Annual Report 2000
USGS Global Change Research Program

Climate Change and Thresholds of Ecosystem Change: Invasibility of Tundra in the Northern Rocky Mountains

Principal Investigator

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Introduction

The aim of this research is to assess the sensitivity of alpine tundra to invasion by woody species from treeline in the northern Rocky Mountain region. Whether or not treelines respond sensitively to climatic change – and so could be indicators – is unknown. We are examining the question of whether treeline dynamics are sensitive to climatic change in a nonlinear way – and thus might show little response until a threshold is crossed, when the response would then be great. This analysis is being accomplished by developing simulation models of tree species establishment and growth based on a combination of more physiologically mechanistic models and spatially explicit forest gap models. Additional simulations based on cellular automata will be used for analyzing criticality or thresholds in the response. The models are being developed and validated at multiple spatial and temporal scales using remote sensing interpretations, including 1 m resolution mulstispectral data and mixture modeling, and by field work that will quantify wind, snow, and soil factors that result in positive feedbacks for the growth of woody plants versus tundra. The results allow the interpretation of past and ongoing changes at and above treeline in the wildlands of the western US. The sensitivity of tundra to invasion is significant because considerable areas of natural resource – with value for wildlife, recreation, and aesthetics – exist just above the treeline ecotone and this ecotone may or may not be a sensitive indicator of climatic change.

Overview of Progress and Results

This cooperative project with five university investigators (listed below) primarily funds summer field work and supports a number of graduate students. This report will cover field work in 2000 plus interim analyses and model development. The work will be summarized under three headings: process field studies and analyses; remote sensing studies and analyses; modeling studies and analyses.

The 2000 field season was very productive, facilitated by good weather during the 2-3 weeks of intensive data collection. The weather stations survived a winter on Lee Ridge, and snow collections provided key information for analyzing tundra spatial patterns. Several theses and dissertations are nearing completion and integration of results between investigators has resulted in a number of publications.

Principal investigators:
George Malanson, Dept. of Geography, University of Iowa
David Cairns, Dept. of Geography, Texas A&M University,
David Butler, Dept. of Geography and Planning, Southwest Texas State University,
Daniel Brown, Dept. of Geography, University of Michigan,
Stephen J. Walsh, Department of Geography, University of North Carolina,

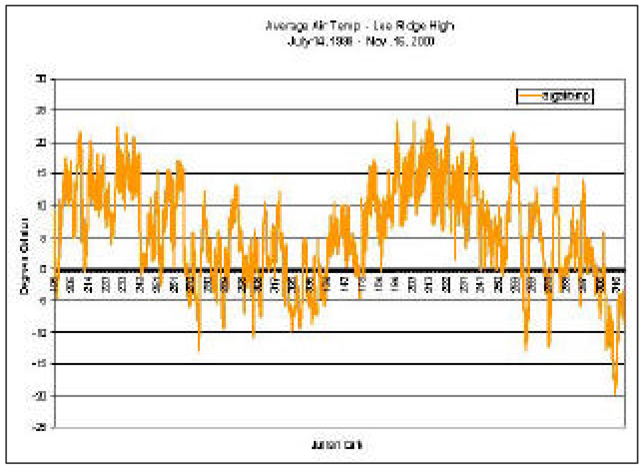
Specific Accomplishments and Results

PROCESS FIELD STUDIES AND ANALYSES

Field studies on processes at treeline included continuing studies of microclimate; annual variation in needle mortality patterns; decadal to century scale studies of patterns of establishment of trees in tundra; and studies of the pattern of sediments and their effect on and response to tree invasion of tundra.

Climatology for Lee Ridge

In July of 1999 we installed two climate stations on Lee Ridge, one at 2171m and the other at 2046m in elevation. We presently have 18 months of data for wind speed and direction, solar radiation, air temperature, relative humidity, soil temperature, soil moisture, and precipitation.



In May of 1999 we set up a snow survey which covers a grid east and west across the top of Lee Ridge, and which incorporates open wind swept areas and timbered areas. These points were measured for snow depth and snow water equivalent and visited in May and June of 1999 and April, May and June 2000. A total of 57 points were measured in 1999 and 71 in 2000.

We will be visiting Lee Ridge in early April 2001 to download climate data and conduct a snow survey of this years snowpack.

Microclimate

Sensor arrays were installed on Lee Ridge in May and July. Each sensor array (mast) consisted of 4 quantum sensors, 3 temperature and relative humidity sensors, two anemometers, and two soil temperature probes. The masts were installed in a finger location and in a krummholz location. Preliminary data from 1999 are shown in Tables 1 and 2.

Table 1: Mast C gradients. Data are for a tree finger.

	PAR (µmol s^{-1} m^{-2})	Temperature (°C)	LAI
Upper	0.9513	0.1223	2.96
Lower	0.4457	-0.5119	10.18
Dates	July 19 - Sept. 17	July 19 - August 8	

Table 2: Mast B gradients. Data are for a krummholz location.

