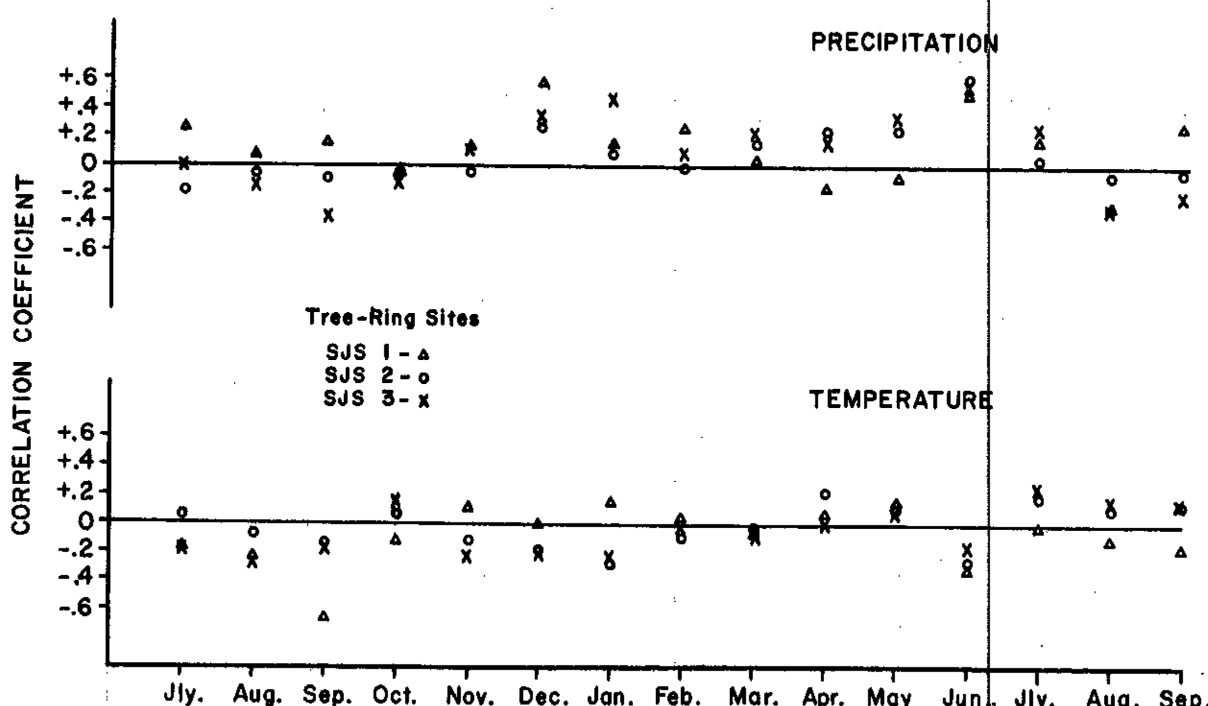

Figure 9. Monthly correlation coefficients of Pagosa Springs precipitation and temperature with San Juan study tree-ring sites (SJS): SJS-1, SJS-2, and SJS-3.

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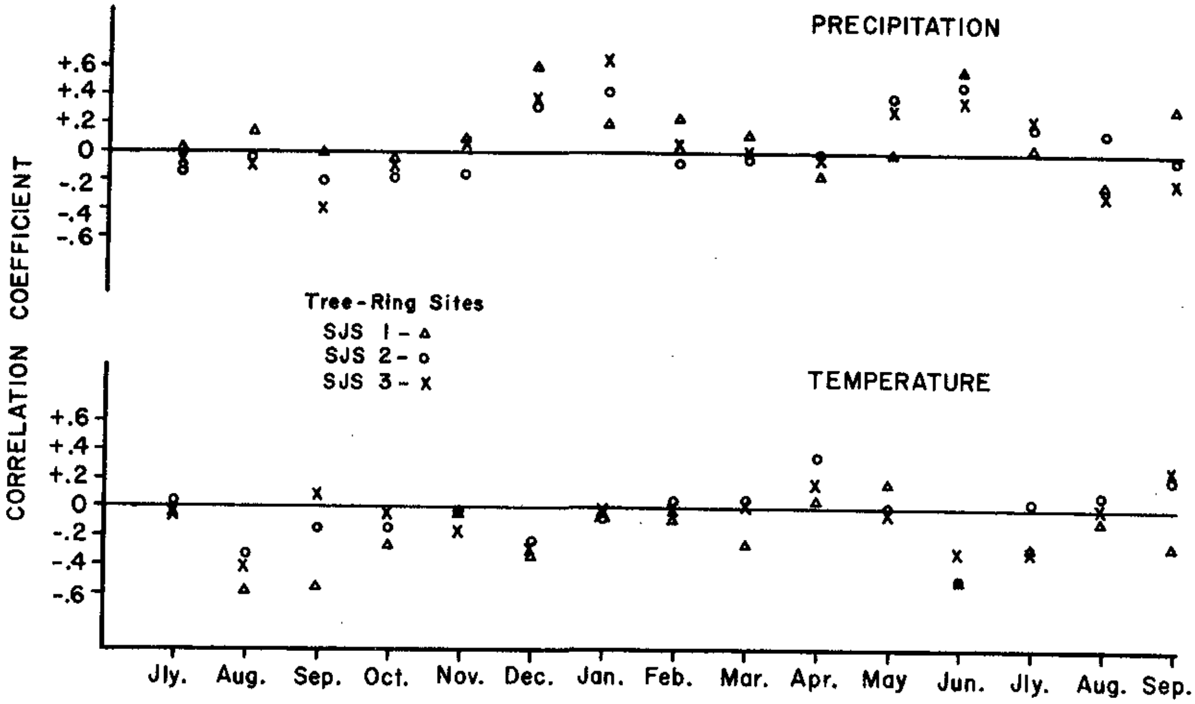

Figure 10. Monthly correlation coefficients of Vallecito Dam precipitation and temperature with San Juan study tree-ring sites (SJS): SJS-1, SJS-2, and SJS-3.

Fritts' work in Arizona and Colorado (Fritts, 1966). This seasonal grouping provides a stability in results that monthly data did not provide. SJS-3 did not show a similar regression relationship and is apparently not well suited for climatic inference. Although it has a high variability in ring-widths (standard deviation: 1.84), the variability does not seem related to variations in temperature and precipitation.

For the period 1896-1970, SJS-1 and SJS-2 have a correlation coefficient of .65. The correlation of both sites with SJS-3 is very low, with a coefficient of about .18 (Table 5). This lack of regional correlation further indicates that SJS-3 is not reflecting the climatic environment in its annual growth layers. For these reasons, results involving SJS03 are considered highly questionable.

The second approach was to compute serial regression coefficients (b) for each month and for each season independently.

$$b = r \frac{S.D.tr}{S.D.cl}$$

b = serial regression coefficient
r = correlation coefficient,
S.D.tr = standard deviation of tree-ring widths,
S.D.cl = standard deviation of temperature/precipitation.

The serial regression coefficients for the four season set using the Durango data and the three tree-ring sites are plotted in Figure 11. For an example of the interpretation of the temperature and precipitation plots shown in Figure 11, consider spring precipitation at SJS-2. The regression coefficient read from the graph is +.06. This means that for each inch of spring precipitation above/below normal the tree-ring width in that year will be increased/decreased .06 mm about tree-ring width. All four seasons shown in Figure 11 affect the size of the growth layer and the factors are cumulative.

Stepwise multiple regression takes into account intercorrelations between variables. This may cause a minimizing of the effect of secondary but essential contributing factors on annual increments. The serial regression discussed above assumes that each season is independent. Physically this is closer to reality, especially in the case of precipitation and also if temperature and precipitation are treated separately, as they have been in this part of the analysis.

Using only the Durango data, two prediction equations were derived: one is based on the stepwise regression and includes the first four or five variables, both temperatures and precipitation, of the regression; the other applies the regression coefficients

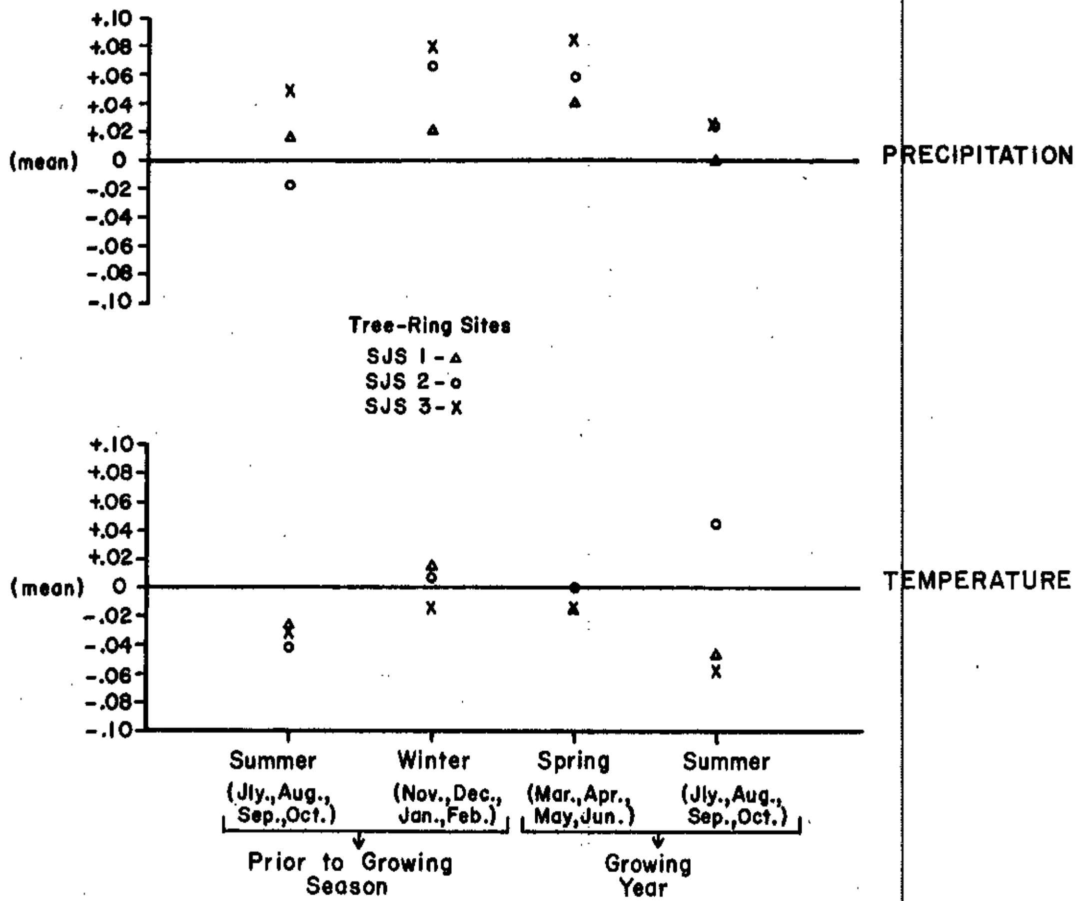

Figure 11. Serial regression coefficients for SJS-1, SJS-2, and SJS-3 for Durango seasonal precipitation and mean seasonal temperature.

for precipitation only. All the precipitation data for the four-season period was used in the prediction. The regression coefficients used are shown in Figure 11 (upper). The coefficients for both types of equation are shown in Table 6. Both of these equations are based on four seasons (Set 1). The equations were used to predict the tree-ring widths for the years 1971, 1972, and 1973, following each winter's cloud seeding, from the Durango seasonal data for those three years based on the relationship between the climatic data and ring-widths for the years prior to seeding (1896-1970).

The results of applying the equations are shown in Table 7. The differences in the sites is striking, whereas the differences in the results between the two types of equations are small. For station SJS-1, the residuals for two out of the three years are well within the confidence of limits. Although the weather modification sample is far too small to be conclusive, this suggests that at SJS-1 the variability in tree-ring width is most influenced by temperature and precipitation. The predictions for SJS-2 are outside the confidence limits of the equations, yet the station has reasonably consistent correlations with winter and spring precipitation. The high positive residuals for station SJS-2 indicate that the weather regime in that area for the seeded years is different from the climatic data set for Durango. It is interpreted that if the weather regime influencing SJS-2 has been changed, the growth response of the trees at SJS-2 is reflecting this change. The predicted values are based on correlations with climatic data outside of the seeded area for post-1970 if there were no seeding. The marked difference between the predicted values

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Table 5. Means and standard deviation of tree-ring widths of each study site chronology during the periods for which there are temperature and precipitation data. Correlation coefficients between the tree-ring tree-ring chronologies for the same periods.

Tree-ring Site	Mean (mm)	S.D. (mm)	SJS-1 r_1	SJS-2 r_2	SJS-3 r_3
			Durango 1896-1970		
SJS-1	1.39	.34	1.0	.62	.18
SJS-2	1.33	.54		1.0	.17
SJS-3	2.15	1.84			1.0
			Pagosa Springs 1942-1970		
	Mean (mm)	S.D. (mm)	SJS-1 r_1	SJS-2 r_2	SJS-3 r_3
SJS-1	1.33	.18	1.0	.37	.40
SJS-2	.82	.26		1.0	.75
SJS-3	1.53	.38			1.0
			Vallecito Dam 1944-1970		
	Mean (mm)	S.D. (mm)	SJS-1 r_1	SJS-2 r_2	SJS-3 r_3
SJS-1	1.33	.19	1.0	.37	.37
SJS-2	.79	.22		1.0	.70
SJS-3	1.50	.35			1.0

and the actual values can be used to extrapolate back to the degree of change at this particular location (Figures 8 and 11). Therefore, stations SJS-1 and SJS-2 are indicators of change and can be used to evaluate the years 1971, 1972 and 1973, and to monitor any future extension of weather modification. The large residuals for SJS-3 confirm the results of the step-wise multiple regression that its variance is due to other than climatic factors (a different drummer!).

5.5.6. Recommendations

1. San Juan Study Sites, SJS-1 and SJS-2, should be retained to monitor the effects of cloud-seeding/winter snow augmentation in the San Juans.

2. The monitoring system should be extended to include additional sites, with attention directed to choosing dry areas with precipitation-limited trees, and areas with near-optimum site conditions.

3. Sites should be compared spatially and in time in order to derive the maximum amount of climatic information.

4. Analysis based on seasonal rather than monthly data appears the most promising for determining the relationships between growth layers of ponderosa pine and climatic data in the San Juan Mountains.

5. Because there is a question as to how much the Durango weather station, upwind and outside the seeded area, reflects any winter precipitation increase due to seeding, it is recommended that computation of serial regression coefficients be tried with the closer Pagosa Springs and Vallecito Dam data.

6. The two closer weather stations, Pagosa Springs and Vallecito Dam, although with only 32-34 years of record, should be included in further studies of the dendrochronology of the area. Durango inclusion should be continued.

7. In satisfying the above six points, prediction of expected growth increments for ponderosa pine is possible using climatic data obtained during weather modification periods (short-term effect), or using projected climatic parameters of precipitation and temperature resulting from potential weather modification.

8. A monitoring methodology for both short-term and long-term effects of weather modification is feasible using dendrochronology.

ACKNOWLEDGMENTS

The authors are indebted to Paul R. Julian for suggestions and assistance on the statistical analysis, to Margaret Eccles for assistance in computer programming, and to Marilyn Joel for drafting of figures.

Table 6. Stepwise multiple regression coefficients, a; and regression coefficients, b, used in prediction equations.

Site	a	Var	b	Var	c	Var	d	Var	e	Var	C	Stand. Error
SJS-1	+.0392	spring precip	-.0161	summer prior precip	-.0327	summer prior temp	+.0209	winter precip	+.0192	winter temp	2.57	0.32
SJS-2	+.0537	winter precip	+.0508	spring precip	-.0524	summer prior temp	+.0295	spring temp	X	X	2.44	0.49
SJS-3	-.4638	summer temp	-.2313	summer prior temp	-.0891	winter temp	+.0726	winter precip	X	X	45.99	1.58

Equation for above coefficients:

$$\text{Annual tree-ring width} = a\,(x_a) + b\,(x_b) + \ldots + e\,(x_e) + C \qquad (1)$$

Where: a, b, ..., e are stepwise regression coefficients

$x_a, x_b, \ldots, x_e$ are the climatic variables for the growth year

C is a constant

Site	a	Var	b	Var	c	Var	d	Var	C	S.E.
SJS-1	+.0166	summer prior precip	+.0317	winter precip	+.0406	spring precip	+.0001	summer precip	1.3854	M
SJS-2	-.0177	same	+.0671	same	+.0592	same	+.0243	same	1.3291	M
SJS-3	+.0499	same	_.0789	same	+.0840	same	+.0250	same	2.1537	M

Equation for above coefficients:

$$\text{Annual tree-ring width} = a(x_a-\bar{x}_a) + b\,(x_b-\bar{x}_b) + c\,(x_c-\bar{x}_c) + d\,(x_d-\bar{x}_d) + C \qquad (2)$$

Where: a, b, c, and d are regression coefficients

x_a, x_b, x_c, x_d are seasonal precipitation totals for the growth year

$\bar{x}_a, \bar{x}_b, \bar{x}_c, \bar{x}_d$ are mean seasonal precipitation values

C(onstant) is the mean ring width

Table 7. Predictions of tree-ring widths (mm) for 1971, 1972 and 1973 from equations in Table 6.

		Equation 1				Equation 2		
	1971	Predict	Actual	Resid.	S.E.[a]	Predict	Actual	Resid.
SJS-1	1971	1.20	1.16	+.04		1.02	1.16	-.14
	1972	1.21	1.84	-.63	±.32	1.24	1.84	-.60
	1973	1.37	1.35	+.02		1.25	1.35	-.10
SJS-2	1971	2.32	.99	+1.33		1.96	.99	.97
	1972	2.48	1.03	+1.45	±.49	2.47	1.03	+1.44
	1973	2.71	.77	+1.94		2.63	.77	+1.86
SJS-3	1971	4.48	1.07	+3.41		3.22	1.07	+2.15
	1972	4.65	1.36	+3.29	±1.58	3.88	1.36	+2.46
	1973	5.53	1.08	+4.45		6.35	1.08	+5.27

[a]Add ± 0.10 mm, the estimated error of measurement, for confidence limits.

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5.6. ECOLOGICAL OVERVIEW. PART I. VEGETATION MAPPING. (Paula V. Krebs and David P. Groeneveld)

5.6.1. Introduction

The vegetation maps of the San Juan Mountains were originally intended to provide a point-in-time data base from which details could be extrapolated from specific study sites to the entire area under consideration. However, several interpretive uses of the mapping became apparent. First, the entire area can be characterized by descriptive categories based on stability and/or instability of the macrovegetation (Krebs, 1973) (distinct vegetation belts reflect the past and current land use practices). Second, the macrovegetation may indicate ecological units for detailed analysis. Third, a generalized vegetation classification indicates the areal extent of the major units from which areas potentially subject to environmental alteration could be selected for specific study.

The descriptive cover-type maps of vegetation generated by this project provide a synoptic view of land use patterns. Their interpretation is based on the relationships between vegetation cover and topography, and the understanding of predictable ecological phenomena. Extrapolation of results from detailed studies to the entire San Juan area provides a means for evaluation of the overall impact of weather modification. Further, changes in vegetation can be detected over periods of prolonged weather modification. The mapped area also includes a spectrum of vegetational units outside the cloud seeded area which may be compared with units inside the seeded in order to detect alterations in the rate of successional change. Separation of existing successional trends from those inducted by long-term weather modification is thus possible. Recommendations for interpretive uses are made in Section 5.6.11 and 5.6.12.

5.6.2. Mapping methodology

The study area covers 14 USGS 7 1/2' quadrangle maps along a belt near the southern border of the San Juan Mountains (Figure 1). Using these maps,

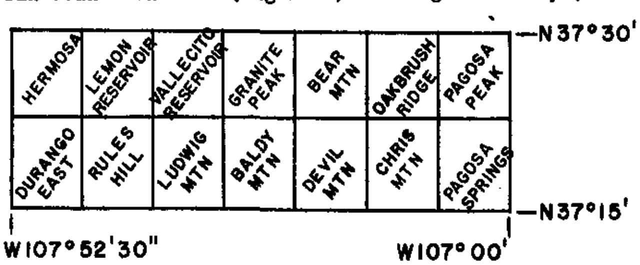

Figure 1. Area covered by detailed vegetation maps at a scale of 1:24,000.

spatial relationships of plant communities and topographic features become apparent. The cover type categories chosen (Table 1) represent recurring plant communities and provide manageable information without confusing detail.

Field-verified cover type standards were noted on preliminary maps and used in photointerpretation to insure a high level of accuracy in the laboratory. The quadrangle-centered 1971 Hurd series of aerial photographic map documents are available for the part of the study area. This Hurd photography facilitates both photointerpretation and spatial correction when transferring the cover type boundaries to the base maps. NASA color infrared imagery (Mission 248, Roll 24, and Mission 238, Roll 48) allows for accurate identification of species. The photointerpretive results from the color infrared aerial coverage were delineated directly on the Hurd photographs. Correct placement of boundaries was insured by keying on geographic points and topographic features visible on the two types of aircraft coverage (Figure 2). For portions of several quadrangles, complete Hurd coverage is not available; thus, photointerpretation is based strictly on the NASA coverage.

The color and hue of the various cover types are distinctive on the color infrared film (Table 2); however, accurate photointerpretation in areas of shadow requires an awareness of both topographic features and elevation. The cover type categories and their boundaries within the shadow areas are, therefore, inferred.

U.S. Forest Service and U.S. Geological Survey aerial photography was used for the preliminary maps. Hurd aerial photographic map documents were acquired from the Colorado Office of State Planning. To obtain aerial coverage for the entire area, however, would be prohibitively expensive. But acquisition of NASA mission coverage (National Aeronautics and Space Administration Aircraft Mission Center) of infrared and color positive films in support of the ERTS-1 and Skylab investigations (contract numbers NAS5-21880 and NAS9-13380, respectively) solved this problem. The NASA flights used in the vegetation mapping are Mission 213 (September 1972), Mission 238 and Mission 239 (June 1973), and Mission 248 (August 1973).

5.6.3. Human influence on vegetation cover

Mining, the first economic attraction in the San Juan Mountains, and associated activities are responsible for more of the present vegetative cover than any of man's other influences. Cultivation is minimal within the study area and is limited primarily to a hay crop at lower altitudes. Riparian communities are maintained along irrigation ditches which supply water to the haying fields. Periodic clearing and burning of the hay fields ensures the continuation of a hay-meadow disclimax and favors the feral establishment of grass and herb exotics As range use increases, a heavy demand is placed upon hay meadows for winter fodder; more land is therefore being converted to this type of agricultural use.

Grazing has a considerable effect upon the ecosystem. Within the grazing range, selective pressure is gradually eradicating those herbs which cattle and sheep find most palatable. As a result thurber fescue (Festuca thurberi) is becoming a rare species in heavily grazed areas. The flocking behavior of sheep and their feeding habits, including uprooting and eating entire plants, produce erosional problems. Continued cycles of sheep grazing may interrupt the normal successional pattern. Large meadow areas,

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Table 1. Vegetation symbol system for wide range usage with corresponding ERTS (Earth Resources Technology Satellite) categories.

Numerical code	ERTS	Category	ERTS category
00.	B.1	Non-vegetated	Exposed rock Exposed soil
01.	W	Water	Water
02.	U	Urban	Urban
110	161	Grasslands	Agricultural
121	C.6	Colorado Blue Spruce	Colorado Blue Spruce
122	D.1	Cottonwood-Willow	Cottonwood-Willow
130	N.1	Montane/Subalpine meadow	Meadow
141	N.2I	0-30% vegetative cover tundra	0-30% vegetated tundra
142	N.2II	30-70% vegetative cover tundra	30-70% vegetated tundra
143	N.2III	70-100% vegetative cover tundra	70-100% vegetated tundra
144	N.3	Graminoid wet meadow Usually tundra	Wet meadow
145	D.2	Alpine shrub	Alpine shrub-Willow
151	D.6	Wet shrub	Wet shrub
152	D.3	Dry shrub	Oak-shrub
153	D.4	Oak	Oak
211	D.5	Aspen	Aspen
221	C.1	Pinon Pine/Rocky Mountain Juniper	Pinon Pine/Rocky Mountain Juniper
222	C.2	Ponderosa Pine	Ponderosa Pine
222.1	C.2	Ponderosa Pine with shrub	Ponderosa Pine
223	C.2	Ponderosa Pine/Rocky Mountain Juniper	Ponderosa Pine
224	C.2.3	Ponderosa Pine/Douglasfir	Ponderosa Pine/Douglasfir
225	C.4	Engelmann Spruce-Subalpine Fir	Spruce/Fir
Shaded	C.5	Krummholz	Krummholz
225.1	C.4	Engelmann Spruce/Douglasfir Londge Pole Pine	Spruce/Fir Lodge Pole Pine
227		Limber Pine/Bristlecone Pine	Not extensive
228	C.3	Douglasfir/White Fir	Douglasfir/White Fir
229		Mixed Coniferous (DF/WF/ESP/PP)	Special analysis required
231	M.1	Douglasfir/Ponderosa Pine/Aspen	DWF, P. Pine, other conifer
232	M.1	Douglasfir/White Fir/Aspen	DWF, Aspen/Oak
233	M.1	Lodge Pole/Aspen	LPA
234	M.1	Mixed Coniferous-Deciduous	CD
161	A.3	Pasture	Pasture
162	A.1	Cultivated crop	Cultivated crop
163	A.2	Cultivated pasture	Cultivated pasture

interspersed with aspen clones are heavily grazed. Browsing destroys the seedling aspen and prevents the expansion of the clones thus insuring the maintenance of extensive meadows.