	PAR (μmol s^{-1} m^{-2})	Temperature (°C)	LAI
Upper	0.2561	-0.1002	16.18
Lower	0.0694	-0.5224	1.73
Dates	July 20 - August 5	July 20 - August 8	

Needle mortality

Additional samples of the annual pattern of needle mortality were collected during the summer. Winter desiccation is not predictable based on any single environmental variable. When outliers are removed, winter desiccation shows a strong correlation with elevation (r = 0.97). Patch level winter desiccation amounts are, however, highly predictable from elevation, slope, aspect and topographic context when considered together. In general, injury increases with elevation and on more southwesterly facing hillslopes. High slopes and sheltered locations decrease winter desiccation. Within patches, most winter desiccation is located at the windward edge of the patch. This trend may be modified by the presence of leaders above the mean canopy surface of the krummholz patch, or by local micro-topographic features such as dead branches or the proximity of large rocks. The winter of 1998/1999 was a high winter desiccation year compared to the two previous winters. The winter of 1998/1999 had high snowfall, and meltout did not occur until later than the previous two winters. The extended period of snow cover is hypothesized to be one of the causes of the increased winter desiccation for the 1998/1999 winter.

Invasion

Additional tree-ring data was collected along fingers of trees that advanced into tundra low on Lee Ridge at the end of the Little Ice Age by doctoral student Matt Bekker. Within the fingers, a repeating pattern of older trees with progressively younger trees immediately leeward was evident. These results suggest that existing trees improved conditions for the establishment and growth of new trees to their lee, thus facilitating the linear pattern of tree invasion.

Sediments

During 2000, seven new sediment traps were installed to extend the areal monitoring of fine-particle deposition in alpine soils. Two traps were installed on Lee Ridge, on the leeward side of protective boulders in the alpine tundra. These protected sites are hypothesized to be locations where large amounts of wind-blown sediment may accumulate, subsequently offering excellent establishment sites for treeline seedlings. They may also offer sites that are easily excavated by birds burying seeds. Three sediment traps were installed in Preston Park, two at treeline-meadow interfaces, and one at the uppermost treeline patch along the trail that leads to Siyeh Pass. Two additional traps were installed in Baring Basin, above the trail on the upper margins of treeline patches encountered there. Data from sediment traps installed in 1999, on Lee Ridge and in the Scenic Point bowl, were recorded.

At Lee Ridge, numerous solifluction risers appear to have been "blown out", that is, their vegetative cover is missing and fan-shaped, fine-grained sediment deposits occur on the underlying solifluction tread. Thirty of these blowouts were sampled for morphometry (size and shape) and compaction (employing three measurements on each blowout, and three on the adjacent exposed treads, with a penetrometer), and soil samples were collected at fifteen of the thirty sites for particle-size and organic matter analysis. Statistical analyses of the penetrometer data reveal that the exposed blowouts are statistically significantly less compacted than are the surfaces of the adjacent treads. Particle size and organic matter analyses are currently underway in the Biogeography/Geomorphology Lab at Southwest Texas State University.

In related work, doctoral students Forrest Wilkerson and Ginger Schmid, who assisted in the installation of the new Lee Ridge sediment traps, continued their monitoring of approximately 30 debris-flow sites in the Otokomi (Rose Creek), Iceberg, Ptarmigan, Cracker (Canyon Creek), Appistoki, and Poia Lake (Kennedy Creek) basins, through the use of repeat photography. This monitoring has revealed drastic changes in the amount of sediment deposited and subsequently eroded by debris flow events.

Soil depth in tundra was systematically sampled just above treeline at two spatial scales: 10 m spaced points in a 50 x 50 m grid and 1 m spacing in a 5 x 5 m grid. Results indicate that soil depths vary from <10 to >50 cm in a single large grid; depths in the smaller grids can be in the same range and with about the same variation in a single grid (Table 3). Spatial patterns seem to be random, and do not exhibit patterns that would produce the observed patches and fingers without biotic feedback (Figure 1).

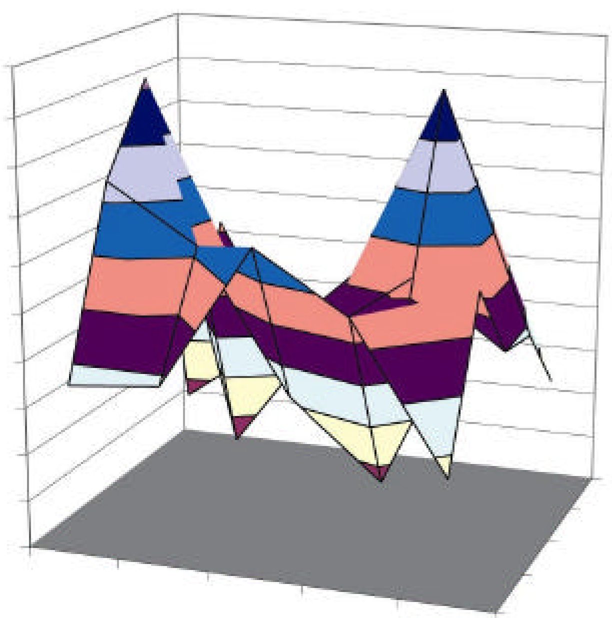


Figure 1. Soil depths in tundra.