Public opinion and pressure in recent years have forced discontinuation of the clear-cut logging practice because of the unsightly patchwork deforestation. The selective harvest method, although

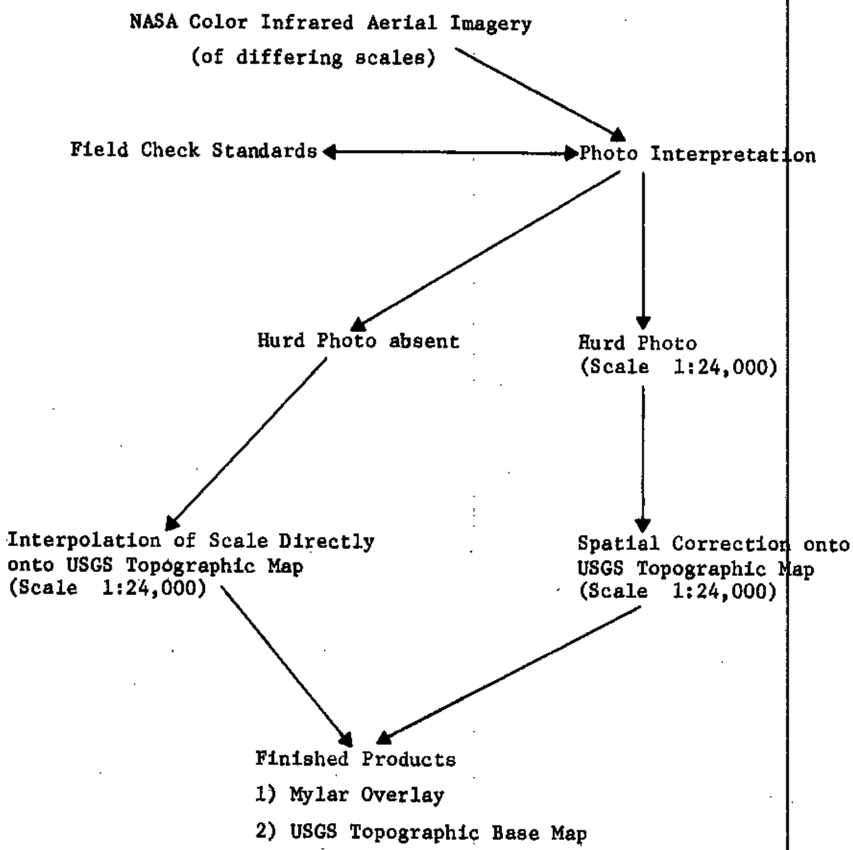

Figure 2. Vegetation mapping methodology.

less efficient, leaves enough trees standing to make the logging scars less noticeable. Both logging practices are ecologically sound. The edges of these logged sites provide a habitat for small fauna and an increase in browse species for big game (Odum, 1953). Fire control is of concern in the San Juans. A strict regime of fire prevention, however, increases the amount of potential fuel in the form of brush and dead trees. This in turn increases the possibility for an extremely widespread and destructive blaze (Odum, 1953). Owing to the intense heat and hurricane force winds, once a crown fire is generated, it will usually burn until topography, moisture gradient, or rainfall halt its advance.

5.6.4. Climatic factors

Vegetation cover is determined by the complex interaction of edaphic, topographic, and climatic influences. In combination, these three factors form discrete microclimate groups, each with a characteristic climax vegetation community.

Influence of elevation on precipitation and temperature is discussed by Barry and Bradley (1971, Fig. 11,15). A complex relationship exists between solar radiation and elevation. At higher altitudes solar radiation is reduced by increased cloud cover but radiation that does penetrate is of greater intensity. The denser tree canopies at high elevations provide insulation that moderates the temperature variations produced up to tree line.

Slope aspect and slope angle determine the incidence and photo-period of solar radiation and consequently drying rates which in turn control available soil moisture, temperature fluctuations, and humidity. During summer an exposed site with high sun incidence tends to dry quickly. Vegetation on these sites must be adapted to water stress during much of the growing season. Dependent upon sun incidence, winter snow sublimation directly affects available moisture for spring melt and the melting rate of the snow which determines the amount of water available during the greatest phase of annual tree growth.

Exposure and other dependent factors determine the elevational zonation of vegetation while air circulation and photoperiod directly affect the evaporation-sublimation rate. Temperature fluctuations are dependent upon site exposure which determines the insulating capabilities of the vegetation cover. These factors either raise or depress the elevational limits of vegetation associations (Figure 3). Broad open valleys or mountainsides, therefore, tend to support vegetation characteristic of lower elevational belts than do steeper and narrower ones.

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Table 2. General photointerpretation characteristics of tree species on color infrared film.

Cover type	Color IR characteristics
Aspen	Blotched, fluffy, and bright red with yellow spectral shift with fall color change. Comparable color to oak, but differentiable in overlap due to shadow length from taller crown form.
Oak	Fluffy, bright red, blotched only at periphery of stand where vegetation becomes discontinuous. Spectral shift in fall but occurring later than in aspen. Leaves are shed much later and the shifted color appears grayer and grainier than that of aspen.
Meadow	Bright red, smooth in spring and early summer due to isolated shrub or moisture patches surrounded by gray brown, bluish, or sand color, indicating reflectance from bare soil and bloomed-out grasses and herbs.
Ponderosa pine	Red brown and fluffy textured with round full crown form.
Douglasfir	Red-brown, fluffy textured, and with same crown form as ponderosa when mature. Differentiable from ponderosa pine only when photointerpreter is thoroughly familiar with ecological amplitude of these two species and pays strict attention to topographic effects in the map area. Usually, Douglas fir grows with a short conic form in areas of ponderosa pine growth. Where Douglas fir grows tall and exhibits a mature, broad crown form, ponderosa pine is usually absent.
White fir	Dark red, conic, and coarsely textured. Easily distinguishable from surrounding tree crowns.
Engelmann spruce	Dark blackish red, darker and less coarse in texture than white fir. Engelmann spruce cover boundaries are easily distinguishable from surrounding forest. Conic in form.
Subalpine fir	Tall, dark red, less dark than Engelmann spruce, but darker than white fir. Tall, spire-like and of the same texture as spruce, usually indistinguishable from Engelmann spruce.
Limber- and bristle-cone pine	Indistinguishable because of limited, scattered, and restricted occurrence. Areas or probable occurrence can be located on ridges with low percentage cover characteristic of these two species.
Pinon pine	Dark brownish red, coarse in texture, and forming rounded bumps. Usually found by checking slope angle, aspect, and elevation and then consulting the photo.
Rocky Mountain juniper	Purplish brown, rounded, small, smooth texture. Distinguishable from pinon pine due to darker color and slightly larger size.

5.6.5. Successional factors

Microclimates are linked to stable climatic factors and change with succession. As light-competing canopies close, soil moisture and duff layers increase, soil pH decreases, and due to increased insulation, diurnal temperature fluctuations are moderated. Each succeeding stage, known as a sere (Clements, 1916) produces microclimate modifications that allow invasion and dominance of another sere. At climax, the vegetation cover maintains one stable microclimate produced stepwise by its predecessors.

Competitive ability for any cover species depends mainly upon shade tolerance (Baker, 1949). Increasing shade primarily eliminates seedlings and as a result a climax stand will usually contain a proportion of relics from the preceding sere. Due to the long lifespan of trees, a climax equilibrium seldom is reached before a fire again denudes the forest cover and allows these trees to repopulate (Daubenmire, 1968). Relics, however, are not well adapted to the microclimate of the climax stand and the increased humidity and crowding tend to induce susceptibility to insect damage, disease, or fungus infection (Vaartaja, 1962).

5.6.6. Cover types

The frequency of deciduous cover dimishes with an increase of the elevation. This is caused by increased moisture and lessening of the fire potential (Van Wagner, 1970).

Coniferous-deciduous cover type represents a successional stage. The selective cutting of logging usually produces this cover type without large and pure deciduous stands. Coniferous-deciduous cover surrounding these deciduous stands usually indicates recolonization of conifers following fire.

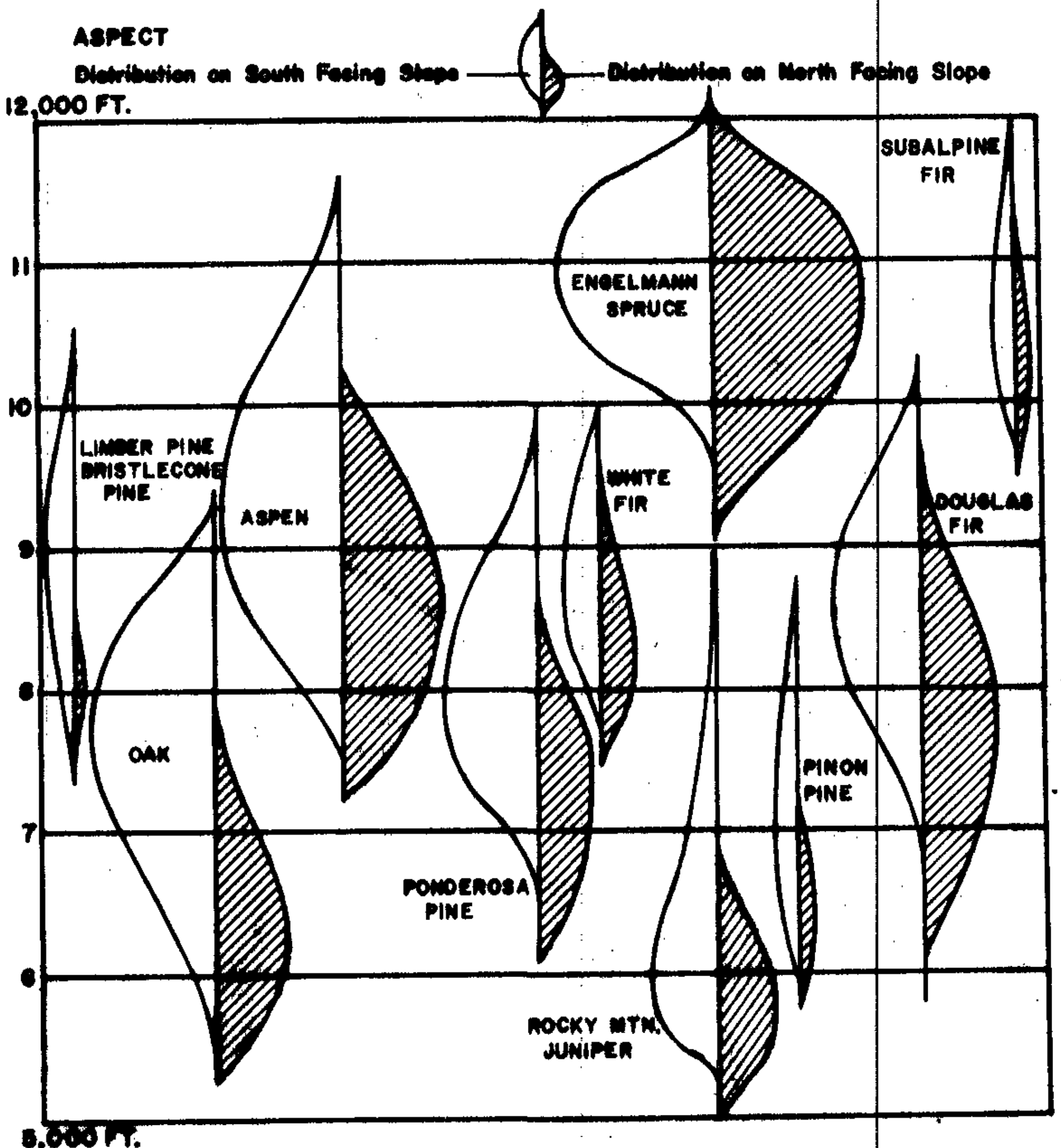

Figure 3. Distribution of forest species relating to elevation and slope aspect.

Mixed coniferous stands may also represent logging or an undisturbed seral stage. In these stands the logging probably occurred late in the successional stage and aspen-oak stands are few and scattered. In the absence of logging this mixture indicates a seral stage. Logging crews must operate in accessible areas. Most of the mixed coniferous stands are located either in inaccessible regions or on steep north-facing slopes where logging has not been attempted.

Topoedaphic stands and pyric climaxes are particularly noticeable in their relationship to topography. The location of these stands is determined largely by the incident angle of sunlight, but also by edaphic conditions. On the steeper north-facing slopes of the Pagosa Peak quadrangle, snow accumulation for avalanche occurrence is particularly high. The presence of riparian deciduous shrubs and aspen within sell-defined tracts indicate areas of regular avalanche occurrence.

On floodplains two basic tree species, blue spruce (Picea pungens Engelm.) and narrow leaf cottonwood (Populus angustifolia James), can serve as indicators. Blue spruce tends to grow on the more stable areas of the stream course. Narrow leaf cottonwood, willows, and alters grow on floorplain areas subject to annual flooding or stream meander. These species form clones which make them adapted to a shifting substrate.

Meadows may represent either fire damaged areas or areas of poor drainage. Low aerobic conditions in the saturated soil tend to eliminate tree species.

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The grassland area which extends through Oakbrush Ridge, Chris Mountain, and Pagosa Springs quadrangles is a product of repeated fire and grazing. Invasion by shrubs and tree species is prevented by browsing of the shoots of deciduous species and periodic burning of conifer seedlings. Oak and aspen stands are plentiful to the east of this region, and are an indication that fires travel with the prevailing westerly winds.

5.6.7. Map products

Detailed vegetation maps of the San Juan Mountains were originally prepared at a scale of 1:24,000. These maps are filed at INSTAAR for use by interested persons. A reproducible map on matte acetate film provides low cost reproduction capability for these maps. A reduced copy (1:48,000) of each of these maps is included with this report. The coding system for the cover type categories is given in Table 1.

The final colored vegetation map at 1:120,000 (for Final Report) was compiled from the detailed vegetation maps and portrays a generalized trend of vegetation changes. The following combined cover type categories were used: coniferous, deciduous, deciduous-coniferous, meadow-grassland-agricultural, tundra, creek community, water bare rock-bare soil, urban. The code system (Table 1) used on the detailed maps was designed for easy combination of categories. For example, all codes in the 220s represent coniferous forest, 230s represent deciduous-coniferous forests, and 160s represent agricultural lands. This coding system permitted an easy translation into the terminology of the classification of the generalized map at a smaller scale, and it permitted formation of new complex which are genuine vegetation entities in spite of their composite character. (Some funds for production of the maps were provided by NASA contract NAS5-21880, NASA contract NAS9-13380, NASA grant NGL-06-003-200, and Bureau of Reclamation contract 14-06-D-7052.)

Translation from detailed to generalized vegetation must be reasonable and must correspond to an accurate portrayal as closely as the scale permits. If a cover type occupies only a very small area, it is usually suppressed altogether. But there are cases when a small area is enlarged enough to be visible on the smaller scale map. This applies to instances where special types of cover help to contribute to a better understanding of the map as whole. Because of the importance of creek communities and bare rock-bare soil in an ecological overview these units were exaggerated for their inclusion on the smaller scale map. Often the deciduous-coniferous category highly interdigitated with the coniferous category. The boundary between these two has been smoothed to give a more continuous and balanced representation.

5.6.8. Areal distribution of cover types--detailed maps

Planimetric measurements of the areal distribution of cover types were made on the detailed maps as well as other quadrangles in the northern portion of the test site. These were selected on the basis of a "typical" distribution which was characteristic of the region. In this way the cover type distributions can be inferred. A comparison of these values for the different quadrangles illustrates the dynamic nature of the major vegetation units and emphasizes those areas where extensive changes have occurred. These data are beneficial in interpretation of the vegetation maps. Many subtleties which are not apparent in looking at the maps are brought to one's attention when expressed in tabular form. Tables giving areal extent of cover types as portrayed on the detailed vegetation maps are available in INSTAAR files.

5.6.9. Automatic data process mapping

The entire San Juan Mountain block was a site for generating a generalized map of vegetation by automatic data processing. The multispectral scanner data from ERTS-1 (Earth Resources Technology Satellite) used in the analysis includes:

Band 4	green wavelength	0.50 to 0.70 micrometers
Band 5	red wavelength	0.60 to 0.70 micrometers
Band 7	infrared	0.80 to 1.10 micrometers

The date of the satellite pass was September 8, 1972 (Scene ID 1047-17200). The classification was provided by the Laboratory for Applications of Remote Sensing, Purdue University (NASA contract no. NAS5-21880). Supportive data for this analysis was provided by INSTAAR.

The area included in this analysis extends from 37° 15' N to 38° 7 1/2' N latitude and from 106° 45' W to 107° 52 1/2' W longitude. The corner USGS quadrangles are Mount Sneffels, Durango East, Elk Park, and Wolf Creek Pass SE (Figure 4). The cover types are coniferous, deciduous, cultivated agriculture, herbaceous, tundra, lightly vegetated rock, bare rock-bare soil, shadow, and water. An estimate of the areal extent for each of these cover types has been determined for the individual quadrangles as well as for the entire mapped area. Table 3 summarizes the areal extent of these cover types; additional tabulated data is filed at INSTAAR. Because of the difficulty in spectrally separating water from shadow there is an over-estimate in the areal extent of water. In some areas the herbaceous cover type actually includes some tundra areas where the percentage of cover is 70-100%, thus the estimate for herbaceous cover is high. Those areas which have a coniferous-deciduous cover have been included in the coniferous cover type. The estimated differences in cover type are as follows:

High Estimate	Low Estimate
water	shadow
herbaceous	tundra
coniferous	(coniferous-deciduous) (not represented)

5.6.10. Areal distribution of cover types--automatic data processing

An estimate of the areal extent of cover types (INSTAAR files) has been generated from the automatic data processing of ERTS-1 data for 63 quadrangles. The entire mapped area has been subdivided into four units (Figure 4). Unit 1 corresponds to area 1 and area 2 (in part) of the San Juan Ecology Project, unit 3 to area 3, and unit 4 to area 4. The constructed unit 2 does not include any significant portion involved in the San Juan Ecology Project as it lies mainly to the east of the Continental Divide. This unit however should be looked at if there is a significant expansion of the cloud seeding program. These data are summarized in Table 3 for the area corresponding to the San Juan Ecology Project. In addition totals are provided for the entire 63 quadrangle area mapped by automatic data processing.

5.6.11. Interpretive uses

One main interpretive use of these maps is in planning since vegetation reflects the effective environment. Using vegetation analysis, environmental potentials and limitations can be detected. This approach also makes possible the assessment of related man-imposed modifications of the natural landscape to the basic ecosystem units. Land and resource suitability can be judged and extrapolated in an ecological framework. The natural ecological unit of the landscape is often indicated by vegetation (Poulton, 1972). This natural ecological unit becomes the base through which management policies, research results, and related information can best be generalized. This becomes the necessary conclusion as man's future activities are guided to achieve compatibility with the potentials and limitations of the environment.

Once correlations are made between vegetation cover types and environmental parameters, the influence of such parameters and their extent can often be deduced from the vegetation. Several inferences may be drawn from vegetation stand types: for example, successional stands are indicative of past disturbance and the degree of disturbance. A correlation between the vegetation and the disturbance could provide a sliding scale for predicting what additional disturbance an area can tolerate. Further, answers to such questions as, How similar is a particular area to others?, could be based on map interpretation.

Trends in vegetation are evident when the general vegetation map is examined. (These maps are presently in INSTAAR files and will be included in the Final Report.) The forested area along the Continental Divide is primarily a climax vegetation. with Engelmann spruce-subalpine fir, and pockets of ponderosa pine and Douglasfir. In some of these areas a deciduous-coniferous stand type is the result of fires. Lower elevations show much evidence of fires and logging. Most of this is in the ponderosa pine-Douglasfir belt. The valley floors and other large grassland areas have an extensive history of agricultural usage. This is mainly grazing and haying meadows. The forested areas in these lower vegetation belts show a high level of disturbance from these three factors--fires, logging, and grazing.

The particular type of land-use is controlled by topographic features which determine accessibility.

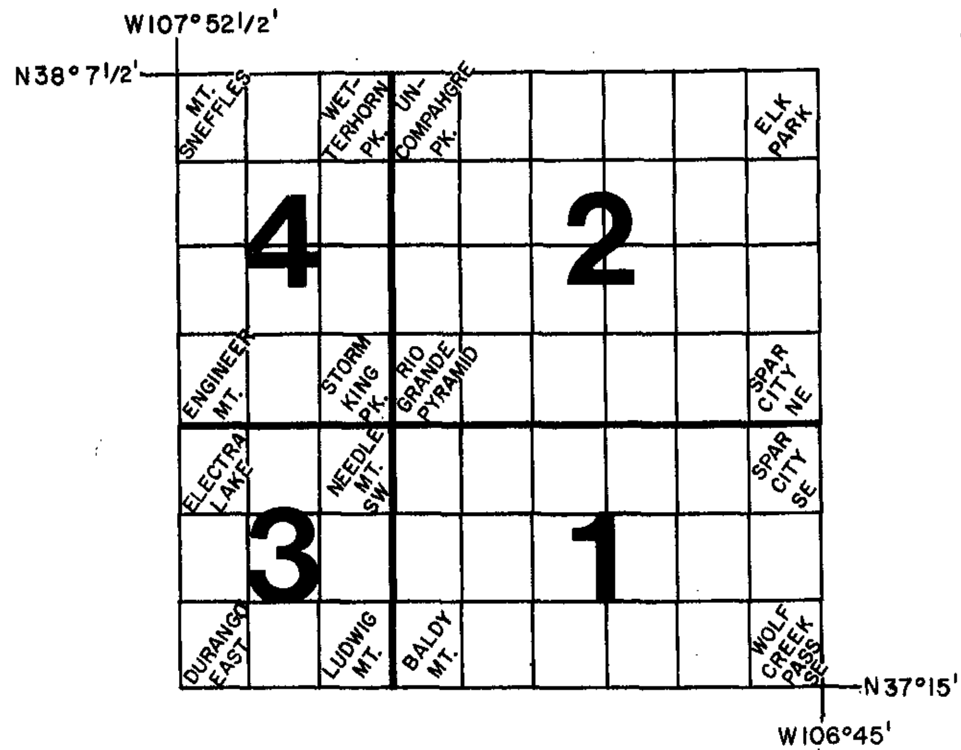

Figure 4. Area mapped by automatic data processing of ERTS-1 multispectral scanner data.

Table 3. Summarized data of areal extent (km^2) for cover types for the San Juan Ecology Project (39 quadrangles) and for the greater San Juan Mountains (63 quadrangles).

	Coniferous	Deciduous	Cultivated Agriculture	Herbaceous	Tundra	Lightly Vegetated Rock	Bare Rock-Bare Soil	Shadow	Water
San Juan Ecology Project									
Unit 1	1792	318	35	330	25	114	22	81	13
Unit 3	698	201	33	229	10	68	15	26	18
Unit 4	624	98	17	431	36	248	129	190	47
Total[a]	3114	617	85	990	71	430	166	297	78
Percentage	53	11	1.6	17	1.2	7	3	5	1.2
Greater San Juan Mountains									
Unit 2	1609	58	3	821	23	571	95	424	28
Total[b]	4723	675	88	1811	94	1001	261	721	106
Percentage	50	7	0.8	19	0.6	11	3	8	0.6

[a]Calculated total 5747 km^2; actual total 5970 km^2.

[b]Calculated total 9586 km^2; actual total 9644 km^2.

In general the areas below an elevation of 3,200 m demonstrate a state of vegetational instability. The successional stages are varied and in some instances continued disturbance over a long period of time (100 years) has drastically altered the dominant vegetation. Many of the successional areas are at a critical stage where slight modifications in the environment could result in an irreversible trend. This is evident in much of the oak-sagebrush areas where the natural climax vegetation of pinon pine-Rocky Mountain juniper has all but disappeared. Similarly much of the ponderosa pine-Douglasfir stands are replaced by aspen, oak, and white fir. There is no estimate of the rate of succession from one sere to the next but the general trend is one leading to extensive oak areas and Douglas fir forests.

The northern areas of the San Juan Mountains are extensively forested with Engelmann spruce and subalpine fir (sometimes corkbark fir). There are many pockets where mining activity has altered the climax vegetation. In these areas stands of aspen and white fir have replaced the spruce-fir forest. Timberline has been depressed at a few locations by logging activity and fires. Most of the successional areas relate directly to man's activities and the mining industry (Krebs and Groeneveld, 1974). Again, there is no documentation of the rate of succession in this area for the spruce-fir cover type.

Within the San Juan Mountains where winter orographic snow augmentation has been projected, approximately 60% of the area is forested; 20% is tundra, bare rock, and soil; and 20% is utilized in some agricultural aspect. Approximately 50% of the total area is in some stage of succession or shows some type of alteration due to man's activity. These trends are reflected in the general vegetation map (scale 1:120,000). More detail is available from the 1:24,000 scale vegetation maps where the mapping units are based on community types.

Since the vegetation responds to its environment, the stability of that environment is important. Secular variations in climate have long been known and should cause changes in the vegetation. In contrast to such long-term changes are those occurring on a shorter time scale. These include the temporary and partial destruction by grazing animals, insects or diseases, and changes brought about by windstorms, floods, fire, etc.

5.6.12. Recommendations

All vegetation changes continuously, although the rates of change vary from abrupt to extremely slow. The changes brought about naturally or by man usually imply changes in the quality of the vegetation and hence its usefulness to man. Superimpose upon this, climatic modification affecting a relatively large land area, and the need for an ecological overview becomes paramount. Vegetation maps then become useful when they illustrate improvement or deterioration in the quality of the vegetation resulting from man's use, or abuse, of the land and its cover.

5.6.12.1. Small scale, generalized vegetation map

Generalized vegetation maps at a small scale (1:96,000 to 1:250,000) provide a source of information to make a preliminary evaluation of the area being considered. Interpretive information should be used in the following ways:

1--characterization of the entire area by descriptive categories as to the stability/instability of the macrovegetation.

2--certain features of the macrovegetation give an indication of several ecological units which should be considered in a detailed ecological analysis.

3--a generalized classification of vegetation indicates the areal extent of major units. From this, selection could be made of specific studies in those areas which might potentially be influenced by environmental alteration.

4--a generalized vegetation map will emphasize certain units which might be otherwise overlooked and not considered for study--as in the San Juan Ecology Project, successional trends.

5.6.12.2. Large scale, detailed vegetation maps

As part of an ecological analysis in an area to be considered for environmental modification detailed vegetation maps at a large scale (1:24,000 to 1:12,000) are an essential approach to evaluate the potential changes, both beneficial and detrimental. The following recommendations are made for map content and interpretive uses:

1--all essential features of the vegetation are shown and the detailed maps must retain a high quality.

2--the detailed maps provide a point-in-time data base for evaluating change on a long-term basis.

3--areal distribution and extent of the specific cover types provide a means of extrapolating investigation results from specific sites to the entire area under consideration.

4--data derived from planimetry of areal extent can be statistically evaluated to yield an ecological description of areas of similarity and dissimilarity. This gives an index to land use potential and limitations. Also, rates and direction of change can be evaluated. Correlations between vegetation and disturbance provide a sliding scale for predicting what additional disturbance an area can tolerate before a successional trend becomes irreversible.

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5.7 ECOLOGICAL OVERVIEW. Part II. THE GEOMORPHOLOGICAL AND GEOLOGICAL OVERVIEW (J. T. Andrews)

5.7.1. Introduction

This final report on the work and results of the Geomorphological Overview includes (1) a brief resume of results reported in earlier Interim Progress Reports; (2) a discussion of results obtained during the 1973-1974 research year; (3) a discussion of the inferred environmental impact of snow augmentation with regard to geomorphology; and (4) an analysis of the role and importance of "overview studies" in future impact statements. In particular the report by L. D. Williams (Section 5.8) indicates some of the avenues that can be profitably explored under the general framework of an overview, and which we plan to examine in this coming fiscal year (1974 - 1975).

5.7.2. Objectives

The overall purpose and objectives of the overview project have shifted since the inception of the project in 1969. As first conceived, the Ecological Overview was designed to provide regional maps of landforms and vegetation, to produce a geomorphic stability index related to the effect of snow augmentation; and provide photographic documentation (both ground and by air photographs) of the San Juan Mountains with the aim of producing "a graphic reference of the overall San Juan ecology as it exists at the beginning of the 1970s" (Ives et al., 1971, p. 275).

This last objective has since been dropped due to a cut-back in funding. In addition the Ecological Overview was divided in 1971-72 into two parts; the first is involved with vegetation mapping and the second is concerned with landforms. The majority of funding was transferred to the vegetation mapping project and the landform mapping changed primarily into an analysis of existing information based on the 11 USGS 1:24,000 quadrangles (which we have already mapped) and the writing up of the field work carried out in 1971, 1972, and 1973. Thus in the 1973 Interim Progress Report, Andrews and Carrara (1973, p. 118) describe the objectives of the geomorphological program as: (1) to provide basic descriptive data; (2) to assess the two intensive study sites within the continuum of the alpine zone; and (3) to develop a geomorphic stability of the San Juan Mountains by examination of the stratigraphy of bogs and the location of glacial and periglacial deposits.

These general objectives will be discussed below in terms of our final results and assessments.

5.7.3. Statement of results

The final statement of results is subdivided into four sections, which are the same as those recognized and discussed in the 1973 Interim Progress Report (and detailed above).

5.7.3.1. Descriptive data and regional assessment

In any environmental impact study there is the basic need for descriptive data on the distribution, and controls on that distribution, of the broad landforms and surficial geology as well as the vegetational patterns. Although commonly overlooked it must be remembered that the "environment" includes biotic and abiotic elements and certainly within the alpine zone it appears that they are mutually interrelated.

Examples of the 1:24,000 maps that we have produced are illustrated as Figures 1 and 2. These might serve as base-line information sources for reassessment of the cloud seeding program, if it becomes operational, in about 20 years' time. Ideally these maps should have been tied into a program of ground- and low-level aerial photography to serve as detailed documentation of geomorphic processes, such as the amount of erosion on certain scree slopes. At their scale and degree of generalization, the 1:24,000 maps will not provide information on the occurrence of small scale processes, such as individual mud slides. Even at this scale the topographic maps capture the area in a "time snapshot" and natural processes will affect the mountains regardless of whether they are seeded or not. In such a stressed environment the concept of a "base line" might be inappropriate.

The variability within the San Juan Mountain block is visually illustrated by these maps but in a more quantitative sense it is better illustrated by the tabulated values in Table 1 listing the areas, percentage of the area on each map sheet, and the number of certain features for each of the 22 quadrangle maps. This table serves as a rapid method of evaluating certain aspects of the physical environment of the mapped area. For example, the area of permanent snowbeds is of general interest in a program concerned with snow augmentation. The persistence of a permanent snowbed is a function of winter accumulation and summer mass loss. (Both these can be modulated by topography which could cause increased snow catch as well as providing protection from summer insolation.) The Storm King Peak quadrangle has the greatest area covered by snowbeds, followed by Howardsville and Silverton. Thus, any tendency to increase the winter snow accumulation through cloud seeding would be felt first, in all probability, in these three areas. In a similar fashion the increase of avalanche activity, which may result from winter seeding, would be most severely felt in the Red Cloud Peak quadrangle closely followed by the Silverton region. These are different regions (apart from the Silverton quadrangle) from those that possess permanent snowbeds and hence may respond differently to potential snow augmentation. This work could have served as a useful device for predicting the relative impact of the cloud seeding program over the entire mountain range if complete map coverage has been obtained. This topic will be discussed again in the last section of this report. Part of the mapping problem was the unavailability of 1:24,000 maps in an east-west swath immediately south of the Storm King Peak map sheet.

Table 1. Areas (km^2), percent of area covered and number of features for the San Juan Mountain, Colorado based on the 11 1:24,000 quadrangles of Figure 5.

	Avalanche Chutes Area (km^2)	% of total area	Bedrock Area (km^2)	% of total area	Cirques Area (km^2)	% of total area	Forest Area (km^2)	% of total area	Rock Glacier Area (km^2)	% of total area
1. Gray Head	.713	.0048	39.805	26%	none	-	63.531	42%	none	-
2. Howardsville	5.92	.0398	76.45	51%	22.80	15%	14.54	.0979	2.06	.0138
3. Ironton	5.29	.0356	31.58	21%	8.01	5.39	32.13	21%	3.83	.0257
4. Little Squaw Creek	2.20	.0148	51.20	34%	5.00	3.36	84.63	57%	.0793	.0005
5. Red Cloud Peak	10.82	.0728	18.60	12%	20.32	13%	35.80	24%	4.28	.0288
6. Rio Grande Pyramid	1.547	.0104	64.994	33%	11.837	7.97	46.4	31%	.637	.0042
7. Silverton	9.08	.0611	29.25	19%	14.04	9.45	50.75	34%	2.55	.01071
8. Snowden Peak	5.658	.0381	30.93	21%	7.00	4.71	51.716	35%	1.07	.0072
9. Storm King Peak	3.277	.0220	75.42	50%	28.0481	18%	28.82	19%	2.12	.0142
10. Telluride	3.26	.0219	28.76	19%	21.68	14%	56.58	38%	7.24	.0487
11. Weminuche Pass	4.381	.0295	59.325	39%	6.513	4.38	43.028	29%	.301	.0020

	Old Rock Glacier Area (km^2)	% of total area	Snowfields Area (km^2)	% of total area	Moraines Area (km^2)	% of total area	Lakes Area (km^2)	% of total area	Active Scree Area (km^2)	% of total area
1. Gray Head	none	-	none	-	none	-	.124	.0007	4.467	.0300
2. Howardsville	.72	.0048	1.52	.0102	.03	.0002	.47	.0031	38.22	26%
3. Ironton	none	-	.22	.0014	none	-	.26	.0017	39.89	27%
4. Little Squaw Creek	.026	.0001	.0614	.0041	none	-	.768	.0081	19.33	13%
5. Red Cloud Peak	.93	.0062	none	-	none	-	.05	.0003	73.85	49%
6. Rio Grande Pyramid	.494	.0033	.083	.0005	none	-	.679	.0045	19.433	13%
7. Silverton	.319	.0021	1.19	.0080	none	-	.056	.0003	25.49	17%
8. Snowden Peak	0	-	.435	.0029	none	-	.648	.0043	20.66	14%
9. Storm King Peak	.200	.0013	3.55	.0239	.169		1.34	.0090	32.95	22%
10. Telluride	.301	.0020	.6	.0040	none	-	.67	.0045	41.65	28%
11. Weminuche Pass	none	-	none	-	.011	.000074	4.192	.0282	13.230	.0890

	Inactive Scree Area (km^2)	% of total area	Alluvial Deposits Area (km^2)	% of total area	Number of Cirques	Number of Rock Glaciers	Number of Snow Patches
1. Gray Head	30.290	20%	1.901	.0128	-	-	-
2. Howardsville	.63	.0042	3.76	.0253	35	16	21
3. Ironton	20.99	14%	1.61	.0108	26	15	5
4. Little Squaw Creek	2.25	.0151	2.476	.0166	11	2	2
5. Red Cloud Peak	none	-	5.26	.0354	34	23	-
6. Rio Grande Pyramid	5.615	.0378	.894	.0060	14	4	2
7. Silverton	24.85	16%	4.27	.0287	34	15	12
8. Snowden Peak	.9805	.0066	.986	.0066	32	10	6
9. Storm King Peak	0	-	4.967	.0334	48	18	23
10. Telluride	14.30	.0962	3.93	.0264	35	32	7
11. Weminuche Pass	12.105	.0815	7.064	.0475	13	3	-

Figures 1 and 2 (fold-outs). Geomorphic maps of Howardsville and Telluride quadrangle using U.S. Forest Service black and white photography. These maps were originally drawn at 1:24,000 and reduced here to 1:48,000.

Legend for Figures 1 and 2

Rg	rock glacier
Rgi	inactive rock glacier
Sc	scree
Sci	inactive scree
Br	bedrock and till-mantled bedrock (on steep slopes)
Br-Sc	bedrock ribs with intervening gullies filled with scree
Ls	landslide
Rm	regolith - parent material Mancos Shale
Qd	glacial drift
L	lake
F	forest
Pr	protalus rampart
Al	alluvium
Af	alluvial fan
Co	colluvium
Mt	mine tailings
Mf	mudflow
	dominant ridge
	cirque
	lateral meltwater channel
	avalanche track
	moraine

Table 2 lists the relative ranking (on a range of 5) of the impact of snow augmentation on each of the 15 categories of Table 1 and specifies the reason for the ranking. (Location of the quadrangles is given on Figure 3.) Quantification of the ranking/area data might serve as an initial tool for delimiting those areas upon which snow augmentation would have little or no impact from those where serious concern might be justified. However, it is not immediately clear how these data can be combined. A tentative approach might be simply to multiply the area (or number) by the ranking for the 11 quadrangles. Thus the areas of avalanche tracks are multiplied by 5 whereas the area of bedrock is multiplied by 1. This new set of numbers thus represents a judgment of the relative impact over the 11 maps. There should be some degree of spatial correlation between adjacent map sheets because the map boundaries are arbitrary and do not delimit geological regions. However, the 11 x 15 matrix might be used to see if spatially coherent map clusters occur which in turn can be ranked against the potential environmental impact of the cloud seeding program.

For the purpose of this study the analysis was restricted to deposits which were ranked (Table 2) 2 to 5 in terms of snow impact. These categories included avalanche tracks, cirque floor area, area of rock glaciers, area of snowbeds, and area of scree. Table 3 lists the map sheets and the total figure derived from these calculations. There is no inherent physical meaning in the figure of 310.38 for the Red Cloud Peak map sheet; it can be assessed relatively against a value of 760 which would represent a map sheet where all deposits are ranked as 5 (highly susceptible to increased snow augmentation). Table 3 shows the area under this maximum impact, as well as the percentage relative to the Red Cloud Peak map sheet. Cluster analysis of the individual totals that make up column 2 of Table 3 indicate that there are 3 or 4 significant clusters. These are shown on Figures 3 and 4 where clusters marked A are least sensitive and those of C and D, most sensitive to increased accumulation. Relatively little change would occur in cluster A under an increased snow augmentation program whereas clusters B, C, and D would probably show some degree of response to the program. It is important to note that the Williams Lakes intensive study lies in category A and the Eldorado site in D. However, this relative ranking on regional criteria does not agree with the small scale site studies of Caine (1973). This indicates the problem of extrapolating from either end of our research spectrum. A second way to determine potential impact from cloud seeding is to examine the present sites of rock glaciers and snowbeds and determine the controls of them. The large bowl-shaped cirques of the high alpine mountains represent very efficient snow traps. They owe their form and development to Pleistocene glaciation. The cirques form a potential elevational limit to increased snow accumulation. Snow augmentation is unlikely to result in a simple, uniform increase in the snowpack but rather the increase in snowfall will be redistributed and stored temporarily. Within the forested areas the storage is limited and there are relatively few good snow trap areas. However, in the alpine regions the cirque basins cover up to 18% of certain map

Table 2. Ranking of surficial deposits (cover types) and features related to snow augmentation.

Snow augmentation impact ranking:
1 = none, 2 = none, 3 = moderate, 4 = medium/heavy, 5 = major.

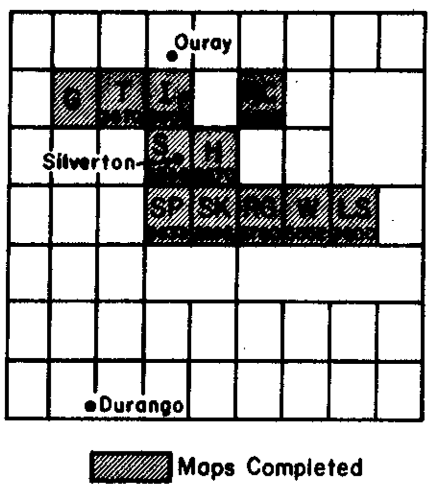
Cover Type (Feature)	Ranking and Remarks
Avalanche chutes	(5) Increase in number and size of avalanches; hazard in areas of roads.
Bedrock	(1 or 2) No obvious impact.
Cirques	(3) Areas will serve as the sites for wind-distributed snow that falls at 4000 - 3500 m.
Forest	(2) Might have some impact in areas if avalanche runs through established forest.
Rock Glacier	(2 or 3). Will cause a more positive mass balance on those rock glaciers that have an active accumulation (snowbank) zone. Some increase in velocity (about 5%) from 0.5 - 0.1 m/yr to slightly higher values. As dirt roads are cut around and across rock glaciers some possible problems.
Old Rock Glaciers	(1) No impact.
Snowfields	(3 to 5) Existing snowfields indicate efficient snow bogs. Low in solution sites; they are likely to increase in size, possibly to early twentieth century extents.
Moraines	(1) No obvious impact.
Lakes	(2 or 3) Might cause a change in the break-up date.
Active scree	(2 to 3) Scree activity does appear to correlate with an increase in glacial conditions; reasons not too clear.
Inactive scree	(1) No impact (?)
Alluvial deposits	(2) Some increase in sedimentation and erosion of runoff. Season increases in length and volume of water increases.
Number of cirques	(1)
Number of rock glaciers	(1)
Number of snow patches	(3) Some increase in number of snowbanks is possible if a real change in snow accumulation occurs.

Table 3. Ranking of 11 USGS 1:24,000 map sheets by sensitivity to snow augmentation program.

Map Sheet	Total[1]	Ranking (high to low)	Cluster	% of Red Cloud	% Total
Gray Head	14.72	11	A	4	1
Howardsville	218.74	2	D	70	29
Ironton	160.54	6	B	51	21
Little Squaw Creek	74.72	10	A	24	10
Red Cloud Peak	310.38	1	C	100	41
Rio Grande Pyramid	93.7	8	A	30	12
Silverton	161.77	5	B	52	21
Snowden Peak	105.12	7	B	33	14
Storm King Peak	200.61	4	D	64	26
Telluride	205.66	3	C	66	27
Weminuche Pass	75.25	9	A	24	10

Average % Total
Cluster A = 8.25
B = 18.7
C = 34)
D = 27.5) 30.75

[1]The maximum possible number in this column would be 750.



G-Gray Head
T-Telluride
I-Ironton
RC-Red Cloud Peak
S-Silverton
H-Howardsville
SP-Snowden Peak
SK-Storm King Peak
RG-Rio Grande Pyramid
W-Weminuche Pass
LS-Little Squaw Creek

Figure 3. Location and names of the topographic quadrangles referred to in this study.

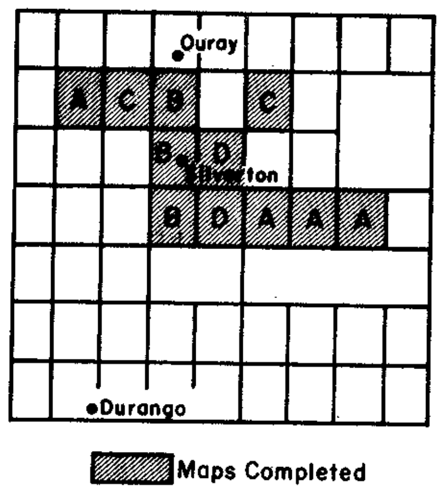


Figure 4. Map of the location of the quadrangles (see Figure 3) with the cluster membership (A...C) from Table 3.

sheets (28 km^2 in the case of the Storm King peak quadrangle) and hence form a significantly large snow storage area that would give a long summer run-off because of their generally northerly orientation and protection from insolation. Some of these ideas are carried further in the report by L. D. Williams and will be examined in more detail during the 1974-75 research year.

The average elevation of all cirque floors in each of the 4 major quadrants (N-NE, E-S etc.) is listed in Table 4 for the 11 map sheets, as are the mean elevations of cirque floors that have snowbanks and for rock glaciers in their basins.

There is remarkably little variation in these data on a regional basis; for example, the average floor elevation of high, northeast-facing alpine basins that contain no rock glaciers or snowbanks only varies between 3555 and 3780 m (the 3900 m value in the Ironton quad is on one cirque). There is a slight tendency for the basin floor elevations to rise toward the Storm King Peak and Rio Grande Pyramid region and thus the regional snow line may have a broad and shallow domed shape.

Table 4. Mean elevation (m) and number of cirques (N=272) in the four different quadrants.

Map Sheet		N-E	E-S	S-W	W-N
Storm King	A[1]	3695(4)	3781(7)	3738(4)	3713(4)
	B[2]	3737(14)	3880(1)	3680(1)	3732(14)
Snowden Peak	A	3633(6)	3620(1)	3680(3)	3590(5)
	B	3599(7)	3660(1)	-	3663(6)
Little Squaw Creek	A	3600(2)	3538(3)	-	3585(2)
	B	3615(2)	3545(1)	-	-
Silverton	A	3555(2)	3650(7)	3683(3)	3630(1)
	B	3612(5)	3899(1)	-	3569(10)
Ironton	A	3902(1)	3671(9)	-	3590(1)
	B	3657(7)	3660(1)	3715(1)	3664(6)
Howardsville	A	3670(1)	3693(3)	3780(1)	3590(4)
	B	3702(16)	3745(2)	3695(2)	3685(4)
Rio Grande Pyramid	A	3780(1)	3605(1)	-	3510(3)
	B	3640(4)	3810(1)	-	3717(3)
Weminuche Pass	A	3552(6)	-	3520(1)	3513(3)
	B	3750(2)	3785(1)	-	-
Telluride	A	3570(1)	3570(1)	-	3410(1)
	B	3708(8)	3647(3)	3696(5)	3639(14)
Red Cloud Peak	A	3690(4)	3790(4)	3720(1)	3590(2)
	B	3744(14)	3818(5)	-	3718(6)

[1]Cirques with no rock glaciers or snowbanks.

[2]Cirques with rock glaciers or snowbanks.

When the alpine basins that are currently empty and those that contain a rock glacier and/or snowbank are compared (Table 4) it is difficult to ascertain any consistent trend, and elevation is not significant in discriminating between these two broad categories. This finding suggests that the presence of permanent snowbeds is primarily controlled by orientation (all in northerly exposures) and by local topography and topoclimate. Out of the total number of 272 high alpine basins in the 11 quadrangles (total area of 145 km^2) 79 are associated with permanent snowbeds and 139 with rock glaciers. If there is an association between the occurrence of snowbeds and the presence of a rock glacier, a snow augmentation program might result in an increase in velocity of the rock glacier population with some possible damage to high country dirt roads. The association can be tested by a 2x2 contingency table (Table 5).

The null hypothesis states that the occurence of rock glaciers and snowbanks is independent. The calculated chi-square value of 2.33 is smaller than that tabled (2.73 and the null hypothesis cannot be rejected at the 5% level. This result is different from that discussed by Andrews and Carrara (1973) based solely on an analysis of data from the Storm King Peak 1:24,000 map sheet and indicates that there is probably regional variability in the association.

Table 5. Frequency of counts of high alpine basins with or without rock glaciers and/or snowbanks. Total from the 11 quadrangles.

		ROCK GLACIERS Yes	ROCK GLACIERS No
Snowbanks	Yes	46	33
	No	89	104
	Total = 272		

The analysis of the cirque floors indicates that the critical elevation for snow augmentation and storage is close to 3600 m a.s.l. As little snow is probably drifted through the forest to the high elevations the possible increase in snowbank frequency and size must be associated with snow redistributed or deposited directly in the Alpine. In the area of irregular topography, the effects of a straight snowfall augmentation or a redistribution effect are best examined through analysis of snow melt models. Part of such a program is given below in the paper by L. D. Williams and this problem will be pursued in the 1974-1975 research year.

5.7.3.2. Geomorphic stability

The clusters produced in the previous section (Figure 4) can be interpreted in terms of general geomorphic stability. However, a specific field criterion is needed to interpret whether or not a specific talus slope or rock glacier is currently stable. To a degree this can be expressed by the age of the feature; thus an "old" slope might be inherently more stable than one that is "fresh." In order to provide some quantitative measure of the substrate stability the technique of lichenometry was employed and Andrews and Carrara (1973) and Carrara and Andrews (1973) derived first approximations for lichen growth curves for the field area. These curves have been used by Sharpe (1974) to assess the age and recurrence interval of mudflows in the San Juan Mountains and by Carrara and Andrews to examine the Holocene (last 10,000 years) glacial and periglacial deposits and to infer the climatic changes that have affected the area over this particular period.

Our results were obtained from cemeteries below tree line and hence the observed rate of growth of Rhizocarpon geographicum s.l. of 30 mm/100 yr is undoubtedly a maximum rate of growth for the alpine. A figure of 15 mm/100 yr, similar to that determined for the Front Range of Colorado (above tree line) might be more appropriate, although on climatic and biological productivity grounds a figure of 20 mm/100 yr might be best. This growth rate probably applies for the first 300 years of the life of the species and thereafter the growth rate probably diminishes to $\geq$ 3 mm/100 yr with a best estimate of 5 mm/100 yr.

Growth-rate stations were established in 1972 using Lecanora thomsonii and Lecidea atrobrunnea. These sites will be rephotographed in the fall of 1974 or early summer 1975 and the direct growth rate of these species established. This work will then enable us to provide a reliable estimate of the growth rate of R. geographicum for the area above tree line.

Lichen size and degree of cover was used to date areas that are currently active and to differentiate them from older, stable deposits dating from the last 10,000 to 4,000 years ago.

5.7.3.3. Holocene glacial, periglacial and climatic record:

The evaluation of the possible impact of a man-induced climatic change can be accomplished by:
1) study of present processes and inference of the magnitude of change caused by some climatic perturbation;
2) modeling based on predictive equations or physical relationships;
3) examination of the past geological record of the area and relation of that record to climatic changes of various orders and causes.

Although there has been considerable internal debate among members of the CU and CSU teams on the value of this last approach it is deemed to be a viable useful approach as is the only way in which our present climate and environment can be seen in its proper context. If, for example, we could show that an area had just experienced a major geologic/climatic change (say 60 years ago, or even 1000 years ago) then changes in the plant and animal populations now observed could be in response to these longer term fluctuations and not in response to some current process such as cloud seeding.

The most accurate method of reconstructing past environmental changes is to investigate a deposit that has a continuous stratigraphic record such as lake sediments or bogs. Under our research plan we have investigated the stratigraphy, radiocarbon age, and pollen record for five bogs that lie at about 3700 m in the northern San Juan Mountains. Radiocarbon dates have been provided by the Smithsonian Radiocarbon Laboratory under the direction of Dr. R. Stuckenrath. The pollen and macrofossil results were gathered by Frances B. King. Andrews and Carrara (1973) provide details on the lithostratigraphy.