Table 3. Soil depths

		10 m grids	1 m grids
Site 1	Mean	15.54	
	SD	6.69	
	CV	.43	
Site 2		16.72	22.44
		12.30	10.95
		.74	.49
Site 3		10.64	11.16
		7.88	4.97
		.74	.45
Site 4		39.70	21.72
		27.91	15.80
		.70	.73
Site 5		10.84	11.20
		5.01	6.05
		.46	.54
Site 6		12.36	8.08
		7.58	5.24
		.61	.65
Site 7		11.18	9.62
		9.25	7.18
		.83	.75
Site 8		21.61	22.52
		7.61	13.35
		.35	.59
Site 9		18.16	10.84
		10.02	8.21
		.55	.76
Site 10		6.52	5.54
		4.45	5.64
		.68	1.00
Site 11		26.64	22.44
		12.0	11.12
		.45	.50
Site 12		18.32	45.36
		11.49	25.33
		.63	.56
All Data		17.36	17.36
		14.41	15.92
		.83	.92

Remote Sensing Studies

The research examined spatially-explicit, digital technologies, framed within a geographic information science (GISc) context, with emphasis on remote sensing, geographic information systems, and scientific visualizations, for the study of the effects of geomorphic processes and patterns influencing the pattern and variability in the alpine treeline ecotone (ATE). The general goal here was to emphasize the use of GISc techniques to map, model, and visualize critical geomorphic elements hypothesized to be direct or indirect influences on the ATE and to include these GISc elements in simulation models. Remote sensing systems from satellites and aircraft were used relative in a multi-resolution approach to characterize the ATE and to represent selected disturbance factors and landscape changes observed and/or simulated over space and time. All spatially-explicit data used in the research were organized within a multimedia, integrated GIS so that multiple views of the landscape could be accommodated by linking data geographically, temporally, and thematically. Also, dynamic visualizations were developed to support the mapping and modeling elements through animations involving model outputs, spatial displays of co-variable and multiple variable combinations, satellite image change-detections, multi-resolution image views, and characterizations of compositional and spatial patterns of the ATE associated with lithologic, topographic, and structural controls. The analysis of ADAR data, flown over our study site in 1999, showed that it could be used to detect relict solifluction terraces, individual boulders, and a band of herbaceous vegetation that may signal conditions into which trees can invade. The basic products developed were a vegetation surface (Figure 2), and tree-no tree surface (Figure 3). An analysis of treeline vegetation patterns at various scales using ADAR imagery in contrast with entropy calculated on the spectrally unmixed tree fraction from a Landsat image has been initiated. This analysis will permit comparison remotely sensed information derived from fine (ADAR) and moderate (Landsat) scale imagery.

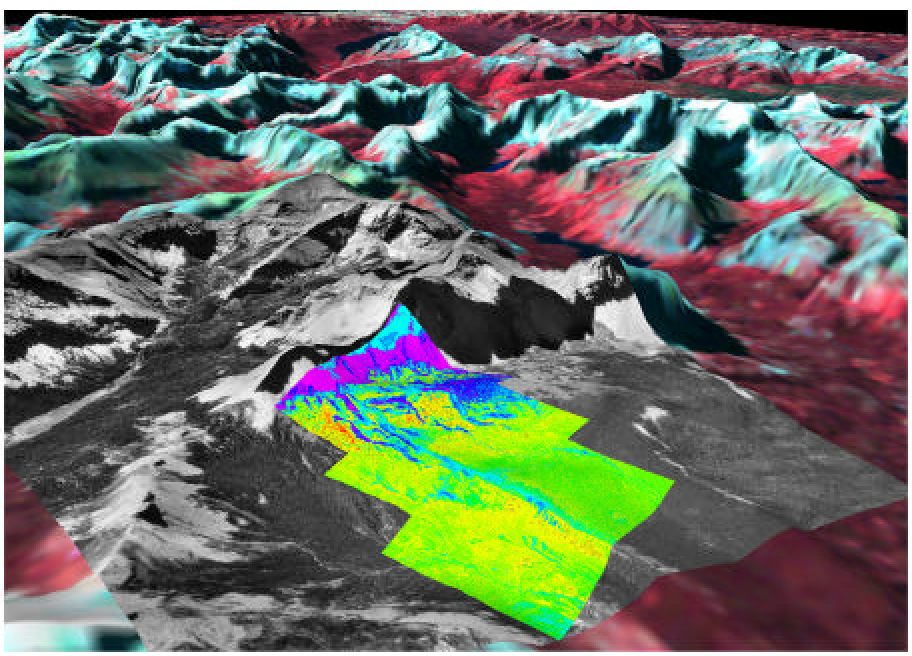


Figure 2. ADAR-derived vegetation surface for Lee Ridge study site.

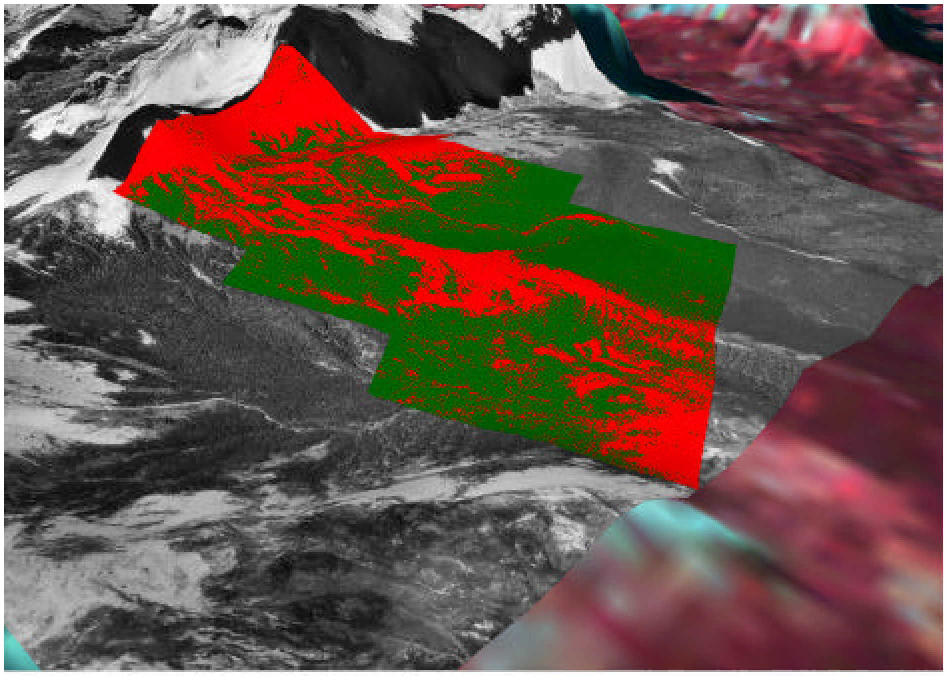


Figure 3. ADAR-derived tree-no tree surface for Lee Ridge study site.

Additionally, ground –truth data were collected to test the usefulness of radar to quantify the characteristics of the ecotone. Field activities were focused on evaluation and use of synthetic aperture RADAR (SAR) data for evaluation of tree canopy structure. Table 4 lists the data collected during the 2000 field season.

Table 4: SAR data collected, Summer 2000

- GPS Ground Control (~ 30 total) for SAR image registration.
- Soil Samples from tundra and forest (27 total)
- vegetation samples (needles - 4 samples, branches - 8, stems - 6)
- soil and vegetation temperatures (57 samples)
- surface roughness (30 samples)
- Tree Structural Attributes (3 trees)
  - Branching Geometry
  - Branch Lengths
  - Branching Density (branches/m^3)
  - Needle Density (needles/m^3)
- trihedral sites for SAR calibration/registration (4 total) – to coincide with scheduled data-takes throughout the duration of our field campaign
- plant sampling plots for vegetation composition and structure (4 krummholz and 12 upright)
- qualitative field classification of 21 sites to upright, krummholz, or mixed

Field data processed include: (a) gravimetric and volumetric water content analysis of soil and vegetation samples, (b) particle size analysis on soil samples, and (c) computation of RMS height and correlation length for surface roughness measurements. These data will be used in as parameters in a model RADAR backscatter (called MIMICS). Initial sensitivity analyses have been performed using field-based parameter values, and generated initial class responses. Radarsat images of the field site have been acquired from the Alaska SAR (standard beams 2 & 7 taken during our field visit). Our goal is to evaluate the potential of Radarsat imagery to distinguish, through classification, upright and krummholz vegetation.

Hi-Resolution DEMs are being generated by (a) interpolating from digitized contours and (b) through softcopy stereo photogrammetry. Our goal is to generate two DEMs for the Lee Ridge study site, the first at a resolution of 10 meters (from contours) and the second at a resolution of approximately 5 meters (from photography). The photography has been scanned and camera models have been built from camera calibration reports and our GPS field data. Contours have been acquired from the 1:24,000 topographic map (Gable Mtn.). Final steps in generating each DEM are currently underway.