Figure 5 illustrates our interpretation of the lithostratigraphy in terms of changes in tree line and changes in the rates of basin sedimentation. The figure illustrates that a major environmental change occurred about 5000 BP. Prior to that date the high alpine basins appear to have been quite stable and the sedimentary record is characterized by the buildup of organic peats. Macrofossils indicate that tree line extended into the basins and hence was 100 m+ that of today. However, about 5000 years ago conditions changed. The sedimentary record becomes much more varied and wedges of inorganic sediments are laid down on top of the organic peats and mucks and are in turn covered by peat. This period of varied climate is known in North America as the Neoglacial and in many mountain ranges it witnessed (as the name suggests) a renewed period of glaciation with several distinct glacial episodes or stades (Figure 5). The bogs indicate that the last period of high sedimentation into the alpine basins occurred very recently, probably in the last 300 years. These sediments are now vegetated although the date of the recolonization is probably within the last 60 years or so.

The central question is how this record relates to snow augmentation and what it can tell us of future impacts of this program. We can state that:
1) The current climate and geomorphic stability have changed repeatedly over the course of the last 5000 years.
2) Current geomorphic stability is higher now (i.e., there is less sediment transport into the high basins) than it was 3000 years ago and certain areas are probably being recolonized and hence a successional vegetational process is probably in progress.
3) The periods of high sedimentation yield correlate in a general way with periods of glaciation in the western mounts of the U.S.A. (Porter and Denton, 1967; Benedict, 1973; Birkeland, 1973).
4) These temporal relationships strongly suggest that periods of high sediment yield occur during times of climatic deterioration.
5) The climatic deteriorations are caused by either an increase in winter snowfall, or a decrease in

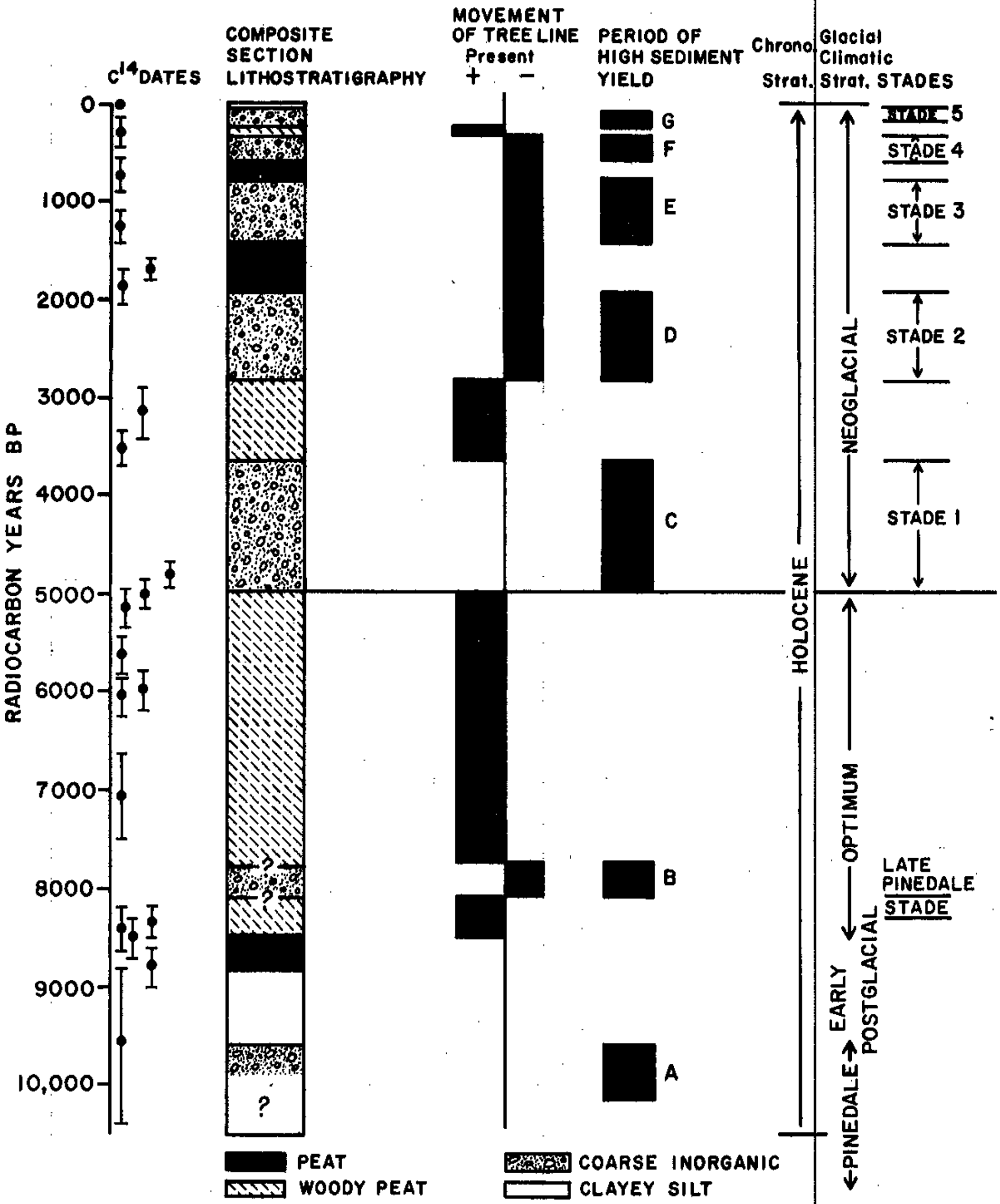


Figure 5. Radiocarbon data, composite lithostratigraphy, periods of tree line upward movement and high sediment yield, and inferred climatic periods from the investigation of five high basins above timberline in the northern San Juan Mountains.

the summer ablation rate or some combination of both. However, the net effect is to increase the frequency and size of glaciers and snowbeds.

6) In the San Juan Mountains there is no conclusive evidence that glaciers occupied any of the cirque basins during the Neoglaciation. Hence the high sediment yields are associated with run-off from snowfields.
7) During these periods of peak sediment yield there is probably an increase in mudflows and probably in late-lying snowbanks which may cause the tundra to die or become susceptible to stripping and hence increase soil erosion.

Whether any of these effects can be caused by a snow augmentation program that calls for a 15 to 30% increase in snowfall is difficult to say, but I suspect that a 30% increase continued for some period of time (say 100 to 200 years) is of the right order to cause changes in the geomorphic stability of slopes. This is tantamount to saying that the proposed snow augmentation program is within the range of climatic changes that have occurred in the last 10,000 years. However, it cannot but have an impact on the physical environment.

Estimates of the changes of tree line by palynological methods (F.B.M. King pers. comm., 1974) indicate that between about 8000 and 5000 years ago tree line was probably 100 m higher than it is today. In contrast, since about 1200 BP the tree line has been 100 to 200 m lower than today. The pollen data do not record an apparent downward movement of tree line sometime immediately prior to 300 BP; however, dead trees, radiocarbon dated, indicate that tree line fell by 100 m or so in the last 300 years.

As an approximation these figures indicate that the "complex" July temperature at 3600 m or so has varied by $\pm$ 2°C for significant periods. The term "complex" is used because temperature is but one control on tree line elevation and the viability. Further insight as to whether snowbanks in the San Juan Mountains are more responsive to temperature or snowfall changes should be provided by the snow melt modeling.

5.7.4. Environmental Impact of Increased Snowfall: An Assessment

The assessment of the impact of the cloud seeding program is not easily quantified nor can many statements be supported by so-called "hard facts." Rather, the assessment is based on the objective and subjective appraisal of the information at hand and is thus one "expert's" opinion.

The proposed cloud seeding program would increase the number and size of existing permanent and semi-permanent snowbeds and over a long period of time (100 years) would probably result in increased soil erosion in the high alpine basins. The degree of climatic change is that experienced in the area over the last 10,000 years in general and in the last 5,000 years in particular. The proposed program could cause a slight increase in rock glacier velocities and an increase in scree fall and mudflows.

The natural system will respond to the man-induced climatic change; there are no aspects of it that can be turned off. Whether the changes are adverse or not is a subjective judgment. My own judgment is that changes of the magnitude being considered will not cause adverse effects although certainly changes will occur.

It should be borne in mind that increased snowfall could lead to a situation where significant amounts of water are stored in the high country in the form of snowbanks. This could lead to a decrease in water yield. Experiments are required to estimate at what point the increased snowfall would lead to an increase in permanent storage. This possibility will be tested in 1974-1975 using the snow melt model (of Williams, Section 5.8.).

5.7.5. Recommended Procedures for Future Impact Statements

Although individual field areas involve different problems it seems that an overall research strategy that can be applied to the general problem should be developed. An overview project involving both vegetation and geomorphic mapping as well as regional climatology should be a central part of the research design initially involving a description of the area and the subdivision into homogeneous units which can then be sampled through detailed field studies; these detailed studies can be placed back into the regional context. These ideas are expressed below and in Figure 6.

I) The overview project should consist initially of three separate endeavors: development of an inventory of the vegetation; geomorphic features and surficial deposits; and available climatic data. The first two should be accomplished rapidly by using photo mosaics such as the HURD orthophoto maps or else some computer mapping procedures such as are currently being developed by LARS (Purdue University) and INSTAAR using ERTS-1 Satellite imagery.

II) Analysis of these data should then be carried out to produce either discrete climatic, vegetation, and geomorphic units or a total assessment to produce 'natural regions' that have rather homogeneous characteristics. Figure 7 illustrates a computer clustering of the 11 San Juan Mountain quadrangle based on the data in Table 1. Figure 7 shows how the clusters are arranged spatially and illustrates that they form coherent spatial entities. Thus the northern San Juan Mountains form four main geomorphic units. Analysis of the relationship between cluster membership and the raw data indicates that the primary variables were area of cirque floors, number of cirques, and the number of rock glaciers. Table 6 lists the variables related to the first four principal components (which explains 95% of the variance). INSTAAR's two intensive study sites lie in clusters 1 and 4. The main controlling variables are reflecting degree of discussion and the amount of steep slopes and thus clusters 1 to 4 rank from low to high with regard to potential geomorphic activity.

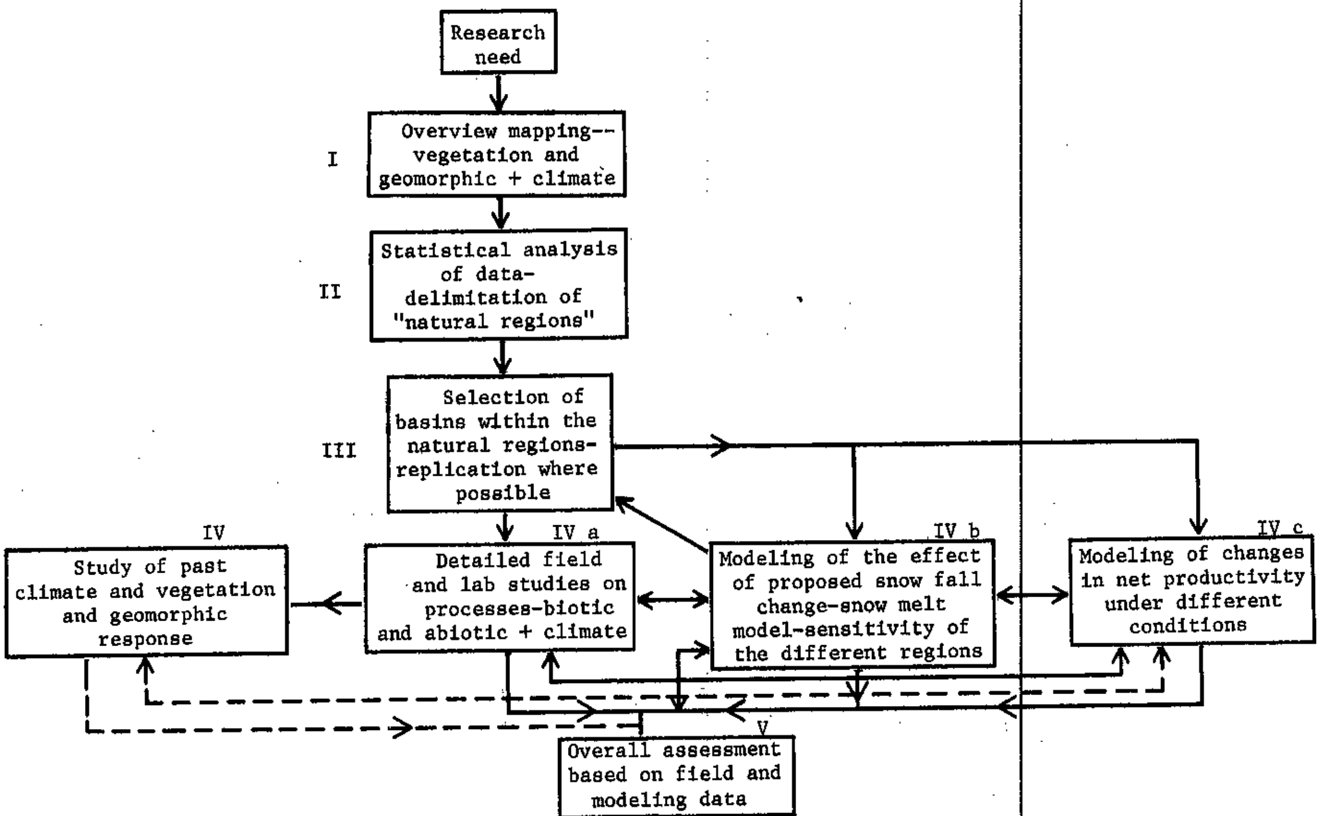


Figure 6. Proposed flow chart operational model for the implementation of a study to investigate the impact of snow augmentation in a mountainous area.

III) Given the subdivision of the target area into regions, individual sites for detailed biotic and abiotic processes and climatic measurements can then be selected.

IV) The fourth step has three parts:
A) Detailed field studies;
B) Examination of the impact of the proposed cloud seeding program by use of snow melt models. The impact on the different regions should be investigated and the presence or absence of suitable climatic data at various elevations should be assessed to provide input into the climatic program;
C) Modeling of the effect of the proposed man-made climatic change by using existing programs that relate micrometeorological parameters to primary productivity. Again this step will involve feedbacks with the field studies.

V. The final step is the evaluation of the impact of the program. Step IVA above enables the research team to consider present processes and to some extent they can use these data to speculate on the possible impact over 5, 20, or 100 years. However, the advantage of IVB and IVC is that these programs could be used to predict the future impact on the basis of physical equations.

Table 6. Geomorphic cover types delimited in the San Juan Mountains, Colorado

lakes	moraines
bedrock/thin till	forest
"fresh" scree and talus	"old" scree and talus
"fresh" rock glaciers	"old" rock glaciers
snowbanks	avalanche tracks
alluvium	alluvial fans
	protalus ramparts
	landslides

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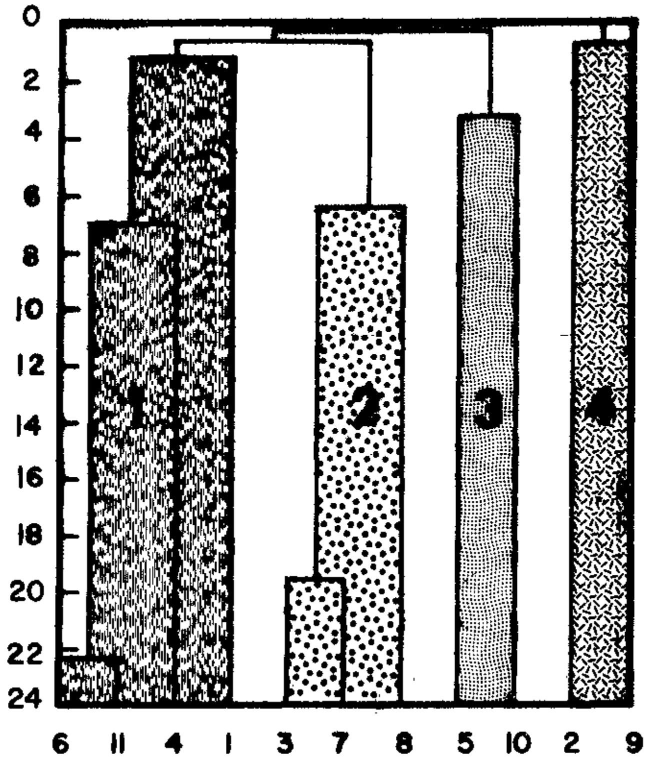

Figure 7: A. Clusters of the 11 quadrangles using the area and frequency data of Table 1.

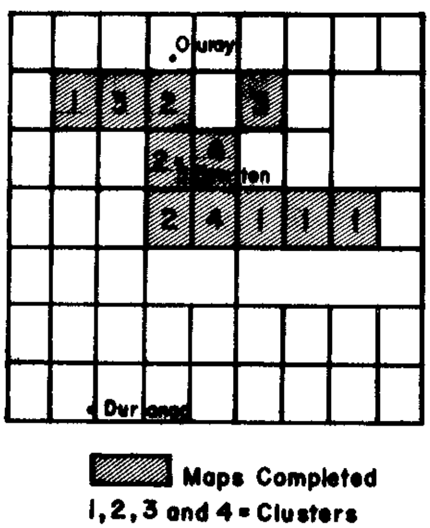

Figure 7: B. A location map showing the spatial arrangements of the clusters delimited on Figure 7A.

5.7.6. Assessment of the geomorphic overview project

The main utility of the project has been to develop the outline of a methodology to study the impact of cloud seeding programs in other mountain ranges in the western United States. Above tree line the major impact might well be on changes in geomorphic processes that will eventually lead to changes in the plant and animal communities. Mountains can be subdivided into units and the impact of cloud seeding will vary depending on the characteristics of each. Regional mapping and climatic data inventory form the basis (or should) of detailed field studies as eventually the impact of cloud seeding has to be brought back from the detailed local field site to the wider regional overview.

Any mountain environment has a past (100- to 10,000-year) history and a knowledge of this past response to Holocene climatic changes is essential to understanding the present distribution of plants and animals and deposits and it should serve as invaluable data for the snow melt and productivity modeling; a knowledge of the past is probably our best means of ensuring an intelligent prediction of future trends.

Finally, one of the stated objectives of the research was to provide a regional framework for the more detailed process studies (cf. Caine, Sharpe, and Clark, this report). In addition the study was intended to provide information on the position of the two intensive study sites within the continuum provided by the 11 USGS mapped quadrangles. The aerial quantities (Table 1) can be, and have been, used to project overall "work rates" related to specific processes (Sharpe 1974). However, the "overview" and "detailed" site studies are not easily transferred upwards or downwards in scale because we lack information of processes and deposits at the intermediate scale of 10 km^2. This is in fact a difficult working scale as it falls between the two methodologies. This problem requires some thought and it needs to be recognized in future research designs.

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5.8. ECOLOGICAL OVERVIEW. Part III. SNOW MELT MODELING. (L. D. Williams)

This study is a first look at the potential for establishing permanent snowbanks in alpine basins of the San Juan Mountains through increased snowfall. If perennial snow (or ice) occupies a substantial portion of a basin, it can have a considerable effect on the runoff from that basin. Because snow stores a certain amount of meltwater before contributing to runoff, permanent snowbanks provide storage in excess of that existing in the annual snowpack, thus affecting the timing of runoff. Furthermore, the variability of runoff from year to year is greatly reduced by the presence of substantial amounts of perennial snow or ice (Krimmel and Tangborn, 1974). This is because in a year with low snowfall when, in the absence of perennial snow and ice, the water yield would be lower than normal, greater melting of the snowbanks and glaciers (aided by earlier removal of the high albedo annual snow cover) tends to make up the deficit. Thus, the possibility of establishment of permanent snowbanks (or even glaciers) is of great importance to the hydrology of a basin.

In this study we attempt to estimate the increase in number of permanent snowbanks for a given long-term snowfall increase. Later studies will estimate the associated changes in areal extent of perennial snow. The area chosen for analysis is that covered by the Silverton, Howardsville, Snowden Peak, and Storm King Peak quadrangles of the USGS 7 1/2-minute topographic series (Section 5.7, Figure 1). Since the study deals with discrete sites, it is necessary to choose those most likely to support development of snowbanks in as nonarbitrary way as possible. The topographic features known as cirques (or corries) are good choices for such sites, for their form indicates that at some time in the past they contained glaciers, and these would have grown initially from permanent snowbanks. Aerial photographs taken in late August 1964 were studied to determine the locations of all cirques and all snowbanks in the area under consideration. Of the cirques identified, 81 did not contain snowbanks in 1964, while 139 snowbanks existing in that year were found. From topographic maps, the elevation and orientation of each snowbank and of the base of the backwall of each cirque without snowbanks were measured. The results are shown in Figure 1.

The persistence of snow at any site depends upon the amount of snow which accumulates there, which is primarily a function of elevation and local relief, and the amount of heat energy which has been supplied for melting, which depends upon elevation, slope, and aspect. Clearly, snowbanks may exist only where, in the long run, snow accumulation exceeds snow melt, and the distribution of snowbanks in Figure 1 demonstrates the favorability of north-facing slopes and higher elevations for retention of snow. The lowest snowbanks face due north, for which incoming radiation is minimum. The range of snowbank orientation becomes greater with increasing elevation, as temperature and water vapor pressure decrease and snowfall increases.

Since the source of greatest variability in snow melt with respect to orientation is incoming radiation, and since this is fairly symmetric about due north, we may simplify the analysis by considering distributions with respect to elevation and absolute orientation, the latter defined as degrees from north, either east or west. Figure 2 shows the distribution of snowbanks and cirques without snowbanks with respect to these two variables. Any point on the diagram is associated with a distinctive energy environment, or potential for snow melt, for a given set of meteorological conditions. If various parameters such as air temperature and humidity, cloud cover, wind speed, and precipitation are known, the energy environment can be calculated at each point by theoretical or empirical estimates of the terms of the heat balance. That is, the heat available for melting snow is equal to the sum of net radiation, sensible heat, latent heat, and heat conduction at the surface. There are a number of difficulties involved in obtaining precise instantaneous values of these terms, but methods have been devised which give satisfactory estimates of the net heat balance over the entire melt season. References to these methods are given in Section 5.8.1. Furthermore, for the purpose of this study it would be impractical to be concerned with the year-to-year variation of the heat budget, for only representative values (for a given climate) of the potential snow melt as a function of elevation and orientation are required. This is justified on practical rather than theoretical grounds, for while variations in weather from year to year may cause substantial changes in the size of snowbanks, their locations tend to remain fixed over a number of years. It is therefore assumed that mean climatic conditions can account for the locations of snowbanks, and the change in favorability of sites for snowbank development due to a change in climate can be estimated.

Table 1 shows the results of calculating representative values of potential April-September snow melt for the San Juan study area at 100-m intervals of elevation and 10° intervals of orientation (for an arbitrary slope of 20°), using climatic data from nearby weather stations for the years 1960 to 1964 (i.e., the five years preceding the year of aerial photography of this region in the ablation model described in Section 5.8.1.). On Figure 2, the upper bound of cirques without snowbanks has been drawn (the solid line). Some snowbanks occur below this line, but cirques in this area with elevations and orientations which plot above this line inevitably contain snowbanks. The line thus represents a boundary for sufficient but not necessary conditions of elevation and orientation for permanent snowbanks in 1964. Transferring this curve (solid line) to Table 1, the amount of snow to remain above the line, but not below, is given by the values of snow melt on the line (i.e., on the line, snow melt equals snow accumulation). These values are given in the next-to-last column of Table 1 (extended to fit measured values at lower elevations, although strictly these are not comparable as the snow bank sites will naturally accumulate much more snow than is typical for their elevations). In the last column of Table 1, the accumulation values are increased by 15%. The locus of points where snow melts equals snow accumulation with the latter increased by 15% are then plotted on Table 1 and transferred to Figure 2 as a dashed line. In Figure 2 it is seen that new snowbanks would be predicted to become

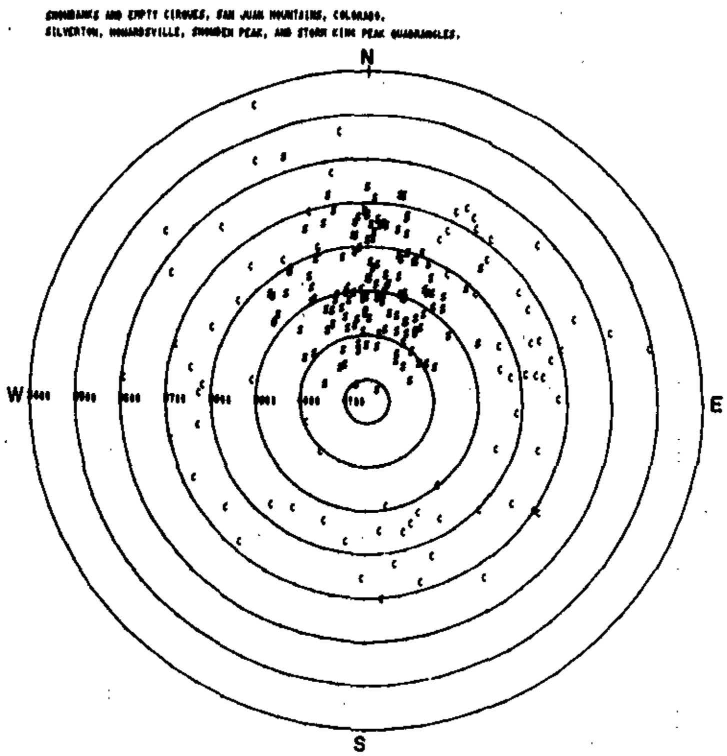

Figure 1. Elevations (meters) orientations of snowbanks (s) and empty cirques (c) for the Silverton, Howardsville, Snowden Peak, and Storm King Quadrangles.