MODELING STUDIES

Simulations were done using ATE-BGC to determine if there were significant differences in where the model predicts trees can grow when the altered light and temperature gradients were included in the model. Incorporation of the new light gradients (and LAI) values into the model results in significantly different predictions of where trees can grow for the krummholz growth form (Figure 4). The temperature gradient did not come across as a very important contributor to carbon balance. However, this may change in the future when the diurnal variability is included. Similar results were found for the finger locations (Figure 5).

A simulation model was developed to test the resource averaging hypothesis of treeline. The simulation was constructed so that the presence of trees on a cell of the model depended on the average of conditions on that cell and some of its neighbors. The patterns of trees could be quite complex, but depended strongly on the abiotic pattern (Figure 6). Particular patterns seen at treeline, such as large patches and fingers, were not produced by the simulation – which did not include any positive feedback effect of the trees themselves.

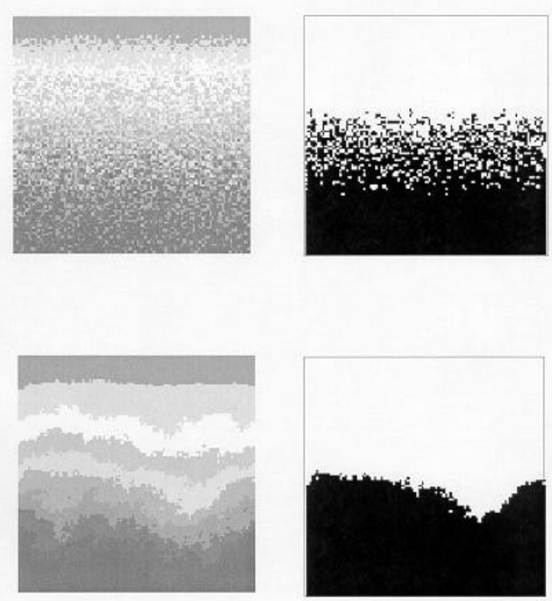


Figure 6. Patterns of tree presence in cells resulting from simulation model with various underlying abiotic patterns.

Figure 4: ATE-BGC simulations under various assumptions about canopy structure for a krummholz location.