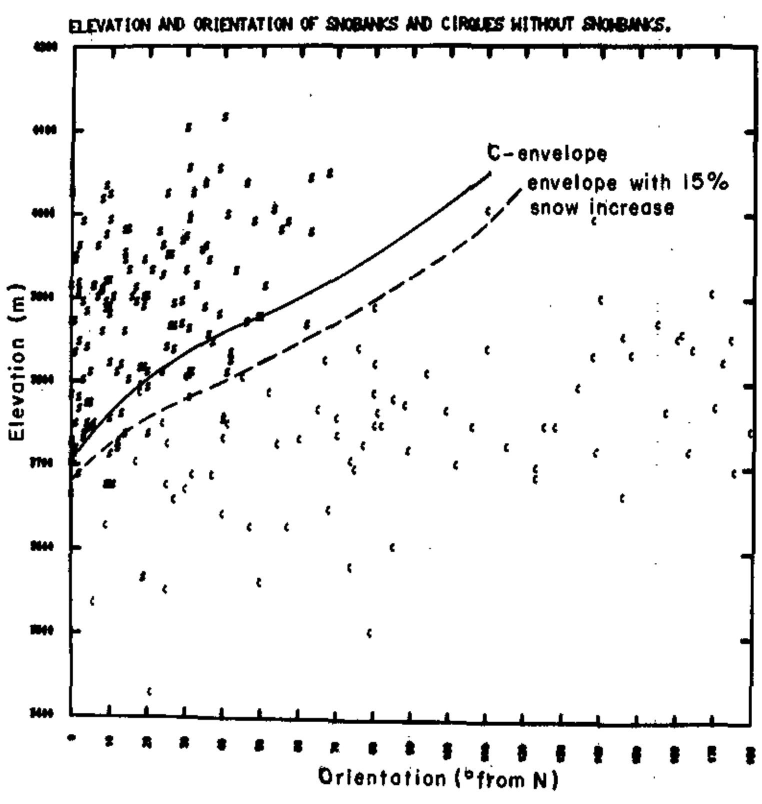

Figure 2. Elevation and orientation of snowbanks (s) and cirques without snowbanks (c).

Table 1. Representative values of potential April-September snow melt for the San Juan study area.

Elev. (m)	Aspect (degrees from N) 0	10	20	30	40	50	60	70	80	90	100	110	120	130	140	150	160	170	180	Measured/ required snow accum. (cm)	15% increase
4200	161	164	172	185	201	219	237	255	271	285	296	304	310	313	315	315	315	315	315	300	345
4100	170	172	181	193	209	227	245	263	279	293	304	313	318	322	324	324	324	324	323	290	333
4000	178	181	189	202	217	235	253	271	287	301	312	321	327	331	333	334	333	333	333	276	317
3900	187	190	198	210	225	243	261	279	295	309	321	330	336	340	342	343	343	343	342	252	290
3800	196	199	207	219	234	251	270	287	303	318	329	338	345	349	351	352	352	352	352	206	237
3700	206	208	216	227	242	259	278	295	312	326	338	347	354	358	360	362	362	362	362	161	185
3600	215	218	225	236	251	268	286	303	320	334	346	356	362	367	369	371	372	372	372	130	150
3500	224	227	234	245	259	276	294	312	328	343	355	364	372	376	379	380	381	381	382	107	123
3400	234	236	243	254	268	284	303	321	338	353	367	377	385	391	394	397	398	399	399	88	101

established in only five or six of the 81 cirques as a result of a 15% increase in snow accumulation. Of course, this does not take into account the possibility that a 15% snowfall increase might be redistributed by the wind in such a way that the actual accumulation of snow in certain locations would exceed 15%.

A more refined model which estimates accumulation as a function of elevation and local relief from a snow survey and then computes daily values of snow ablation at the points of a grid covering a given topography has now been developed (Williams, 1974). With this model it will be possible to obtain a much better picture of the possibilities for change in areal distribution of snow throughout the summer and the potential for establishment of permanent snowbanks in areas of particular interest.

5.8.1. Description of ablation model

This appendix will briefly describe the computer program used in this study for estimation of ablation. The computations are based upon energy balance at the surface, as discussed for example by Paterson (1969, Chapter 4) and Sellers (1965). A variety of sources has been used for construction of the model. Much has been written on this subject, and no attempt will be made here to discuss theory, but only to give references to methods used, except where further explanation is called for.

Daily values of ablation were obtained by summing over half-hour intervals any positive values of melting, evaporation, or sublimation given by the model. These are dependent upon the diurnal variation of (1) shortwave radiation, which can be computed, (2) of near-surface air temperature, which is assumed to vary sinusoidally with amplitude 3°C and maximum at noon, and (3) of water vapor pressure in the air near the surface, which is unknown and so is calculated as a function of air temperature (List, 1966, p. 350) and mean relative humidity. Mean seasonal ablation was approximated by summing over June, July, and August the amounts determined for the middle of each month.

The major contribution to ablation is melting, which is assumed to take place whenever the energy balance (i.e., the sum of net radiation, sensible heat, and latent heat) is positive, provided the surface temperature is 0°C. Here a simplification must be made, for surface temperature is unknown. Its computation is possible (Outcalt, 1972) but too costly in computer time for this study. Therefore, snow surface temperature is assumed equal to air temperature up to 0°C (as in the model by Willen et al., 1971, p. 5).

Clear-sky shortwave radiation is computed as in Williams et al. (1972). This is accomplished by means of a formula for direct radiation on a slope given by Garnier and Ohmura (1968) and a formula for diffuse radiation given by List (1966, p. 420; attributed to S. Fritz). Atmospheric transmissivity was taken as 0.7 according to measurements by J. Johnson (pers. comm.). Global radiation is adjusted for cloud cover (C) by decreasing clear-sky direct and diffuse radiation in proportion to (C) but then increasing diffuse radiation by the factor 0.2C times shortwave radiation above the clouds. The factor expresses the assumption that cloud albedo = 60%, and cloud absorption = 20% (cf. Kondratiev, 1969, p. 443). Albedo of the snow surface is expressed as a function 0.74 - 0.015 x (days since snowfall) + 0.12 x (cloud cover), derived by regression on data collected on the Boas Glacier in 1970) Jacobs, Chapter 4 in Andrews and Barry, 1972), the regression explains 55% of the variance and is significant at the 0.1% level. Albedo was further adjusted for angle of incidence θ (Barkstrom, 1972) by adding 0.17 (0.7- sin θ). Longwave counter radiation was computed by the Angstrom equation:

$$\sigma T_a^4 \ (A_1 - B\exp\ (-Ce))$$

(Where σ is the Stefan-Boltzmann constant, T_a is air temperature, and e is water vapor pressure) using coefficients A_1 , 0.82, B , 0.25, C , 0.29, according to Kondratiev (1969, pp. 571, 579-580). Both shortwave diffuse radiation and longwave counter radiation were adjusted for slope

(Kondratiev, 1969, p. 681). Longwave radiation emitted by the surface is σT_s^4 (where T_s is assumed surface temperature), net longwave radiation was adjusted for cloud cover by a formula given by Ambach and Hoinkes (1963, p. 28). A computer program by Outcalt (1962) was adapted for use in approximating sensible and latent heat. Freezing of rain or meltwater as a source of latent heat was neglected. Finally, whenever the energy balance was positive and air water vapor pressure less than surface water vapor pressure, latent heat was assumed to be used for evaporation (surface temperature 0°C) or sublimation (surface temperature below 0°C).

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7. DISPOSITION AND ENVIRONMENTAL EFFECTS OF SILVER IODIDE FROM CLOUD SEEDING

7.1 DISPOSITION OF SILVER (H.L. Teller, D.R. Cameron and R.A. Mead)

The silver disposition study has now completed its third year. At the time of writing, the fourth spring sampling is about to be made, but the results will not be available in time for this report. Since the last report (Teller and Cameron, 1973) the modeling study of silver movement through the soil was completed, the spring 1973 monitoring data were collected and analyzed, and analytical studies were undertaken to determine if relationships could be established between seeding activity and silver concentration in snow, and between silver concentration in streamflow and that in snow. An attempt was also made to determine what sampling intensities were required to detect changes in silver concentration in soil and vegetation during monitoring operations on the San Juan target area.

7.1.1 Target Area Monitoring

The objective of the monitoring program remains the same, namely to determine silver concentrations in soil, litter and foliage of aspen, spruce and grass communities on the San Juan target area. Although initial sampling was carried out twice a year, in spring and fall, budget cuts have reduced sampling during the last two years to annual monitoring in spring only. The past history of sampling and the methods used are described in our previous report (Teller and Cameron, 1973). As before, the detection limit of the pyrosulfate fusion method used for silver analysis was 0.008 ppm silver in ash.

- Comparison of Components

The means and standard deviations for each sampled component (soil, litter or foliage) of spruce, aspen and grass are shown in Table 1, for the spring, 1973 sampling only.

Table 2 gives mean silver concentrations in all components for the three spring samplings, 1971, 1972 and 1973. Statistical analysis shows no significant differences between the three years, indicating that the sampling intensity has not been sufficient to detect any changes during this period. Mean concentrations on an ash basis (Table 2) in general show decreases between 1971 and 1973, though none of these are statistically significant.

In view of the above conclusion, no further tests were carried out to determine differences in silver concentration between components of each community type. Those conclusions reached in our last report are considered to be still valid, namely that, on an ash basis, spruce foliage and litter contain more silver than spruce soil. There are no significant differences between components in aspen and grass, though the foliage and litter silver means are about twice the soil silver mean in 1973 (see Table 2).

No further tests could be made between silver concentrations in spring and fall, as only spring sampling was carried out in 1972 and 1973. Similarly, no further analyses were made between transects. The two westerly transects (Million Dollar Highway and Rico Road) were again not sampled in 1973.

7.1.2 Sampling Requirements for Monitoring

The monitoring of small quantities of chemicals which are added to natural ecosystems during weather modification operations presents a number of difficult sampling problems. In the current study, extremely small amounts of silver are added in snow to an area which already contains fairly high natural concentrations of the metal. These vary considerably from place to place. In attempting to determine whether the cloud seeding operation in fact adds measurable amounts of silver to the soil and vegetation of the target area, sufficient samples must be taken to account for both the natural variability of silver on the target area, and the temporal and spacial variability of the annual additions.

Past reports in this series have addressed themselves to the problem. In our first report (Teller and Cameron, 1971), we estimated that the annual addition of silver from seeded precipitation during the Upper Colorado River Pilot Project would be between 0.002 and 0.006 ppm to litter and surface soil (ie. 0.002 to 0.006 mg kg^{-1}). This is based on the assumption that seeded precipitation delivers 0.01 to 0.03 gm Ag per hectare per cm of precipitation (Cooper and Jolly, 1970). In our second report (Teller and Cameron, 1973), we estimated that the top 3 cm. of litter and 2 cm of surface soil already contain 4.0 x 10^3 mg/ha

Table 1. Mean silver concentrations, percent ash, and standard deviations of each of the sampled components of spruce, aspen and grass. (Data averaged for all plots, spring 1973 sampling only.

		SPRUCE			ASPEN			GRASS	
		F	L	S	F	L	S	F	S
Percent Ash	Mean	4.0	28.4	73.6	9.9	31.5	71.5	9.4	87.2
	S.D.	0.8	10.6	15.9	16.0	14.7	16.8	1.6	4.2
Silver ppm (Ash basis)	Mean	0.22	0.15	0.06	0.17	0.22	0.08	0.10	0.03
	S.D.	0.20	0.07	0.06	0.18	0.45	0.11	0.16	0.02
Silver ppm (Dry wt. basis)	Mean	0.01	0.04	0.04	0.04	0.09	0.04	0.01	0.02
	S.D.	0.01	0.02	0.04	0.14	0.26	0.04	0.02	0.02
No. of Samples			25			18		25	

Note: S.D. = Standard Deviation, F = Foliage, L = Litter, S = Soil

Table 2. Results of analysis of variance comparing silver content of target area components sampled in spring of 1971, 1972 and 1973

	ppm-ash basis				ppm-dry wt. basis			
	1971	1972	1973	difference*	1971	1972	1973	difference*
Spruce								
Foliage	0.24	0.22	0.22	NS	0.01	0.01	0.01	NS
Litter	0.18	0.11	0.15	NS	0.04	0.03	0.04	NS
Soil	0.08	0.05	0.06	NS	0.06	0.04	0.04	NS
Aspen								
Foliage	0.19	0.13	0.17	NS	0.01	0.01	0.04	NS
Litter	0.21	0.12	0.22	NS	0.05	0.03	0.09	NS
Soil	0.21	0.05	0.08	NS	0.14	0.04	0.04	NS
Grass								
Foliage	0.12	0.09	0.10	NS	0.01	0.01	0.01	NS
Soil	0.15	0.07	0.03	NS	0.13	0.05	0.02	NS

*Statical difference at 95% level of confidence
NS = No significant difference

and 7.0×10^3 mg/ha silver respectively, while the annual addition from snow amounts to about 3.0×10^2 mg/ha, or about 1/40 of that already present in the surface 5 cm.

The determination of sample numbers is, of course, the first task in any monitoring program. In the case of the present study, sampling sites were originally selected on the basis of areal distribution (ie. by major drainages), altitudinal distribution, proximity to precipitation gages and budgetary constraints. The total number of plots and the frequency of sampling were not determined statistically. We are currently sampling only once a year on 27 plots in the present target area. The program began with 40 plots, when the western portion of the San Juans was still included in the study area.

A statistical analysis was carried out to determine the number of samples which would be required to detect a given difference in silver concentration over various periods of time, ranging from one to five years, with varying degrees of confidence. The following assumptions were made for the analysis:

Component analysed: Spruce litter
Standard deviation of Ag concentration (mean value for 1970-1972): 0.08 pp Ag as dry wt.
Minimum annual addition of silver: 0.002 ppm dry wt./yr.
Maximum annual addition of silver: 0.006 ppm dry wt./yr.
Original number of sample plots used: 40 (This gives the degrees of freedom for the subsequent analysis)
Range of confidence levels: 60%, 80%, 90%, 95%
Sampling procedure (hypothetical):
- Case 1 - Only two sampling times, one before and one after the seeding period, which may be 1, 2, 3, 4 or 5 years.
- Case 2 - Annual sampling, so that degrees of freedom accumulate yearly, ie. 40 in the first year, 80 in the second, etc. After the 5th year, 200 samples would have been collected.

The following equation was used to calculate required sample size to detect specified annual accumulations of silver:

$$n = \frac{4\, t^2 s^2}{d^2}$$

n=required sample size
t*=value from standard tables for appropriate degrees of freedom
s=standard deviation (the mean of 0.08 ppm in dry wt. was used in all computations. Note that the spring 1973 standard deviation of 0.02 ppm for spruce litter would reduce all sample numbers in Table 3 by a factor of 16)
d=mean annual accumulation of silver (ie. for
the minimum - 0.002 ppm after 1st year,
0.004 ppm after 2nd year,...
0.01 ppm after 5th year.
the maximum - 0.006 ppm after 1st year,
0.012 ppm after 2nd year,...
0.03 ppm after 5th year.

*Case 1 - Confidence level - 60% 80% 90% 95%

	60%	80%	90%	95%
t value	0.851	1.303	1.684	2.02

*Case 2 - Confidence level - 60% 80% 90% 95%

Year		60%	80%	90%	95%
		t value			
1	t (40)	0.851	1.303	1.684	2.020
2	t (80)	0.847	1.293	1.665	1.989
3	t (120)	0.845	1.289	1.658	1.980
4	t (160)	0.842	1.282	1.645	1.960
5	t (200)	0.842	1.282	1.645	1.960

Table 3 gives the sample numbers which would actually be required to detect a minimum annual silver addition of 0.002 ppm dry wt., and a maximum annual addition of 0.006 ppm dry wt., to spruce litter in the San Juan target area, at four confidence levels, under two hypothetical sampling regimes, assuming a standard deviation of 0.08 ppm silver as dry wt. This standard deviation was obtained from 40 samples per sampling time, between 1970 and 1973.

Table 3 shows clearly that the sample numbers which are being used in the present program are entirely inade-

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Table 3. Calculated number of samples required to detect annual additions of 0.002 and 0.006 ppm silver (dry wt.) in spruce litter on San Juan Target Area

CASE I*

Number of Samples Required

Years after which difference is measured	Confidence Levels 60%		80%		90%		95%	
1	515	4635	1207	10866	2017	18149	2902	26115
2	132	1159	310	2716	518	4537	746	6529
3	58	515	136	1207	226	2017	326	2902
4	32	279	75	655	125	1093	180	1573
5	21	185	48	435	81	726	116	1045

Left hand column: Annual accumulation of Ag = 0.006 ppm dry wt.
Right hand column: Annual accumulation of Ag = 0.002 ppm dry wt.

CASE II**

Number of Samples Required

Years after which difference is measured	Confidence Levels 60%		80%		90%		95%	
1	515	4635	1207	10866	2017	18149	2902	26115
2	131	1148	305	2675	507	4436	723	6330
3	57	508	133	1182	220	1955	314	2788
4	31	273	72	633	119	1043	170	1481
5	20	181	47	420	77	693	109	983

*Assume 40 degrees of freedom for all years, ie., samples are taken once before seeding begins, and only once thereafter, after 1, 2, 3, 4 or 5 years.

**Assume initial degrees of freedom (first year difference) are 40 and the degrees of freedom accumulate for successive years, ie., samples are taken annually.

quate to detect silver accumulation at the rates indicated, at a reasonable level of confidence.

Note, however, that the spring 1973 standard deviation of silver concentration in spruce litter was reduced from 0.08 to 0.02 ppm in dry wt. If this value had been used in Table 3, all sample numbers could be divided by 16. If silver accumulated at the minimum rate (0.002 ppm dry wt. per year), differences should be detectable with about 65 samples after 5 years in both Case I and Case II, at the 95% confidence level.

We conclude from this analysis that, if we assume a 0.08 ppm dry wt. standard deviation, a 0.002 ppm dry wt. annual increase of silver concentration in spruce litter will be detectable with about 40 samples per year only after 5 years with 60% confidence. An annual increase of 0.006 ppm dry wt. per year, with about 20 samples per year, should be detectable after five years with 95% confidence. The detection of the lower annual increase (0.002 ppm/yr), at 95% confidence, would require about 200 samples per year for 5 years, for each component being sampled. At present prices, for the number of components we are currently sampling, this would mean a cost of about $8,000 per year for sample analysis only.

With our present program of 27 samples per year per component, if a 95% confidence level is desired, and if a 0.02 ppm dry wt. standard deviation can be assumed for spruce litter (instead of the 0.08 used above), an annual accumulation of 0.002 ppm should be detectable after about four years. An annual accumulation of 0.006 ppm dry wt. should be detectable after about two years.

7.1.3 Generator Site Monitoring

The Pagosa Springs Generator Site (no. 25) was sampled only in spring 1973 and will be sampled again in spring 1974 (the latter data will be included in the next SJEP report). As previously, samples were collected along four transects in the cardinal directions, at 10, 20, 50, 100 and 200 meters from the generator location. Soil, litter and foliage were collected in grass and *Pinus ponderosa* communities.

During the 1972-73 seeding season, generator No. 25 had minimal use, having burned for only 23 hours, with a total output of 465 grams of silver iodide. This is extremely low compared to the ten generators with highest output for the season, which averaged 2,309 grams AgI. Maximum output of 3,197 grams was obtained from generator No. 23 ('Oak Brush'), located about 8 miles SW of Pagosa Springs. Output from generator No. 25 since the beginning of the current seeding program was:

1970-71	2360 grams AgI
1971-72	3760 grams AgI
1972-73	465 grams AgI

No further studies were conducted to determine what proportion of the silver was inside or on the surface of foliage. Both greenhouse tests with field crops (Teller and Klein, 1974) and parallel research at other generator sites (at Tennessee Pass, near Leadville, Colo., and at Emerald Mountain, near Steamboat Springs, Colo.) have shown conclusively that uptake of silver by plants is possible, and that accumulation does occur in roots, wood and foliage of plants near generator sites. If silver is to be passed on in the food chain, it is immaterial whether it is on the inside or on the surface of plants, except that the latter could possibly be washed off the surface with time.

Table 4 gives silver concentrations in soil, grass, Ponderosa pine foliage and pine litter at varying distances from the generator, for the spring samplings carried out in 1971, 1972 and 1973. Figure 1 shows the spring 1973 data only, and indicates the familiar trend of decreasing silver concentration with distance from the site. It also shows that, in terms of ppm in ash, highest silver concentrations are in or on pine foliage, with decreasing concentrations in litter, soil and grass respectively.

Figure 2 shows mean silver concentrations in each component, averaged over all distances, for each season since sampling began in fall, 1970, through spring 1973. It can be seen that there was a fairly steady increase in mean silver values till fall, 1972. Due to the very low seeding activity at this site during the 1972-73 season, spring 1973 silver values show a consistent decrease, generally to lower values than those noted in spring 1972.

An analysis of variance was carried out on the data from which Figure 2 was compiled in order to ascertain

Table 4. Mean silver concentrations in terrestrial components at Generator Site 25 (Pagosa Springs), for spring sampling in 1971, 1972 and 1973

(a = silver conc. as ppm in ash; b = silver conc. as ppm in dry wt.; SD = standard deviation)

Distance from Generator (meters)		SOIL 1971	SOIL 1972	SOIL 1973	GRASS 1971	GRASS 1972	GRASS 1973	PINE FOLIAGE 1971	PINE FOLIAGE 1972	PINE FOLIAGE 1973	PINE LITTER 1971	PINE LITTER 1972	PINE LITTER 1973
10	a.	.18	.31	.32	.75	.38	.25	-	-	-	-	-	-
	SD.	.04	.16	.15	.46	.27	.14	(no foliage or litter available at 10 meters)					
	b.	.16	.28	.29	.08	.03	.03	-	-	-	-	-	-
	SD.	.03	.15	.14	.05	.04	.02						
20	a.	.11	.20	.18	.09	.44	.07	4.36	12.60	3.85	.52	2.10	2.05
	SD.	.03	.12	.09	.06	.45	.03	1.37	9.05	2.33	.24	.28	.50
	b.	.10	.19	.16	.01	.04	.01	.13	.33	.10	.06	.20	.21
	SD.	.03	.11	.09	.01	.05	.00	.04	.23	.06	.01	.12	.04
50	a.	.09	.11	.11	.08	.17	.10	.95	3.23	1.47	.10	1.24	.74
	SD.	.05	.06	.06	.14	.14	.10	.42	3.62	.55	.10	.64	.58
	b.	.08	.10	.10	.01	.02	.01	.03	.09	.04	.03	.10	.13
	SD.	.04	.06	.05	.02	.01	.01	.01	.12	.02	.03	.07	.10
100	a.	.09	.10	.25	.02	.07	.04	.76	2.08	1.08	.14	.81	.49
	SD.	.06	.07	.29	.03	.04	.05	.33	1.67	.98	.14	.60	.09
	b.	.08	.09	.23	.00	.01	.00	.02	.05	.03	.01	.04	.05
	SD.	.05	.06	.27	.00	.00	.00	.01	.04	.02	.01	.03	.03
200	a.	.07	.08	.09	.04	.07	.05	.49	.86	.63	.12	.82	.47
	SD.	.04	.06	.06	.06	.05	.04	.25	.24	.59	.16	.16	.09
	b.	.06	.07	.07	.00	.01	.01	.01	.02	.02	.01	.05	.04
	SD.	.03	.05	.06	.01	.00	.01	.01	.01	.02	.01	.01	.01

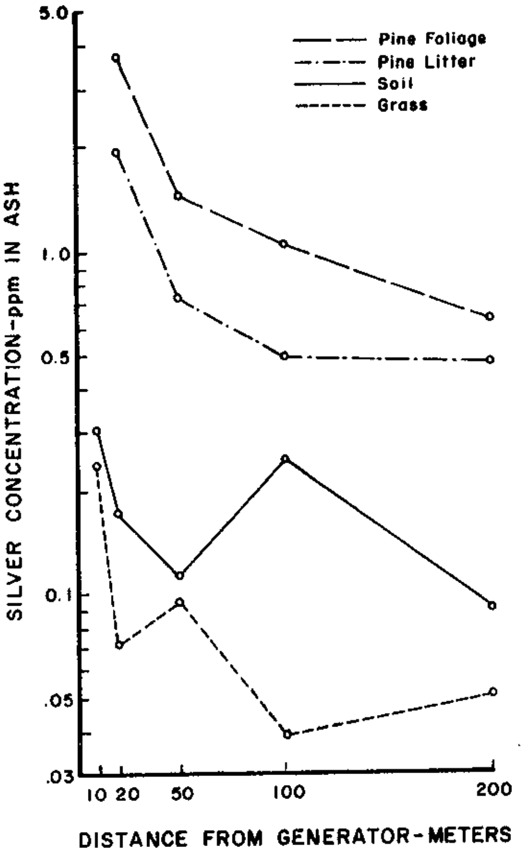

Figure 1. Variation of silver concentration in four terrestrial components with distance from generator (Spring, 1973)

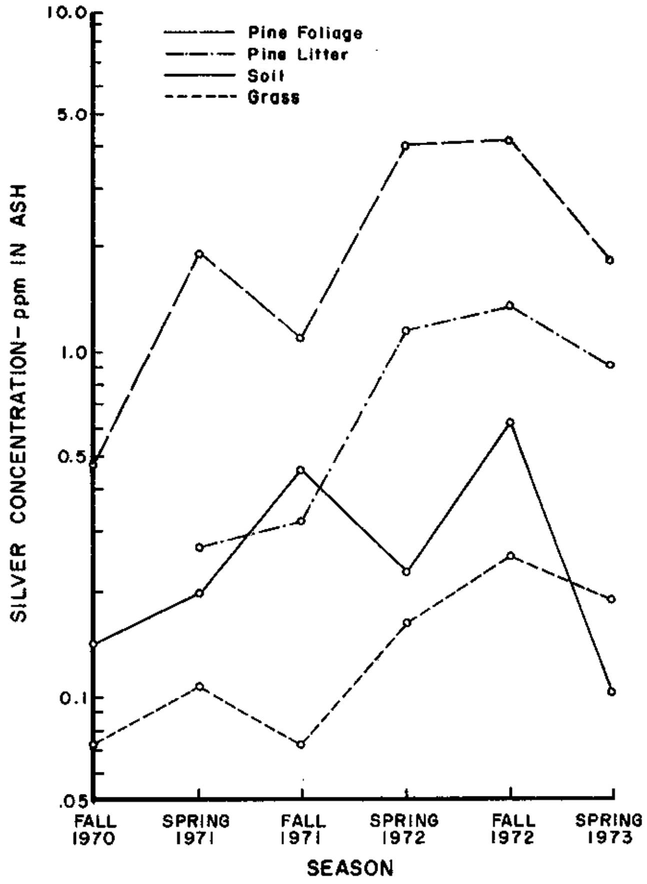

Figure 2. Time trends of silver concentration in four terrestrial components at GS 25 (means of 4 directions and 5 radii)

whether the differences indicated by the mean values were, in fact, statistically significant at all distances from the site. In view of the very high variability of the original data, which can be seen in the high standard deviations in Table 4, it is not surprising that Table 5 shows a large number of non-significant differences between sampling times of all components.