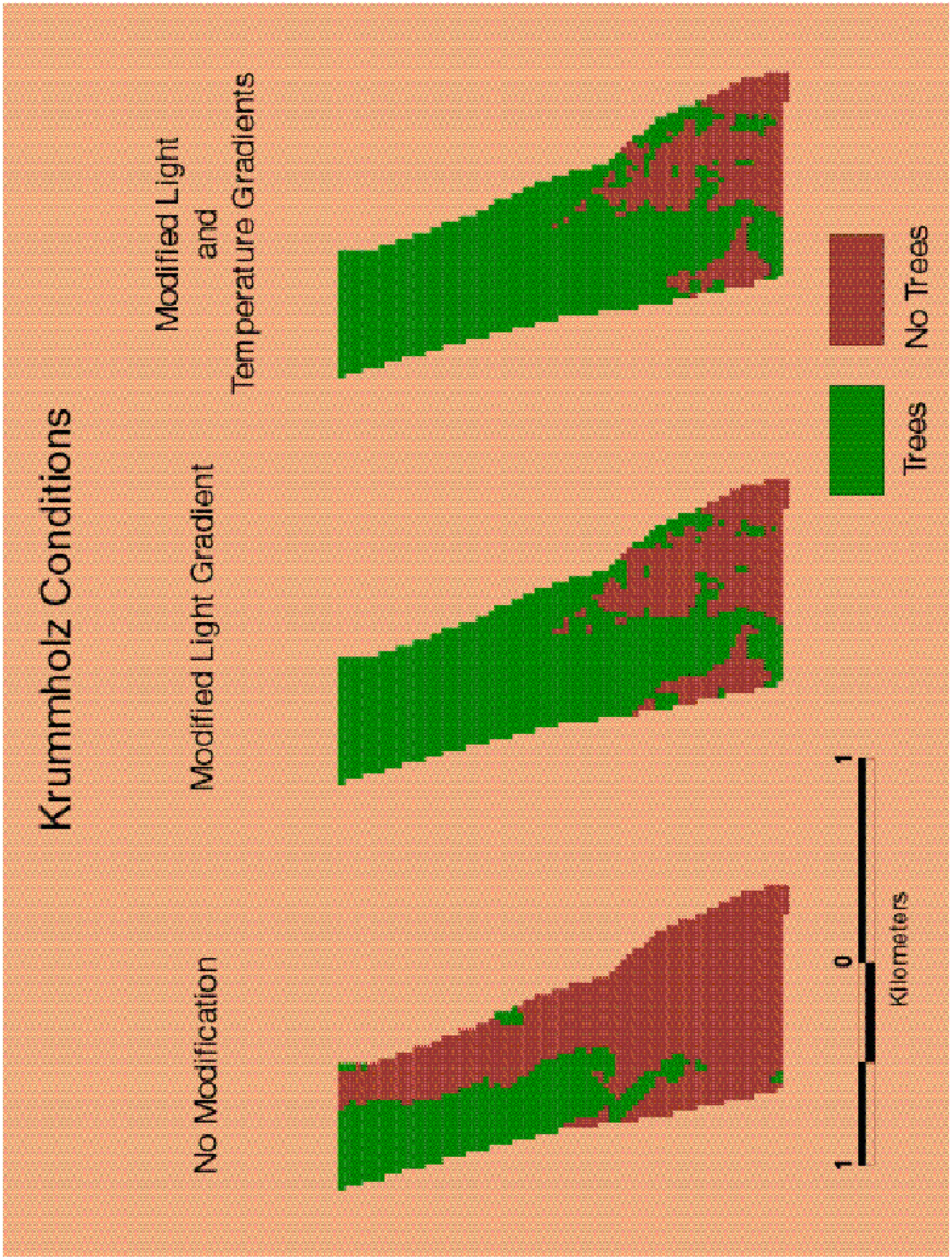
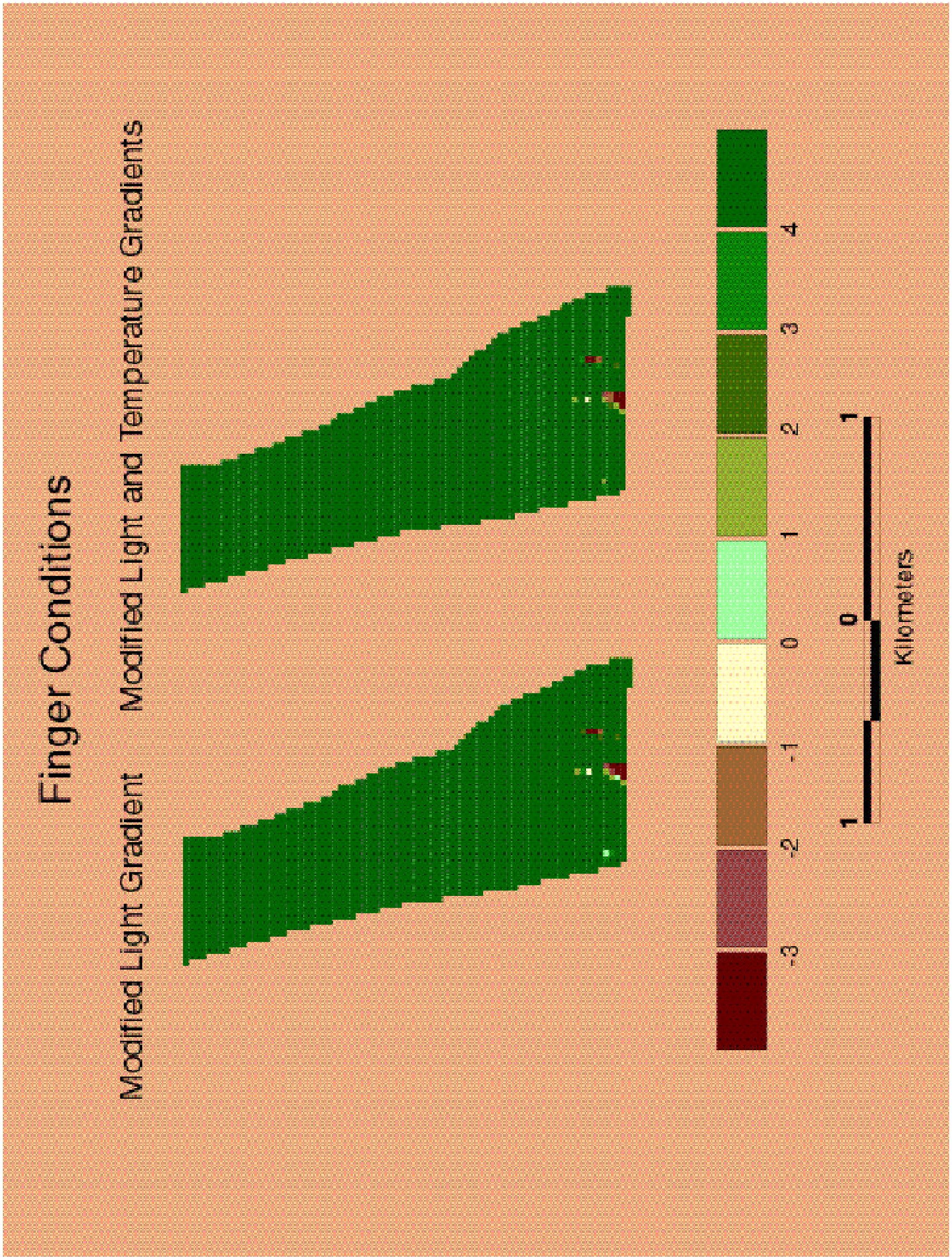


Figure 5: ATE-BGC simulations under various assumptions about canopy structure for a finger location.