Table 5. Analysis of variance of mean silver concentrations (as ppm in ash) in four terrestrial components at varying distances from generator sit 25, between fall 1970 and spring 1973

	Component			
Distance m.	Soil	Grass	Pine Foliage	Pine Litter
10	*	*	-	-
20	*	NS	NS	**
50	*	NS	NS	NS
100	NS	*	NS	*
200	**	NS	NS	**

*Difference between sampling times significant at 95% confidence level
**Difference between sampling times significant at 99% confidence level
NS = No significant difference
- = No samples taken

The apparent increases in silver shown for pine foliage and grass are not statistically significant (at the 95% confidence level) at most distances, while those indicated for soil and pine litter are generally significant.

Our general conclusions from the above analysis are:

- There has been an accumulation of silver at generator site 25, up to fall 1972. The small amount of seeding during the 1972-73 season apparently added less silver than was removed by natural means, resulting in a slight decrease in silver concentration in all the components.

- If the decrease in silver concentration noted for the spring 1973 sampling is real (ie., is not caused by changes in laboratory technique), this indicates that a significant portion of the silver is surface deposited, and may be amenable to gradual removal by rain or wind.

- Silver concentration in all components decreases with distance from the generator and reaches background levels at about 200 meters from the site.

- Larger numbers of samples than those taken here would be required to show more highly significant differences between years. However, the consistent trend noted does appear to be a logical result of the seeding activity.

7.1.4 Modeling Silver Transport in the Soil

Our previous report (Teller and Cameron, 1973) indicated that a model for silver transport was being developed on the basis of Darcy's law for solution flow and Fick's law for solute diffusion. The model has been completed and tested on reconstituted soil cores in the laboratory (Cameron, 1973), with silver from both AgI and $AgNO_3$.

Cameron concluded from his experimental results that the silver concentration in soil solution at any given time can be estimated reasonably well by subtracting the silver removed by adsorption (N) from that added in the flow (F). The amount being added can be said to follow the laws of Darcy flow and Fickian diffusion, ie.:

$$F = qC - D\theta\frac{\partial C}{\partial t}$$

Where F = mass of silver added in solution
q = volume of solute added
C = concentration of silver in the solute
D = diffusion coefficient
θ = moisture content of soil by volume
t = time

The silver removed from solution by adsorption (N) can be attributed to either an equilibrium - type reaction or a kinetic type reaction, or both, ie.:

$$N = k_1C + \sum_{o}^{t} (k_2C - k_3N)$$

Where N = amount of silver removed from solution (amount of silver adsorbed by soil particles)
C = concentration of silver in solution
k_1 = equilibrium reaction constant
k_2 = adsorption rate constant
k_3 = desorption rate constant
t = time

The conclusions reached from the modeling study with AgI may be summarized as follows:

(i) The silver adsorption model is best represented by a kinetic-type reaction coupled with an insignificant equilibrium-type reaction, so that k_1C above can be neglected.

(ii) The dominant parameters in the adsorption model are the adsorption rate constant (k_2), and the desorption rate constant (k_3).

(iii) The adsorption rate constant (k_2) is 100 to 1,000 times greater than the desorption rate constant (k_3), in the case of an AgI source.

(iv) As the rate of adsorption (k_2C) is a finite value less than C_o (the input concentration), a proportion of the silver added (10 to 30% of input concentration) will move through the soil column.

(v) As more silver is adsorbed, the desorption rate (k_3N) will increase, more silver will be returned to the solution, and leachate concentration will increase slowly with time.

When he used the readily soluble $AgNO_3$ source, Cameron found that the dominant parameter in the model is the equilibrium reaction coefficient, k_1. In this case, the adsorption rate of silver is so rapid as to be instantaneous, and silver only appears in the leachate when the soil column is saturated.

Although generalization of the above results, and extrapolation to a field situation, is risky at best, it can be postulated that some silver from surface-deposited AgI is likely to move through the soil profile into the root zone, though most will be adsorbed in surface litter and soil layers. This has been borne out by observations at generator sites, where silver concentrations do decrease from the surface downward, but where enough penetrates to the root zone to be taken up by plants.

7.1.5 Silver Concentration in Snow

Although the monitoring of silver concentrations in snow was not part of the objective of this project, such data were obtained at a number of stations within and outside the target area by another contractor*, and were made available to us for analysis. The data are tabulated in Table 6, which gives the mean annual silver concentration in snow, its standard deviation, and the number of samples used to calculate the mean, for each station.

It is obvious from Table 6 that the sampling scheme was not designed for subsequent statistical analysis, as the sample numbers vary considerably, both between stations and between years. Furthermore, the very high variability of the data can be seen from the large standard deviations, many of which are two to three times the means. (Table 6 is on following page)

Silver-in-snow concentration on and off the target area

An attempt was made to answer the question: Is there a significant difference between silver concentration in snow on the target area, and at sites west and east of the target area?

Silver-in-snow concentration data from Table 6 were averaged for each of the three major zones, to give the means in Table 7.

Table 7. Five-year mean silver concentrations in snow for three zones in the San Juan mountains

	Mean Ag conc. in snow gm/ml x 10^{10}	Standard Deviation	No. of Samples
West of Target Area1/	0.22	0.16	180
Target Area2/	0.62	2.51	209
East of Target Area3/	0.29	0.42	143

1/Molas Divide, Red Mountain, Mineral Ck., Animas
2/Wolf Ck. Pass, Middle Fork Piedra, Vallecito Ck.
3/Alamosa, Creede, LaVeta Pass

A student's t-test on the above data indicated that there was no statistically significant difference (at the 95% confidence level) between silver-in-snow concentrations in the three major zones. (Table 6)indicates

*Western Scientific Services, Fort Collins. Unpublished, occasional reports of analyses of silver concentration in snow.

Table 6. Mean annual silver concentration in snow - San Juan target area and vicinity (gm/ml x 10^{10})*

	1969			1970			1971			1972			1973			All Years		
	Mean	SD	Samp. No.	Mean	SD	Samp. No.	Mean	SD	Samp. No.	Mean	SD	Samp. No.	Mean	SD	Samp. No.	Mean	SD	Samp. No.
W. of Target Area																		
Molas Divide	-	-	-	-	-	-	-	-	-	0.0	0.0	28	0.12	0.23	13	0.05	0.16	41
Red Mountain	0.14	0.19	8	0.26	0.24	19	0.09	0.27	71	1.10	0.75	21	-	-	-	0.29	0.54	123
Mineral Ck.	-	-	-	0.04	0.19	8	-	-	-	-	-	-	-	-	-	0.04	0.19	8
Animas	-	-	-	0.11	0.16	8	-	-	-	-	-	-	-	-	-	0.11	0.16	8
													Total samples					180
Target Area																		
Wolf Ck. Pass	0.11	0.18	41	0.05	0.13	45	2.15	5.06	51	0.30	0.67	44	0.12	0.21	17	0.67	2.73	193
Middle Fk. Piedra	-	-	-	0.09	0.16	8	-	-	-	-	-	-	-	-	-	0.09	0.16	8
Vallecito Ck.	-	-	-	0.00	0.00	8	-	-	-	-	-	-	-	-	-	0.00	0.00	8
													Total samples					209
E. of Target Area																		
Alamosa	-	-	-	-	-	-	0.50	0.66	14	0.25	0.16	32	0.28	0.34	25	0.31	0.45	71
Creede	-	-	-	-	-	-	-	-	-	0.45	0.43	23	0.85	0.76	4	0.51	0.50	27
LaVeta Pass	-	-	-	-	-	-	-	-	-	0.05	0.16	20	0.20	0.26	25	0.14	0.23	45
													Total samples					143

- = No samples taken

SD = Standard Deviation

Note: Values of $<0.03 \times 10^{-10}$ gm/ml were arbitrarily assigned the value of 0.0
*Values in table are gm/ml already multiplied by 10^{10}

that the relatively high mean of $0.6 \pm 2.5 \times 10^{-10}$ gm/ml for the target area was caused by high concentration at Wolf Creek Pass in 1971 ($2.2 \pm 5.1 \times 10^{-10}$ gm/ml). However, both the standard deviation for 1971, and the overall standard deviation for the whole target area over the period 1969-1973, are so high that significant differences will obviously not be shown. It is interesting to note, however, that the target area mean is about twice as high as the downwind (east of target area) mean, and about three times as high as the upwind (west of target area) mean.

Relationship between seeding intensity and silver-in-snow

Due to the location of Wolf Creek Pass in the central part of the target area, and its relatively high silver-in-snow concentrations, an attempt was made to relate silver-in-snow concentration at this site with total seeding intensity from all generators.

Table 8 gives mean silver-in-snow concentrations at Wolf Creek Pass and total grams of AgI burned by all generators, for each month during the three seeding seasons, 1970-71, 1971-72 and 1972-73.

The data from Table 8 are plotted on a time basis in Figure 3 and as a regression relationship in Figure 4. The time-plot indicates that maximum seeding activity occurred in the spring and fall of 1971, and that maximum silver concentration in snow at Wolf Creek Pass coincided with the maximum seeding activity. However, during most months, the relationship between the two parameters is not good, as is also shown in Figure 4. Due to the small number of points available for a correlation analysis, and the obviously poor relationship shown in Figure 4, no statistical calculations were attempted. It is concluded that silver concentration in snow at a given site can not be adequately predicted from total seeding activity for the target area.

7.1.6 Silver Concentration in Water

Although the collection and analysis of silver-in-water data were also not part of the mandate of this project, the availability of the data from the U.S. Geological Survey (1970, 1972, 1973) prompted the following analysis.

Both mean annual silver concentrations in streamflow and mean annual discharge are given in Table 9 for five U.S.G.S. stations in the San Juan mountains, for the three years, 1971-1973. Statistical analyses were undertaken to answer the following questions:

(i) Is there a significant difference between mean silver concentrations in the five streams?

(ii) Is there a significant difference in mean silver concentrations between years?

(iii) Is silver concentration in water related to stream discharge?

Analysis of variance between mean silver concentrations in water at five stations indicated that there was no statistically significant difference between them. This result is obviously due to the high variance of the data, which can be seen in Table 9. The last column in that table shows that the 3-year means vary from 0.12 $\times 10^{-10}$ gm/ml in the Piedra to 0.58×10^{-10} gm/ml in Vallecito Creek. The two highest mean concentrations correspond to the two highest discharges.

Differences between years were also tested by analysis of variance and found to be significant at the 95% confidence level. These differences can be seen in the bottom row of Table 9, where mean silver concentration increases from 0.11×10^{-10} gm/ml in 1971 to 0.57×10^{-10} gm/ml in 1973. Mean discharge also increased during that time from 103 cfs. in 1971 to 160 cfs. in 1973. However, the mean discharge differences between the three years were not statistically different at the 95% confidence level, due to the high variability between individual streams.

Figure 5 (a-f) shows the relationship between annual mean discharge and annual mean silver concentration for each of the five streams in Table 9. Figure 5f combines the means for all streams. It is clear from these figures that a positive relationship does exist between stream discharge and stream silver concentration, but that variability between streams is high.

Individual annual means of silver concentration against discharge, for each stream in each year, are plotted in Figure 6, which indicates that the relationship is not

Table 8. Monthly mean concentration of silver in snow at Wolf Creek Pass, and total grams AgI burned by all generators. (Silver concentration as gm/ml x 10^{10})

	1970-71		1971-72		1972-73	
	Mean Ag conc. in snow	Total gms AgI burned	Mean Ag conc. in snow	Total gms AgI burned	Mean Ag conc. in snow	Total gms AgI burned
November	0.00	4,420	2.89	48,640	0.06	-
December	0.00	-	2.28	1,900	0.13	6,914
January	0.00	-	1.54	10,720	0.08	3,830
February	0.00	3,200	1.35	2,600	0.26	7,564
March	0.00	21,920	-	-	0.41	7,462
April	0.13	39,940	-	10,440	0.48	7,462
May	-	22,795	-	-	-	-

Note: 0.00 indicates $<0.03 \times 10^{-10}$ gm/ml reported

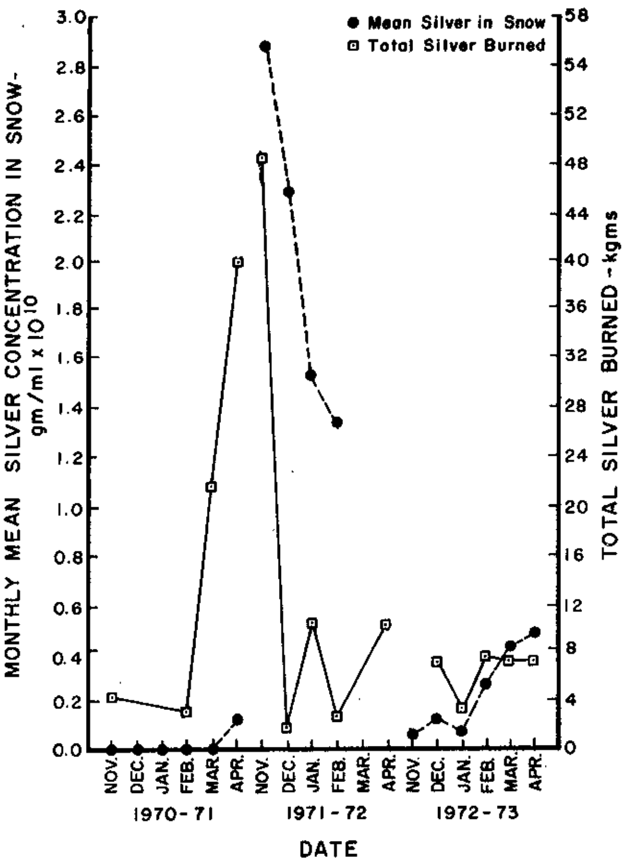

Figure 3. Time variation of total seeding activity and silver concentration in snow at Wolf Creek Pass

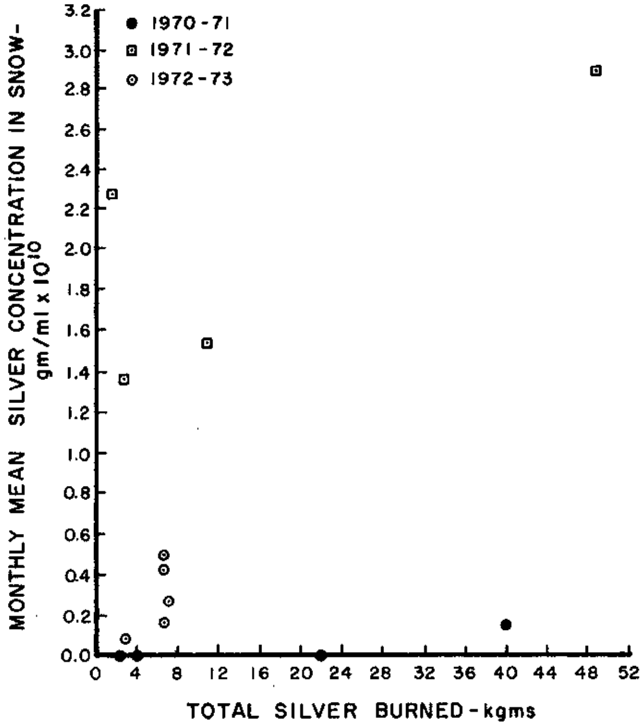

Figure 4. Relationship between total silver burned by all generators and silver concentration in snow at Wolf Creek Pass

Table 9. Mean annual silver concentration in stream flow and mean annual discharge of five San Juan rivers, 1971-1973

		1971		1972		1973		All 3 Years	
		Ag conc. in water g/ml$\times 10^{10}$	Discharge cfs	Ag conc. in water g/ml$\times 10^{10}$	Discharge cfs	Ag conc. in water g/ml$\times 10^{10}$	Discharge cfs	Ag conc. in water g/ml$\times 10^{10}$	Discharge cfs
Wolf Creek	Mean	0.00	41	0.39	53	0.60	93	0.31	61
	SD	0.00	31	0.73	37	1.08	127	0.74	75
Middle Fk. Piedra	Mean	0.03	45	0.09	76	0.26	113	0.12	75
	SD	0.10	36	0.23	55	0.36	142	0.25	87
Vallecito Creek	Mean	0.09	222	0.66	255	1.14	195	0.58	224
	SD	0.18	184	1.05	177	1.96	223	1.25	187
Mineral Creek	Mean	0.07	36	0.09	40	0.40	53	0.17	42
	SD	0.13	32	0.23	34	0.41	63	0.30	43
Animas River	Mean	0.34	170	0.23	229	0.46	260	0.35	213
	SD	0.53	183	0.27	240	0.79	279	0.55	222
All Five Streams	Mean	0.11	103	0.29	130	0.57	160		
	SD	0.29	138	0.61	159	1.07	195		

SD = Standard deviation
Note: 0.00 indicates $<0.03 \times 10^{-10}$ gm/ml reported

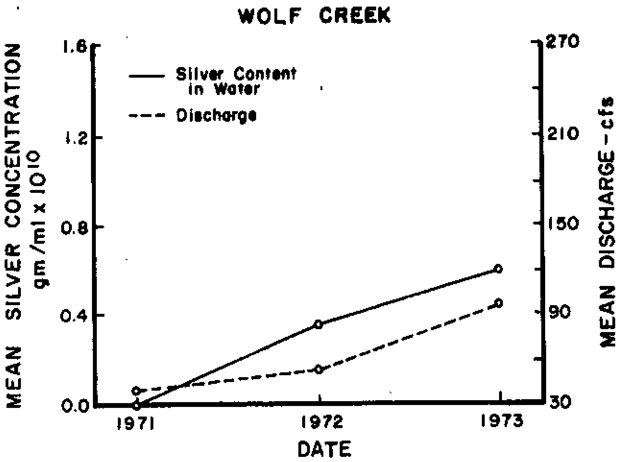

Figure 5a. Time trend of mean annual discharge and mean annual silver concentration, Wolf Creek, 1971-1973

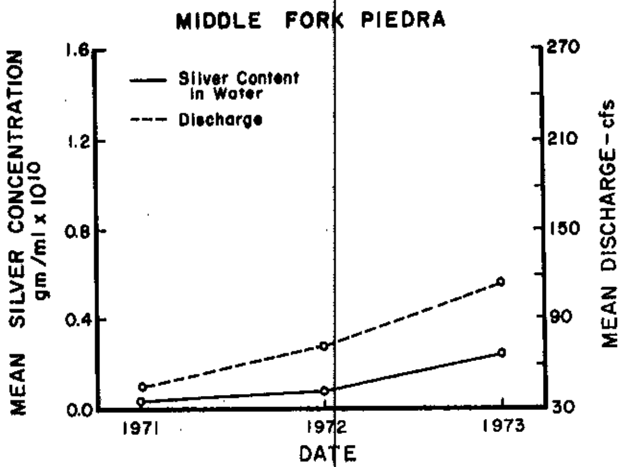

Figure 5b. Time trend of mean annual discharge and mean annual silver concentration, Middle Fork Piedra, 1971-1973

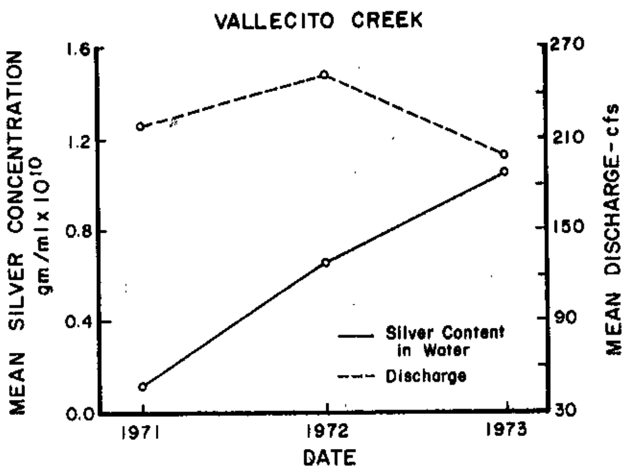

Figure 5c. Time trend of mean annual discharge and mean annual silver concentration, Vallecito Creek, 1971-1973

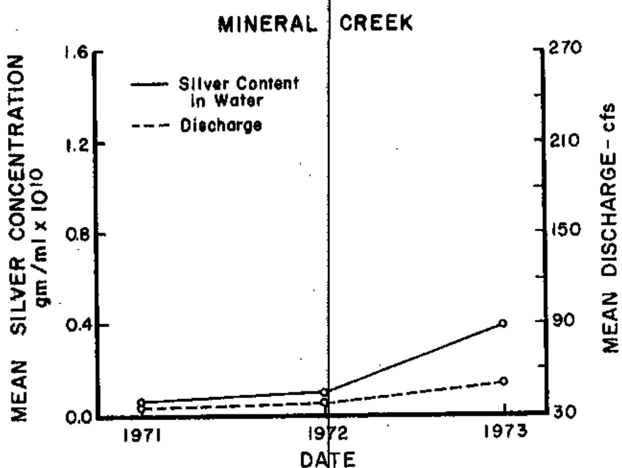

Figure 5d. Time trend of mean annual discharge and mean annual silver concentration, Mineral Creek, 1971-1973

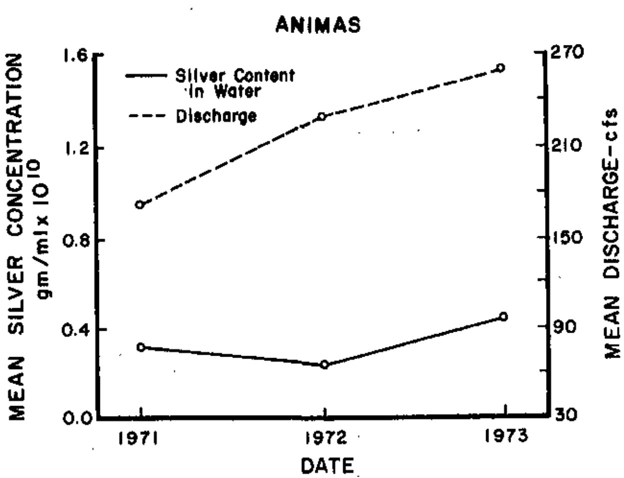

Figure 5e. Time trend of mean annual discharge and mean annual silver concentration, Animas River, 1971-1973

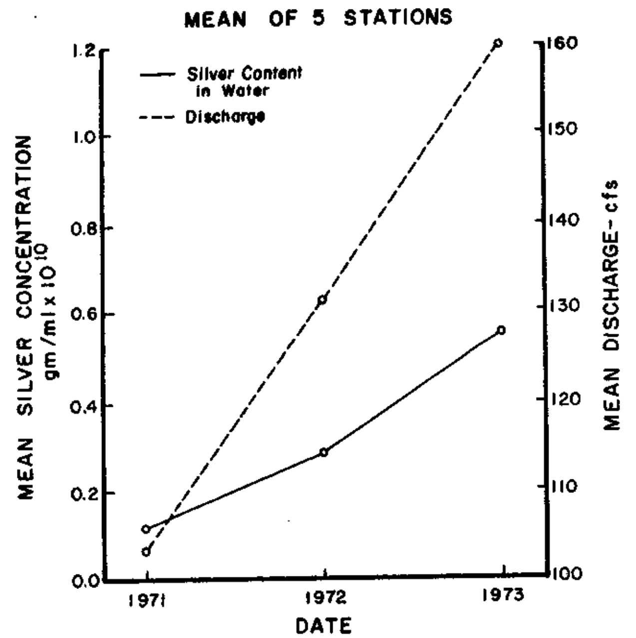

Figure 5f. Relationship between mean annual discharge and mean annual silver concentration in water for 5 San Juan streams

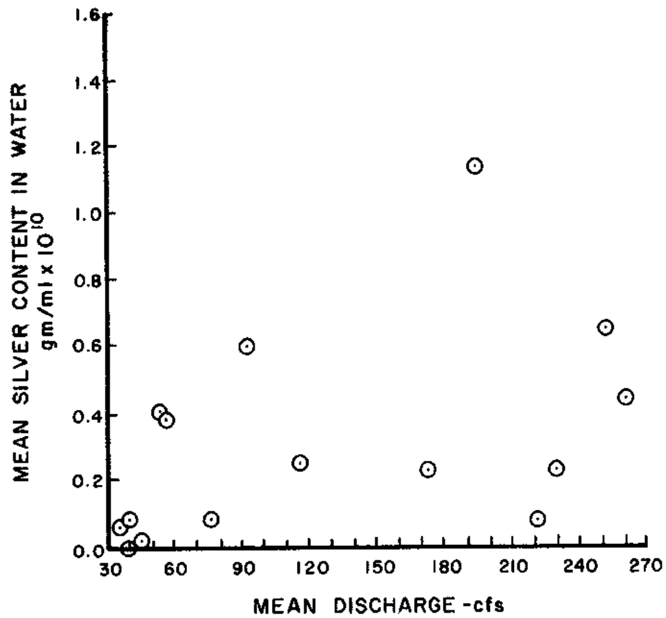

Figure 6. Relationship between mean annual discharge and mean annual silver concentration in water of five San Juan streams*, 1971-1973

*Wolf Creek, Middle Fork Piedra, Vallecito Creek, Mineral Creek, Animas River

good and can not be used for general prediction. A correlation coefficient (r^2) of 0.21 was obtained for the data in Figure 6, and is not different from zero at the 95% confidence level. Hence, no regression line was drawn in the figure. When the variance is reduced by using only three means for each parameter (Figure 5f), a correlation coefficient (r^2) of 0.95 is obtained. However, the use of only three points for the correlation gives it a very low statistical validity.