A model that combines prior models FORSKA and ATE-BGC to simulate the advance of trees into tundra after the end of the Little Ice Age as affected by positive feedback has been refined. Patterns generated from that model have been compared with patterns observed in Landsat imagery. The Landsat imagery were processed to estimate the LAI of the tree fraction of images. The spatial analysis methods involved testing various spatial metrics of pattern. The comparisons yielded ambiguous results.

A cellular automaton has been developed to simulate the patterns of establishment in recent decades as affected by positive feedback. Comparisons of simulation runs with field observations on Lee Ridge indicate that the model produces patterns that match some spatial metrics but not others (Table 5).

Table 5. Selected mean spatial metrics of field and simulation (*standard deviation*)

	TA	LPI	NP	PSCV	TE	AWMSI	AWMPFD	CONTAG
Field	0.28	94.02	53.20	629.40	435.10	3.02	1.27	71.63
	0.01	*5.37*	*35.07*	*215.04*	*325.87*	*1.48*	*0.14*	*18.93*
Sim	0.250	91.15	36.18	537.77	413.51	2.88	1.291	62.025
	0.000	*0.36*	*2.52*	*18.963*	*15.77*	*0.07*	*0.008*	*1.064*

Progress Toward Integration with other Projects within Research Theme

An annual meeting of the principal investigators from this project and personnel from the CLIMET project has resulted in an ongoing effort to combine alpine tundra ecotone data from the parks in the Western Mountain Initiative. These efforts will focus on similarly-scaled remote sensing data to examine commonalities in treeline spatial patterns. Other projects will likely grow out of this initial collaboration. An explicit goal of this project also is to link to the model outputs of mountain processes with CLIMET but the separate modeling developments are not yet mature enough for direct linkage. However, communication between modelers is ongoing and similar ecosystem estimators are being used to ensure eventual integration.

Plans for Coming Year

During 2001 we will continue snow pack data collection during late winter through early summer and maintain weather stations until September. We will coordinate the 2001 summer field season for as many as 15 personnel who will continue studies as described elsewhere in this report. Paleoclimatological studies will commence with the objective of developing a 500-year history for Glacier Park. Results of our work will be highlighted in a special session of the annual meeting of the American Association of Geographers and the **Binghampton Symposium on Geomorphology.**

PRODUCTS

Data Sets

All data collections are ongoing but completed and quality-assured data sets will be produced beginning in 2001.

Presentations, with abstracts:

<u>Association of American Geographers, Pittsburgh</u>

Kathryn J. Alftine. Tree Seedling Establishment Pattern at Alpine Treeline, Glacier National Park, Montana.
Alpine treeline has received much attention due to its potential sensitivity to climate change. Analyzing the pattern of seedling invasion into alpine tundra may provide insight on the importance of processes, such as autogenic feedback, occurring at this sometimes-abrupt ecotone. Spatial pattern of seedling establishment, as well as size, age and species was recorded in quadrats at Lee Ridge in Glacier National Park during the summers of 1998 and 1999. A simple spatial simulation model based on a cellular automata approach was designed to simulate possible seedling establishment patterns under differing feedback strengths and initial conditions. Resulting pattern was then related to pattern found at study site. Keyword: alpine treeline, establishment pattern, cellular automata.

Matthew F. Bekker. Spatio-Temporal Patterns of Tree Invasion into Tundra, Glacier National Park, Montana.
As transition areas between adjacent ecological systems, ecotones represent a particularly interesting focus for studying the interaction between vegetation patterns and environmental processes. In this study, I examined spatial and temporal patterns of tree invasion into tundra on a windswept ridge in Glacier National Park, Montana. I used dendroecology and a GPS unit to reconstruct and map the development of parallel, linear strips of subalpine forest, which begin at the upper limit of closed forest and extend approximately 100 m upslope to the top of the ridge. Tree ages generally decreased with increasing elevation along each forest strip. Within the strips, a repeating pattern of older trees with progressively younger trees immediately leeward was also evident. These results suggest that existing trees improved conditions for the establishment and growth of new trees to their lee, thus facilitating the linear pattern of tree invasion. This study illustrates the potential for biotic feedbacks to modify abiotic controls on treeline ecotones. Keyword: spatio-temporal patterns, tree invasion, ecotones, Glacier National Park.

Brown, D.G. A methodology for comparing spatial vegetation patterns at alpine treeline using remotely sensed observations and vegetation model output.

David R. Butler. Soil Formation, Animal Disturbance, and the Alpine Treeline Ecotone, Glacier National Park, Montana.