The general conclusion from the above analysis is that no statistical difference was found between silver concentration in five San Juan streams, due to the high variability of the data. Silver concentrations did vary significantly between years, increasing from a low mean concentration for all five streams of 0.11×10^{-10} gm/ml in 1971, to a high of 0.57×10^{-10} gm/ml in 1973. Although there is a weak positive relationship between discharge and silver concentration in individual streams, no general predictive model could be derived from annual means for the five streams tested.

7.1.7 General Model and Status of Knowledge for Silver Disposition in Terrestrial Ecosystems

The compartment model depicted in Figure 7 attempts to summarize the more recent relevant information of which the authors are aware, regarding the disposition of silver from cloud seeding in terrestrial ecosystems. As a knowledge of disposition is useful mainly in conjunction with knowledge about ecological effects, Figure 7 includes some indications of biological effects, in so far as the authors are familiar with other work in that area. Apart from these 'effect' compartments, the model attempts to indicate the movement of silver, either in ionic or combined form, from its initial introduction into the air, to its adsorption on plant, soil or animal material.

The model makes no claims for completeness, or even for perfect accuracy, but merely attempts to indicate the current 'state of the art' and where relevant information is available. The number on each compartment refers to the brief commentary and reference section below:

1. Silver in snow: Cooper and Jolly (1970) quote concentrations of silver in seeded precipitation as varying from 10^{-12} to 45×10^{-10} gm/ml, with typical values of 10^{-10} to 3×10^{-10} gm/ml. Warburton (1971) gives silver concentrations of seeded orographic precipitation in the Lake Tahoe area of 22×10^{-12} gm/ml, with a 4×10^{-12} gm/ml background. Mean silver concentration for seeded and unseeded snow in the San Juans has varied from $(0.2 \pm 0.2) \times 10^{-10}$ gm/ml west of the present target area to $(0.6 \pm 2.5) \times 10^{-10}$ gm/ml in the target area.

2. Silver in soil water: No information available from target area. Cameron (1973) has developed a first-generation model which indicates that silver from AgI is adsorbed to soil particles according to a kinetic-type reaction with a high adsorption rate constant, and that 10 to 30% of added silver is likely to move downward through surface layers into the root zone. White (1973) found that silver in runoff water from field plots increases about proportionately with silver applied in simulated precipitation.

3. Silver in streamflow: The general model in Figure 7 shows that silver may enter streamflow either directly, as surface runoff, or through sub-surface flow. In the forest environment of the San Juan mountains there is very little surface runoff. Analysis of U.S.G.S. data (1970-1973) indicates that mean annual silver concentrations in five San Juan streams range from $(0.1 \pm 0.3) \times 10^{-10}$ gm/ml to $(0.6 \pm 1.1) \times 10^{-10}$

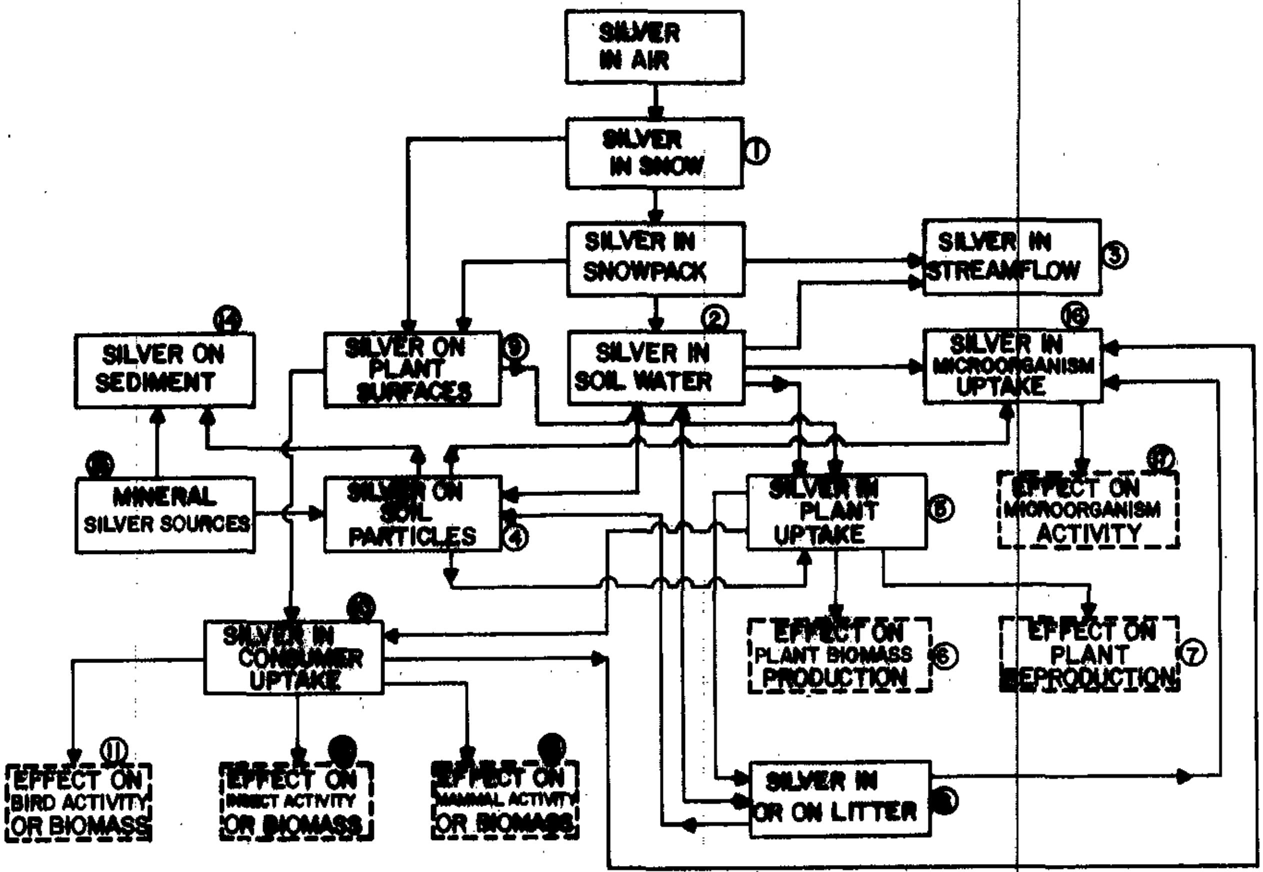

Figure 7. Compartment model of silver movement and effect in a terrestrial ecosystem subjected to winter cloud seeding

gm/ml. The U.S. Public Health Service standard for silver in drinking water is 0.05 mg/l, or 0.5×10^{-7} gm/ml. Teller and Klein (1974) found that mean annual silver concentration in streams and ponds in the Pawnee Grasslands area of northeastern Colorado ranged from $0.05 \pm 0.1 \times 10^{-10}$ gm/ml to $(0.1 \pm 0.2) \times 10^{-10}$ gm/ml.

4. Silver on soil particles: The form in which silver from cloud seeding is adsorbed to soil particles is not known. A model has been proposed (Cameron, 1973) to describe the movement of silver through the soil profile. Mean silver concentrations in soil of the San Juan Target area averaged from 0.02 ± 0.02 to 0.1 ± 0.1 ppm dry weight. Silver levels in surface soil of the Pawnee Grasslands are similar to the lower of the above values, ie., 0.01 to 0.03 ppm dry weight.

At terrestrial sites where AgI generators have operated for a number of years, silver concentrations in surface soils can be high. At Emerald Mountain, near Steamboat Springs, Colo., silver concentration in the 0-2 cm. layer of surface soil averaged 250 ppm in ash at 10 meters from the site, but decreased to 0.2 ppm in ash at 500 meters. Silver concentration also decreased with depth, averaging only 0.8 ppm in ash at the 8-10 cm. depth at 10 meters from the site (Teller and Klein, 1973). At another generator site at Tennessee Pass, Colorado, silver concentration in 0-2 cm. surface soil averaged 15 ppm in ash (unpublished data, Nugent, Teller and Klein, 1974).

5. Silver in plant uptake: There is now a considerable body of evidence to confirm that silver can be taken up by plants, from both natural and artificial sources. Curtin et al., (1971) give maximum natural silver concentrations in roots, trunk and branches of *Pinus contorta* near Empire, Colorado, as 30, 100 and 100 ppm in ash, respectively, while needles contained a maximum of only 3 ppm in ash. Our own studies at generator sites show up to 25 ppm silver in ash in foliage, and 22 ppm in stem wood of young aspen saplings near Steamboat Springs (Teller and Klein, 1973). Concentrations in wood of *Pinus contorta* at 5 m. from a generator site at Tennessee Pass ranged from 28 to 570 ppm in ash, depending on position in the tree (unpublished data, Nugent, Teller and Klein, 1974). Selected crops grown in greenhouse sand which had been treated with 30 ppm AgI burn complex, took up from 12 to 60 ppm silver (in ash) into stems and leaves of corn, sugar beet and Kentucky bluegrass. Roots contained between 40 and 170 ppm in ash, though some of this may have been external adsorption rather than internal uptake (Teller and Klein, 1974).

6. Effect on plant biomass production: Weaver and Klarich (1973) found no growth reduction and no silver uptake in wheat, maize, soybeans and sunflowers which were grown in sand and loam treated with up to 1,000 ppm reagent grade AgI. In greenhouse uptake studies with seedlings of tufted hairgrass and lodgepole pine, 60 ppm applied AgI had deleterious effects on seedling vigor and percent emergence, but lower concentrations (0.6 to 6 ppm) tended to stimulate seedling growth (White, 1973).

7. Effect on plant reproduction: Up to 1,000 ppm reagent grade AgI did not affect percent germination of either tufted hairgrass or lodgepole pine seed (White, 1973). *In vitro* studies of Engelmann spruce pollen germination (Fins, 1972) showed that AgI, in combination with NaI, reduced pollen tube lengths at 2, 3 and 100 ppm Ag. Sodium, as NaI, was also found to be detrimental at 10 ppm, and elemental iodine at 100 and 300 ppm I_2.

In sum, the evidence for deleterious effects of silver on plant reproduction or growth is somewhat contradictory, but does not indicate that there is danger from the concentrations which may be expected from cloud seeding operations. Most experimental work has been carried out with reagent grade AgI or AgI - NaI mixtures, whose behavior does not necessarily bear much resemblance to that of AgI which has been burnt in a generator or pyrotechnic device.

8. Silver in or on litter: Three years' monitoring data from the San Juan target area indicate that the litter of aspen and spruce forests contains between 0.1 and 0.2 ppm silver in ash (0.03 to 0.09 ppm dry wt.). Curtin et al., (1971) found up to 20 ppm Ag in ash in the litter of *Pinus contorta* growing over silver deposits in the Empire District of Colorado. Forest litter tends to adsorb large amounts of silver near silver iodide generator sites. At Emerald Mountain, near Steamboat Springs, Colorado, we found mean silver concentrations of about 180, 480, 260, 30, 10 and 1 ppm in ash at 10, 20, 50, 100, 200 and 500 meters from the site, four years after seeding ceased. A maximum concentration of 1100 ppm in ash was found in mixed hardwood litter at one point 20 meters from the generator site (Teller and Klein, 1973). Mean silver concentrations in *Pinus contorta* surface litter at a Tennessee Pass, Colorado, generator site ranged from 500 ppm in ash at 10 meters, to about 16 ppm in ash at 200 meters. Corresponding values for the decomposed litter layer beneath the surface ranged from about 90 ppm in ash at 10 meters, to about 2 ppm in ash at 200 meters (Nugent, Teller and Klein, 1974).

9. Silver on plant surfaces: A small-scale study was undertaken to determine the proportion of silver on the surface of foliage near a generator site, compared to that which had been taken up inside the leaf (Teller and Cameron, 1973). The results indicated that between 30 and 45 percent of the total silver measured in foliage could not be washed off the surface with detergent and nitric acid. It is not known whether that proportion which remained had entered the leaf through stomata or cuticle, or had been translocated via the roots, or was simply strongly adsorbed on the leaf surfaces. While it has been shown conclusively that uptake of silver into plant stems and foliage can take place via the roots, leaf uptake can not be ruled out as an alternative method of entry at this time.

10. Silver in consumer uptake: Pfadt (1974) has shown that grasshoppers which are fed on AgI burn complex-treated food can apparently take up and retain up to 1.5 ppm silver in dry weight (as compared to 0.1 ppm in control grasshoppers). However, some or all of this apparent uptake may be due to external adsorption of silver, and further work is required. Bailey et al., (1973) showed no uptake or effect of AgI burn complex on intestinal microflora of rabbits and goats.

11. Silver effect on birds: No information.

12. Silver effect on insects: Although the experiments of Pfadt (1974) were designed primarily to investigate silver uptake rather than effect on grasshoppers, survival rates of test insects were recorded at the end of the experiment. Survival rates did not differ between grasshoppers fed with AgI burn complex and $AgNO_3$ - treated food, but survival from both these treatments was 1.2 times higher than from AgI - reagent grade - treated food. Control lots had the same survival rate as silver - treated lots.

13. Silver effect on mamals: See item 10 above.

14. Silver on stream sediments: No information available from this project. Some may be available from Colorado Division of Game, Fish and Parks, Division of Wildlife, and from the U.S. Geological Survey. Stream sediments from nine sampling sites in the Pawnee Grasslands of northeastern Colorado (Teller and Klein, 1974) contain 0.04 $\pm$ 0.04 ppm silver in ash.

15. Mineral silver sources: The U.S. Geological Survey is investigating the use of plant silver concentrations for geochemical prospecting (eg. Curtin et al., 1971). Useful information on the subject is available in a publication by Boyle (1968). In the San Juan target area, silver concentrations already present in soils are generally one to two orders of magnitude higher than estimated annual additions from cloud seeding.

16. and 17. Microorganism uptake and effect: See Section 7.2 of this report.

7.1.8 Summary

Three years' monitoring of silver concentrations in foliage, litter and soil of aspen, spruce and grass communities in the San Juan target area of the Upper Colorado River Pilot Project has found no significant changes in these concentrations over the period of sampling. An analysis of required sample numbers to detect annual additions of 0.002 to 0.006 ppm dry weight of silver from cloud seeding to spruce litter, indicates that detection of the lower annual addition would require about 200 samples per year for five years, at the 95% confidence level, for each component. If the variance of silver concentration can be reduced from 0.08 to 0.02 ppm (as it was in spring 1973), the present sampling program should be adequate to detect an annual addition of 0.002 ppm after four years. At the Pagosa Springs generator site (no. 25) silver levels in foliage, litter, soil and grass, in spring, 1973, were generally slightly lower than in spring, 1972, but still somewhat higher than before seeding commenced in fall, 1970. Concentrations showed a general decline from maximum levels at 10-20 meters, to background levels at about 200 meters from the site.

A mathematical model for the movement of silver from silver iodide through a soil column, was developed and tested. It indicates that the silver concentration in the soil solution at any given time is best represented by a kinetic-type reaction, coupled with an insignificant equilibrium-type reaction. A high adsorption rate constant controls the initial reaction, but 10 to 30% of input silver concentration is likely to move through the profile.

Although silver concentrations in snow were found to be too variable to show statistically significant differences between sites in the target area and others to the west and east of it, the mean silver concentration in snow on the target area is about twice as high as the downwind mean, and three times as high as the upwind mean. Total seeding intensity (ie., gms AgI burned by all generators per month) was not a good predictor of silver concentration in snow at Wolf Creek Pass. No significant differences in silver concentration of streamflow could be found between 5 streams, including 3 on the target area and 2 to the west (upwind) of it. Mean annual silver concentration for the five streams increased from $(0.1 \pm 0.3) \times 10^{-10}$ gm/ml in 1971 to $(0.6 \pm 1.1) \times 10^{-10}$ gm/ml in 1973. However, mean discharge also increased from 103 cfs in 1971 to 160 cfs in 1973. Although a relationship obviously exists between discharge and silver concentration in individual streams, no general predictive model could be developed between the two parameters.

A generalized compartment model for the movement of silver through terrestrial ecosystems is presented, and recent work in some individual portions of the model is outlined.

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7.2 SILVER IODIDE ECOLOGICAL EFFECTS (Dr. D.A. Klein and R.A. Sokol)

7.2.1 Objectives

To monitor soil microbial activities in the San Juan area, to determine if possible silver accretion may have an ability to influence soil microbial processes, and to establish the types of responses which may occur. The major effort in this regard involves analysis of silver imposition in nitrate and iodide forms on microbial oxygen uptake, carbon dioxide evolution and organic matter accumulation in long-term spruce, aspen and alpine grass communities in the Missionary Ridge impact area. Ancillary indices which have been evaluated have included relative silver uptake into plant tissue, and possible effects of silver accumulation on litter decomposition in a spruce environment.

Related laboratory studies are being used to evaluate possible effects of silver iodide on sublethal microbial processes to provide assays with better sensitivity than those presented in the 1972 research report.

Their objectives have been summarized in a series of hypotheses which have been used to direct the studies carried out to date:

Hypothesis I. Accumulation of silver iodide from weather modification will result in no over-toxicity effects, but may result in a slight delay in biological processes.

Hypothesis II. Laboratory studies can give an indication of the degree of possible diminuition of microbial activity which might result from silver accumulation.

Hypothesis III. Soil bacteria can cause a change in silver iodide to forms more easily taken up by plants. This modification of silver form may make it necessary to carry out experiments under field-related conditions as much as possible.

The studies carried out in this year have been directed more towards field-related test systems, to provide information of direct relevance to the San Juan Ecology project.

Annual measurement data for silver accumulation in soils and water in the San Juan impact area have been presented in section 7.1 of this report. Although no significant changes in silver present in soils, foilage or water were found, their calculations indicate that with accretion of silver at 0.006 ppm per year, increases in silver should be detectable within 2 years using the sample numbers available. With a calculated accretion of 0.002 ppm silver per year, at least four years would be required before changes in silver levels might be detected with the sampling intensity used to the present time for this project. These calculations also indicate that each year an amount of silver equal to 1/40 of that present in these soils may be added by weather modification activities.

In consideration of possible biological effects (Cooper and Jolly, 1970) and the forms of silver which may be naturally present in soils (Boyle, 1968) it is possible that silver iodide added in the presence of excess halide in weather modification may have marked differences biological effects from that originally present in soils in more stable and complexed mineral forms.

The possibility of silver uptake by plants (Teller and Klein, 1973) accumulation of silver in iodides and nitrate forms predominantly in the upper soil layers (Teller and Cameron, 1973) and the possibility of silver iodide transformation by soil microorganisms (Klein and Sokol, 1973) made it necessary to predict their effects in sufficiently long time frames to have maximum possible ecological significance.

Prior laboratory studies carried out in conjunction with this project (Klein and Sokol, 1973) have showed that silver iodide presence can retard essential microbial processes of viability retention and enzyme induction, although these occurred at silver levels 2-4 magnitudes higher than those detected in natural systems.

For this reason, the major emphasis in work carried out this year was in analysis of treatment plots where correlations between imposed silver levels and other parameters could be established. This procedure allows possible prediction of trends which might be expected in longer term experiments, and possible establishment of minimum silver levels required before discernable changes in decomposer parameters might occur.

The plots have been in place for two years, allowing carbon flow and primary production to occur in the system in the presence of varied silver levels imposed on the system. It is hoped that this procedure will allow establishment of meaningful relationships between silver impositions and possible microbial responses.

7.2.2 Development of Analytical Procedures

Basic procedures used in this research period have been described in the previous report (Klein and Sokol, 1973) and only a summary of these procedures will be provided here, together with modifications which have been made.

Treatment Plot Analyses - plots which were installed in the spring of 1972 at the San Juan Ecology Project Missionary Ridge area have been used for these studies. They now have had two growing seasons within which the possible effects of silver on decomposer processes could be evaluated. The treatment plots have been set out in spruce and aspen communities in the Little Bear Area, and the grass treatment plot was set out in the Big Bear Area. These plots have been examined for organic matter, residual silver, oxygen uptake and carbon dioxide evolution, as well as for the residual spruce needle and organic layer depths in the surface of the spruce treatment plot. Oxygen use and CO_2 evolution are expressed in ml of the gas used or evolved per 100 g soil per 24 hours. The amount of above ground biomass in the grass plot was examined by making clips of meter square treated areas, and plant materials were examined for silver content to determine if silver from either the iodide or nitrate forms might have been taken up.

Statistical analyses of these data were completed to allow establishment of relationships between changes in activity parameters using linear and non-linear regression procedures.

Due to the inherent variability of data from the respiration index sites carried out in 1972, these experiments were not carried out during the 1973 period when the major emphasis was placed on direct analysis of ecosystem-related phenomena in the San Juan area treatment plots.

Bacterial Growth Rate - Silver Interaction Studies - To develop a more sensitive procedure than the induction and gross growth assays developed in 1973, attempts were made to evaluate the possible role of silver on growth of bacteria through a sterile matrix. This experimental approach we used to attempt to duplicate the possible adsorption of silver on soil particle surfaces where it might directly influence microbial growth processes.

Growth and spread of Arthrobacter through a sand matrix containing silver was monitored using the Stotzky replica plating technique (Stotzky, 1965). The matrix consisted of washed sand (average particle, size ∿ 1 mm) which was adjusted to 70% of moisture holding capacity with a mineral salts medium containing 2.5 mM succinate. Silver nitrate was added to the mineral salts prior to mixing with the sand at a concentration of 2 mg per kg sand (2 ppm). Silver iodide was added as a fine powder to the moistened sand, and then thoroughly mixed. The silver-sand mixtures were then placed in petri dishes (6 replicates per treatment), tamped down to produce a smooth level surface and autoclaved for one hour. After cooling, approximately 10^5 organisms were inoculated into the center of the sand plate. Periodically, replicates were inoculated into plates containing a peptone-yeast extract medium using a multi-needle transfer unit which could be sterilized between uses by dipping in alcohol and flaming.

Statistical Analyses - Analyses of all data were completed using standard procedures (Snedecor and Cochran, 1971). When available, appropriate statistical programs were used to allow establishment of linear and non-linear regression values for relationships between accumulated silver and biological responses in test systems.

7.2.3 Soil Treatment Plot Analyses

- Aspen plot

The aspen plot analyzed in this project is located in a uniform community in the Little Bear Park Area of Missionary Ridge, and there is only minimal undercover contribution to this decomposer ecosystem.

Results for the Aspen Plot are given in Table 1, where averages for the various parameters are given. The treatments in this plot were calculated on the basis of 100, 10 and 1 ppm of silver in the top 2 cm of soil. The silver values given are the actual amounts found during the analysis of the samples taken for biological analysis. As in the silver disposition studies, the wide standard deviation ranges around the means make it difficult to develop generalizations from these grouped data.

A more meaningful way to analyze these data is by use of linear regression calculations between silver and the other parameters (Table 2). Using this procedure where the silver content of each sample could be related to the individual biological activity indices of the same sample, relationships of possible interest were noted. The varied silver levels in the iodide form were strongly related ($P < 0.01$) with carbon dioxide evolution, and a strong but less than 95% significance relationship of silver with soil organic matter was observed. An inverse trend of silver level in relation to oxygen use also was suggested by this analysis.

As would be expected, strong relationships between organic matter and oxygen use were observed.

The silver nitrate treated aspen sub-plots showed no significant relationships between imposed silver and the parameters examined.

As an additional analysis of these relationships, a non-linear variance analysis was completed (Table 3). The linear plot showed an R^2 of 0.376, while a parabolic function showed an R^2 of 0.572. This would indicate that the relationship between these parameters may be better expressed by a non-linear treatment of these data.

Vegetation samples taken from the aspen community sub-plots were analyzed for their silver content, and the relative and absolute concentrations of silver in soil and vegetation were compared (Table 4). It should be emphasized that these plant samples were combined from the respective sub-plots, and included mixed species growing as a community under the aspen stand.

On a relative ratio basis, at the lower silver levels, a greater proportion of the available silver will be taken up by the plants. Silver iodide will be taken up to a lesser extent on this basis than silver in the nitrate form, especially at the higher addition levels. In a comparison of absolute amounts of silver in the plants, the silver from silver nitrate is taken up at 8-10 fold greater levels than found with silver iodide treatments. It should again be emphasized that these results were obtained after two growing seasons during which the silver additions were equilibrating in the aspen soil ecosystem.

Plants thus appear to be able to exclude added silver, and on a relative basis, decreased available silver will be translocated to the plants with increasing silver concentration in soil.

- Sub-alpine grass plot

Similar averaged data for the sub-alpine grass plot are presented in Table 5, showing silver, organic matter, oxygen used and carbon dioxide evolution values. Based on the standard deviation ranges around the means for these plots, it would appear that there is no significant change in these parameters in relation to the imposed silver treatments.

Calculation of relationships between silver concentration and the other parameters based on linear regression correlations showed similar non-significance of imposed silver levels with other parameters (Table 6). Based on the number of data sets used, it would appear that the imposition of silver on this community had no significant effect upon carbon flow.

The non-linear evaluation of relationships between these parameters showed that there may be possible relationships due to the presence of silver in this system (Table 7), although these are not at sufficiently higher R^2 values to be of statistical interest.

The sub-alpine grass plot shows stronger relationships between silver levels in the nitrate form than in the iodide form, a situation not observed with the other test plot systems.

Grass treatment subplots were clipped for above-ground biomass, and the resultant grass samples were analyzed for their silver content (Table 8). After two seasons silver from the nitrate form is taken up by plants to a greater extent than silver from the iodide form. In addition as noted for the aspen plot, the relative amount of silver translocated to the grass decreases with increasing soil silver concentrations. This response is still observed two years after the treatments have been in place, suggesting that within this time scale, that the two different silver forms will not

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Table 1. Aspen Treatment Plot Parameter Relationships

	Parameter			
Treatment, level	Actual Silver, ppm	% Organic matter	O_2 use	CO_2 Evolution
$AGNO_3$ 100 mean	199.25	44.65	11.18	10.33
SD	164.51	17.72	5.56	3.86
10 mean	16.45	40.65	11.98	11.43
SD	17.06	29.98	44.82	9.81
1 mean	15.88	52.65	7.55	12.75
SD	19.95	19.30	2.58	4.03
- mean	0.48	67.10	16.60	13.05
SD	0.19	13.65	6.82	4.90
AgI 100 mean	460.63	42.40	10.18	14.85
SD	698.17	25.85	2.41	5.77
10 mean	46.00	49.80	11.23	9.48
SD	30.04	18.43	3.20	1.65
1 mean	7.75	54.20	13.33	11.83
SD	4.49	11.39	2.56	66.26
- mean	0.38	48.40	10.58	9.95
SD	0.38	12.86	4.82	2.13
Controls mean	1.33	48.67	10.30	12.05
SD	1.73	21.84	1.97	3.98

Table 2. Summary of Linear Correlation Analysis for the Aspen Plot Data

Correlation	N[a]	R[b]	Significance[c]
$AgNO_3$ vs. organic matter	16	0.341	---
$AgNO_3$ vs. O_2	16	0.208	---
$AgNO_3$ vs. CO_2	16	0.122	---
AgI vs. organic matter	16	0.341	---
AgI vs. O_2	16	0.348	---
AgI vs. CO_2	16	0.612	**
All organic matter vs. all CO_2	36	0.377	---
All organic matter vs. all O_2	34	0.488	**

a = number of sample pairs analyzed in set

b = correlation coefficient

c - $P > 0.05$

* $P < 0.05$

** $P < 0.01$

Table 3. Summary of Variances (R^2) for linear and non-linear analysis of the Aspen Plot Data

Correlation	Variance (R^2) Linear	Parabolic	Exponential	Power
$AgNO_3$ vs. organic matter	0.002	0.089	0.111	0.004
$AgNO_3$ vs. O_2	0.054	0.070	0.013	0.019
$AgNO_3$ vs. CO_2	0.013	0.055	0.004	0.001
AgI vs. organic matter	0.140	0.169	0.046	0.067
AgI vs. O_2	0.001	0.088	0.028	0.048
AgI vs. CO_2	0.376	0.572	0.184	0.174

Table 4. Relationship of soil silver level and form to plant silver content in an aspen community

		SOIL[a]			PLANT[b]			
Treatment, ppm		% Ash	Silver in Ash	Silver in Soil	% Ash	Silver in Ash	Silver in Plant	Ratio of Plant Silver / Soil Silver
Control		51	0.47	.23	10.2	2.00	0.20	0.87
$AgNO_3$	1	37	15.60	5.77	10.8	0.97	0.11	0.02
	10	59	16.50	9.74	10.8	7.50	0.81	0.08
	100	55	200.00	110.00	10.0	60.00	6.00	0.05
AgI	1	46	6.00	2.76	12.6	0.78	0.09	0.03
	10	50	46.00	23.00	11.8	1.00	0.12	0.005
	100	68	181.60	123.49	10.8	6.40	0.69	0.006

a = average of data for four separate sub-plots

b = grouped samples from four sub-plots used in analysis

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Table 5. Sub-alpine grass treatment plot decomposer parameter relationships

Treatment, level		Actual Silver ppm ash	Organic Matter % w/w	O_2 use	CO2 Evolution
$AgNO_3$ 100	mean	84.00	14.00	5.93	4.60
	SD	50.14	3.60	2.23	2.08
10	mean	5.32	12.55	4.30	3.98
	SD	6.06	2.86	2.97	1.76
1	mean	0.44	11.50	5.10	4.28
	SD	0.29	0.53	2.24	2.76
-	mean	0.11	9.75	6.03	4.83
	SD	0.08	3.95	1.16	0.93
AgI 100	mean	33.67	11.93	5.10	3.90
	SD	14.84	1.33	0.44	0.87
10	mean	8.08	8.55	5.80	5.18
	SD	9.62	4.67	2.72	2.07
1	mean	0.54	3.20	7.43	4.92
	SD	0.44	3.83	2.93	1.63
-	mean	0.08	13.40	5.18	3.50
	SD	0.03	2.77	1.31	1.23
Controls	mean	0.07	10.33	4.25	2.67
	SD	0.06	1.03	1.59	1.16

Table 6. Summary of regression correlations for the sub-alpine grass treatment plot

Correlation	N[a]	R[b]	Significance[c]
$AgNO_3$ vs. organic matter	16	0.453	---
$AgNO_3$ vs. O_2	16	0.310	---
$AgNO_3$ vs. CO_2	16	0.146	---
AgI vs. organic matter	16	-0.130	---
AgI vs. O_2	16	0.074	---
AgI vs. CO_2	16	0.189	---
All organic matter vs. all CO_2	36	0.224	---
All organic matter vs. all O_2	36	0.350	---

a = number of sample pairs analyzed in set

b = correlation coefficient

c - $P > 0.05$

* $P < 0.05$

** $P < 0.01$

Table 7. Summary of variances (R^2) for linear and non-linear analyses of the sub-alpine grass plot data

Correlation	Variance (R^2) Linear	Parabolic	Exponential	Power
$AgNO_3$ vs. organic matter	0.234	0.233	0.215	0.027
$AgNO_3$ vs. O_2	0.053	0.176	0.047	0.030
$AgNO_3$ vs. CO_2	0.050	0.058	0.083	0.072
AgI vs. organic matter	0.000	0.096	0.030	0.025
AgI vs. O_2	0.008	0.121	0.034	0.056
AgI vs. CO_2	0.037	0.072	0.146	0.171

Table 8. Relationship of soil silver level and form in a sub-alpine grass community to soil and grass silver content and crop yield

	SOIL			GRASS				
Treatments	% Ash	Silver in Ash	Silver in Soil	% Ash	Silver in Ash	Silver in Grass	Ratio Plant Silver / Soil Silver	Grass Yield g/m
Controls - untreated	89.0	0.032	0.028	12	1.8	0.18	5.04	211
$AgNO_3$ Solvent Control	87.0	0.110	0.096	11.8	0.37	0.04	0.42	152
AgI Solvent Control	89.4	0.064	0.057	10.0	.64	0.064	1.12	167
Treatments:								
$AgNO_3$ 1 ppm	89.0	0.096	0.080	9.2	1.60	0.150	1.88	193
10 ppm	83.2	4.800	4.000	10.6	65.00	6.70	1.68	207
100 ppm	84.4	150.000	127.100	13.0	60.00	7.80	0.06	254
AgI 1 ppm	82.4	0.130	0.110	15.0	0.48	0.07	0.62	154
10 ppm	87.5	7.000	6.140	10.2	5.60	0.55	0.09	200
100 ppm	87.4	50.000	43.800	14.0	35.00	4.90	0.11	168

have equilibrated to the point where they will have similar plant uptake characteristics.

Dry weight analyses of the grasses from the control and treated areas did not show any weight differences which are marked differently from the controls.

- Spruce plot

Results for the spruce plot surface soil decomposer community relationships are presented in the next section. In the spruce community it was possible to separate the organic layer from the clay sub-soil layer to allow measurement of specific relationships in these separate decomposer communities. An essential important point of interest in this plot was the absence of primary production activity in this decomposer system. All needles and detritus fall to the forest floor, making this an ideal environment for analysis of microbe seeding agent interactions.

The surface plot data (Table 9) show again that it is difficult to separate out specific trends in response to the treatments using the grouped and averaged data. Under these conditions no significant changes in allover decomposer parameters due to the imposition of silver are observed.

By analysis of these data by use of linear regression correlations, a similar lack of significant relationships was shown (Table 10).

Use of additional curve-fitting techniques with the spruce plot surface data did not provide any better fits, based on the small portion of the variance explained by the particular line given by the statistical program (Table 11).

Also of interest is the analysis of the percent undecomposed needles in relation to the treatments. This is important as a response parameter as there might be a retardation of decomposition in the presence of silver, allowing more undecomposed needles to be retained in the surface litter layer.

The specific percentage of undecomposed needles in the spruce plot are summarized in (Table 12). In relation to solvent and untreated controls, the possibility of an increased spruce needle retention at the 100 ppm treatment level is suggested, although the standard deviation ranges preclude strong significance.

This conclusion of non-significance is confirmed by the use of variance analyses with linear and non-linear curve fitting (Table 13).

A similar analysis of data from the sub-surface clay layer of the spruce treatment plot is presented in (Table 14). In spite of the intensive rainfall movement through the upper organic layer over two winters only minor amounts of silver added to the surface zone has moved to the clay subsoil layer. This again confirms the observation of Cameron (1973) regarding the extremely strong retention of silver in organic surface zones of soils.

Again, by using grouped data, the standard deviations are wide enough to damp out any variations which might be of significance. The AgI 100 ppm organic matter value is of interest, but agin the standard deviations are wide enough to render this relationship non-significant by this procedure.

Analyses of linear correlations between the test parameters for the subsurface spruce zone are given in (Table 15). The major correlation observed is between accumulated organic matter and silver iodide in the system, which was suggested by the grouped data of (Table 14). Thus, this could indicate the presence of silver could be retarding organic matter decomposition, or that there was originally a sufficiently greater amount of organic matter present which was better able to retain the added silver which might have moved through the profile.

An additional non-linear treatment of their data is given in (Table 16). The exponential and power function plots show R^2 values of possible biological significance between imposed silver iodide and the related soil organic matter level, again confirming the observations from the two previous tables.

7.2.4 <u>Silver-Microbe Interactions in a Sand Matrix</u>

As an additional approach to the problem of laboratory evaluation of possible silver sub-lethal effects which would have a more meaningful longer time scale, a procedure was developed to measure the effects of silver iodide presence on a sand surface to represent a soil matrix. When coated with a low level of succinate and mineral salts , an organism's rate of spread from a center point on petri dishes can be followed by use of a replica plating procedure. In this measurement step a multi point transfer stamp was used to inoculate peptone-yeast extract agar plates to follow the progress of microbial growth across the matrix.

In development of this procedure, it was first necessary to establish a nutrient level and a range of silver concentrations within which silver effects could be easily observed. It was found that the use of succinate at 2.5 mM allowed a total time of six days for microbial movement across a distance of approximately 9.0 cm, the diameter across a conventional petri dish.

Test results for this system are presented in (Table 17), where the rate of microbial growth in the control, 10 and 100 ppm AgI systems are given, together with standard deviation data. Silver iodide at either 10 or 100 ppm caused a highly significant decrease in microbial growth rate ($P < 0.01$), although there was no significant difference seen between the 10 and 100 ppm treatments. This would suggest that in this type of test system that silver iodide had essentially equivalent effects at these levels, and that the system was essentially saturated with AgI at the 10 ppm level.

Under similar test conditions, silver nitrate at 2.0 ppm silver completely inhibited growth of the organism. Based on our work with this system to date, this should provide a more meaningful approach to study sub-lethal silver effects on microorganisms and to determine the possible role of soil constituents in inactivating silver.

7.2.5 <u>Discussion and Conclusion From the 1973 Research Period</u>

Previous evaluations of the potential ecological effects of weather modification activities using silver iodide and nucleating agent have suggested that plants (Weaver and Klavich, 1973), animal rumen functions (Bailey, Jones and Roy, 1973), and humans (Standler and Vonnegut, 1972) will not be sensitive to the presence of the low levels of silver iodide which might accumulate as a result of weather modification activities. Based on conceptual considerations, the decomposer compartment has been considered as the main point of concern (Cooper & Jolly, 1970) due to the sensitivity of micro-

Table 9. Decomposer parameter relationships in the spruce treatment plot surface litter layer zone

Treatment Level		Silver ppm Ash	Organic Matter % w/w	O_2 use	CO_2 evolution
$AgNO_3$ 100	mean	55.50	40.90	23.08	19.55
	SD	11.70	25.09	12.21	9.94
10	mean	16.75	50.20	24.35	23.70
	SD	6.50	15.26	4.42	4.66
1	mean	2.23	37.55	23.20	20.00
	SD	1.73	19.53	10.54	9.52
-	mean	0.31	49.63	34.93	29.13
	SD	0.21	20.29	13.97	6.34
AgI 100	mean	238.25	50.15	30.40	26.10
	SD	294.23	19.03	12.81	11.18
10	mean	21.20	41.95	43.83	35.60
	SD	26.22	17.86	22.64	19.44
1	mean	1.29	41.68	37.65	32.18
	SD	0.73	4.64	13.64	10.42
-	mean	0.21	43.08	25.73	24.88
	SD	0.14	23.62	21.98	15.69
Controls	mean	0.49	54.10	33.63	29.58
	SD	0.37	8.87	11.28	4.36

Table 10. Summary of linear regression correlations for the spruce treatment plot surface organic matter samples

Correlation	N[a]	R[b]	Significance[c]
$AgNO_3$ vs. organic matter	16	-0.092	---
$AgNO_3$ vs. O_2 used	16	0.224	---
$AgNO_3$ vs. CO_2 evolved	16	0.288	---
AgI vs. organic matter	20	0.426[d]	---
AgI vs. O_2 used	20	0.214	---
AgI vs. CO_2 evolved	20	0.078	---
All organic matter vs. all CO_2	16	0.559	*
All organic matter vs. all O_2	36	0.513	*
% of undecomposed needles vs. AgI	18	0.332	---
% of undecomposed needles vs. $AgNO_3$	14	0.387	---

a = number of sample pairs analyzed in set
b = correlation coefficient
c = - > 0.05
 * < 0.05
 ** < 0.01
d = value for significance at 95% level = .444

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Table 11. Summary of variances (R^2) for linear and non-linear analyses of the spruce plot surface data

Correlation	Variance (R^2) Linear	Parabolic	Exponential	Power
$AgNO_3$ vs. organic matter	0.009	0.051	0.007	0.008
$AgNO_3$ vs. O_2 used	0.052	0.057	0.071	0.038
$AgNO_3$ vs. CO_2 evolved	0.055	0.057	0.001	0.180
AgI vs. organic matter	0.000	0.165	0.007	0.004
AgI vs. O_2 used	0.030	0.038	0.049	0.064
AgI vs. CO_2 evolved	0.023	0.033	0.031	0.020

Table 12. Analysis of spruce surface layer litter depth and extent of litter decomposition

Treatment Level		Litter Depth, mm	% Undecomposed Needles
$AgNO_3$ 100	mean	49.25	0.68
	SD	25.55	0.07
10	mean	59.75	0.48
	SD	20.84	0.08
1	mean	43.50	0.53
	SD	18.59	0.24
-	mean	57.50	0.54
	SD	11.70	0.11
AgI 100	mean	57.25	0.69
	SD	8.26	0.17
10	mean	42.25	0.64
	SD	10.97	0.10
1	mean	50.75	0.58
	SD	9.43	0.22
-	mean	38.25	0.47
	SD	13.33	0.24
Controls	mean	78.25	0.58
	SD	28.36	0.17

Table 13. Variance (R^2) between spruce treatment plot silver content and percent undecomposed needles in the surface organic layer

Treatment	Variance (R^2) with Curve-fitting Function: Linear	Parabolic	Exponential	Power Function
AgI	0.082	0.095	0.076	0.093
$AgNO_3$	0.051	0.097	0.019	0.086

Table 14. Decomposer parameter relationships in the spruce treatment plot sub-surface clay zone

Treatment Level		Silver ppm ash	Organic Matter % w/w	O_2 Use ml/100g/day	CO_2 Evolution ml/100g/day
$AgNO_3$ 100	mean	0.35	8.33	4.20	3.45
	SD	0.12	4.08	2.04	1.70
10	mean	0.10	8.75	2.48	3.83
	SD	0.02	1.41	2.34	0.78
1	mean	0.07	7.45	3.50	2.28
	SD	0.01	3.01	2.08	1.49
–	mean	0.07	9.40	1.95	4.10
	SD	0.01	3.01	2.08	1.49
AgI 100	mean	0.59	12.80	4.58	3.68
	SD	0.50	3.44	1.52	1.49
10	mean	0.11	8.90	4.70	3.53
	SD	0.08	1.76	1.30	0.76
1	mean	0.09	8.35	4.40	3.63
	SD	0.11	1.18	1.88	1.96
–	mean	0.07	9.75	3.50	3.38
	SD	0.03	3.36	3.17	1.62
Controls	mean	0.10	10.30	5.23	5.88
	SD	0.07	3.49	2.59	1.71

Table 15. Summary of linear correlations for the spruce plot sub-surface mineral soil samples

Correlation	N[a]	R[b]	Significance
$AgNO_3$ vs. organic matter	16	0.104	---
$AgNO_3$ vs. O_2	16	0.340	---
$AgNO_3$ vs. CO_2	16	0.224	---
AgI vs. organic matter	18	0.410	*
AgI vs. O_2	18	0.003	---
AgI vs. CO_2	18	0.068	---
All organic matter vs. all CO_2	36	0.481	**
All organic matter vs. all O_2	36	0.586	**

a = number of sample pairs analyzed in set

b = correlation coefficient

c = – > 0.05

* < 0.05

** < 0.01

Table 16. Summary of variances (R^2) for linear and non-linear analyses of the spruce plot sub-surface data.[a]

Correlation	Variance (R^2)			
	Linear	Parabolic	Exponential	Power
$AgNO_3$ vs. organic matter	0.011	0.231	0.006	0.000
$AgNO_3$ vs. O_2 used	0.185	0.231	0.144	0.000
$AgNO_3$ vs. CO_2 evolved	0.003	0.027	0.073	0.042
AgI vs. organic matter	0.181	0.243	0.446	0.477
AgI vs. O_2 used	0.000	0.015	0.002	0.001
AgI vs. CO_2 evolved	0.000	0.008	0.004	0.002

a = underlined variance indicate possible data fits of interest, from an ecological interaction standpoint

Table 17. Silver iodide effects on Arthrobacter growth through a nutrient broth-coated sand matrix. Growth rate in cm travelled.

Treatment Level	Time After Inoculation		
	24 Hours	72 Hours	144 Hours
Control - mean	1.86	4.60	8.01
SD	0.21	0.06	0.03
AgI 10 ppm mean	1.18	3.57	6.90
SD	0.08	0.07	0.09
AgI 100 ppm mean	1.31	3.45	6.82
SD	0.11	0.15	0.16

organisms to silver, widely used in a medical context.

Our previous report (Klein and Sokol, 1973) have emphasized laboratory-level test systems, as a conceptual framework within which to approach silver-microbe interactions.

These studies have shown that soil microorganisms can change silver iodide to other silver forms, making it necessary to consider work with more ecologically meaningful test systems.

In this context, our major effort this year has been directed towards analysis of test treatment plots, within the conceptual context which has been developed in the last two years. Before this time sufficient growing seasons and snow melt events had not yet taken place to make this a meaningful test system.

Generally, our studies this year have shown no major changes in ecosystem functions which are of statistical significance. The possibility of silver iodide presence in aspen and spruce communities, and silver from nitrate in grass being able to cause changes in CO_2 evolution or organic matter levels is suggested.

Further work during the next season will be carried out to determine if these trends are continued. Our work shows clearly that silver added to surface soils will be retained in spite of snow melt processes, thus, the question of long-term low level effects of silver accumulation must be approached.

Regarding data analysis, this year we had sufficient points on any set of parameters to attempt non-linear fitting. In several cases, possible significant relationships were indicated where a linear plot was not able to show significance. From a biological standpoint, non-linear relationships, if valid, may improve our understanding of silver microbe interactions. There may be threshhold levels required before specific changes in ecosystem functions are observed.

Our plant uptake studies have shown that after two years under field conditions that increased silver concentrations are seen with increased soil silver, and silver from nitrate is concentrated at 8 - 10 times the levels seen with silver iodide.

The major concept which this experiment has given us is that within this time scale, silver added in two different forms has not equilibrated to the point where it will be taken up by plants in a similar manner. Extrapolating from this concept, there is no reason for the silver normally present in these soils to react with biological systems like silver iodide from cloud seeding activities. Thus, the calculation of weather modifications silver additions being insignificant in relation to that being normally present in these soils and having equivelant reactions may not have a logical basis from a biological standpoint. Molise and Klein (1974) have shown that silver iodide is best capable of influencing microbial processes in soils (glucose mineralization) in the presence of excess halide. Without excess halide, activities at 98-100% of controls are seen after 2 months of treatment of soils with silver iodide. This work has shown clear effects of silver iodide in the presence of excess halide at 4.5 ppm silver additions, approaching a meaningful ecological test system.

Our studies with Arthrobacter growth rate inhibition in the presence of seeding agents have been developed to improve on prior systems and to provide an opportunity to evaluate the effects of specific soil organic and inorganic fractions on microbial interactions with silver iodide. We feel that the present test system can be used with a wide range of microorganisms, and it should provide a time scale of greater relevance to field conditions.

7.2.6 Work Planned for Next Year

Laboratory Studies - Continue development of the sterile matrix microbial growth test system, and use this with specific soil organic fractions. The objective will be to work with organic fractions from soils derived from the grass treatment plot.

Field Studies - Our major effort will be to continue our present studies of the grass, spruce and aspen plots to determine if additional time will prove better resolution of changes in decomposer parameters in relation to a wide range of imposed silver levels which approach background conditions. Similar statistical and curve-fitting techniques will be used to provide maximum information on the relationship between silver levels and specific biological parameters.

Plant uptake of silver under field conditions will be examined more closely to determine if there might be species differences of interest.

Silver analysis in aquatic ecosystems - To provide baseline information on possible future concentration of silver from snowmelt in aquatic ecosystems in the San Juan impact area, several lakes in the control and impact areas will be assayed for their silver content in various trophic levels. This information will provide a needed baseline in the event that operational seeding programs are initiated.

7.2.7 Summary

Potential silver iodide nucleating agent effects on terrestrial decomposer community processes have been evaluated using treatment plots in place for two years in aspen, spruce and sub-alpine grass communities, and by testing silver iodide effects on microbial growth through a sterile sand-nutrient matrix.

In comparison of control plot silver-microbial activity relationships the work carried out in this research period suggests that silver iodide can more strongly influence carbon dioxide evolution and organic matter accumulation than silver in the nitrate form, although the levels where these effects are observed are markedly above those found under field conditions. There is an indication that silver in the nitrate form can be related to a retardation of carbon dioxide evolution in the grassland plots.

No significant relationships between imposed silver content and percentage of undecomposed spruce needles were observed. Generally silver from the nitrate form was taken up by annual and young woody plants to a greater extent than silver from silver iodide, although on a ratio basis, a lesser portion of silver from both forms is taken up by plants at higher soil silver concentrations. After two years of soil contact and microbial interactions, silver from nitrate and iodide forms still appear to be taken up in different ways.

A soil Arthrobacter test for its ability to grow through an artificial soil matrix consisting of sand coated with sand plus silver iodide at various levels was significantly inhibited by the presence of 10 and 100 ppm AgI. Further work at lower silver levels and in the presence of isolated soil organic fractions will be completed. The work carried out to date indicates possible ways in which these ecosystems may respond to the imposition of silver iodide. This may involve diminitives of carbon dioxide evolution or increases in organic matter retention in the systems. Oxygen uptake is less strongly correlated with silver imposition than carbon dioxide evolution. Specific information on minimal silver levels required to cause possible changes in ecosystem function is required. Our work in the next year will be directed towards this question, and to also ask related questions regarding silver interactions in aquatic areas in the San Juan mountain impact area.

7.2.8 References

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8. SUMMARY

Summaries are found at the end of each project report so they are not repeated here.