Invasive fingers of alpine treeline in eastern Glacier National Park, Montana, are spatially related to areas of eolian-enriched, fine-grained soils, relict solifluction and modern frost sorting, and animal disturbances. This paper describes these relationships and presents a preliminary model that helps account for the spatial pattern of treeline invasion into the adjacent tundra. Solifluction in the alpine tundra has concentrated finer-grained sediment in solifluction risers. Burrowing animals, particularly the Columbian ground squirrel, excavate burrows in these areas of finer-grained soils, and also create spoil mounds of finer-grained sediment deposited onto the coarser sediment of the adjacent solifluction treads. These burrows may act as sediment traps for subsequent additional eolian influxes that further enrich the soil. The burrows also act as sinks for surface runoff from snowmelt and rainfall runoff, further concentrating fine-grained sediments. Many burrows are subsequently excavated by grizzly bears, creating even deeper runoff sinks and also larger adjacent spoil mounds. These areas of animal disturbance and fine-grained sediment are spatially associated with the trailing edges of invasive fingers of alpine treeline, suggesting that trees have advanced into the tundra where fine-grained sediment has accumulated and been concentrated by subsequent animal disturbances.

Keyword: Treeline, Soil Formation, Glacier National Park.

David M. Cairns. Vertical Gradients of Light and Temperature at Treeline and Their Relevance to Net Primary Productivity.

The alpine treeline ecotone in the northern Rocky Mountains is characterized by the presence of trees advancing into the upslope tundra either as fingers or tree islands. This research investigates the vertical gradients in temperature and light that occur within the canopy at the forest edge at the alpine treeline in Glacier National Park, Montana. Photosynthetically active radiation (PAR) and temperature were measured at three levels within the canopy at 5 locations during the summer of 1999. These data were used to modify the canopy representation of an existing forest process model (ATE-BGC). Comparisons are made between the original and altered canopy representations with regard to net primary productivity estimates. The modified model is then used to evaluate patterns of potential carbon balance across an alpine landscape in Glacier National Park.

Keyword: treeline, simulation, net primary productivity.

George P. Malanson. Simulations of the Resource Averaging Hypothesis for Alpine Treeline.

The resource averaging hypothesis holds that a treeline can be maintained where trees cannot maintain a carbon balance greater than zero when soil resources are too low – averaged over an area greater than needed to maintain non-woody individuals. I examine this hypothesis using a computer simulation model. The initial condition is a gradient of site quality in one direction on a grid of cells. Spatial variation and autocorrelation are added to the gradient, so there are spots of one or more cells that have higher or lower quality. In order for a tree to establish on a cell it must have a certain level of site quality on that cell and the surrounding cells summed. For tundra to establish the quality must be above a certain level but on one cell only. Trees out-compete tundra stochastically. The spatial patterns generated are analyzed and compared to patterns observed in Glacier National Park, Montana. Keyword: ecotone, simulation, treeline.

Southwest Division, Association of American Geographers, College Station

David R. Butler. Multiscale Geomorphic, Structural, and Lithologic Constraints on Subalpine Forest Patterns.
Geomorphic, structural, and lithologic controls operate at a variety of spatial and temporal scales. In Glacier National Park, Montana, regional tectonic uplift associated with the Laramide Orogeny produced structural features that amplify lithologic differences and allow tree growth in certain locations while precluding it in immediately adjacent areas. So-called "ribbon forests", attributed in the past to snowdrift patterns and fire history, are instead a spatial manifestation of this interaction between structure and lithology. Geomorphic processes, ranging in spatiotemporal scale from regional glaciation during the Pleistocene to relict solifluction terraces, modern snow-avalanche paths and debris flows, and modern animal activity, all control the distribution of trees in the alpine treeline ecotone. Keywords: alpine treeline, ecotone, biogeography, Montana.

Ginger L. Schmid and Forrest D. Wilkerson. Soil Characteristics of the Alpine Treeline-Tundra Ecotone in Glacier National Park, Montana.
The alpine treeline-tundra ecotone is an important environment for understanding and monitoring climate change. The dynamic advance and retreat of treeline reflect changes in the suitability of conditions supporting tree growth. As the medium supporting both tundra and tree growth, the soil records the environmental history of the alpine treeline-tundra ecotone. Soil horizonation, structure, texture, and pH are examples of soil characteristics that reflect the influence of vegetation on soil development. The alpine treeline-tundra ecotone on Lee Ridge supports a series of wind-trained krummholz ribbons invading tundra areas. Preliminary sampling shows distinct changes in soil development as seedlings establish and mature. Soil sampling in the Lee Ridge ribbons, along with sampling at additional treeline sites with both patch and finger morphologies, will help to document soil characteristics in the treeline-tundra ecotone in Glacier National Park. Recognition of soil characteristics representative of tree line position changes will provide a pedogeomorphic tool to investigate past environmental conditions within the ecotone. Keywords: treeline, soils, geomorphology

4th International Conference on Integrating GIS and Environmental Modeling, Banff

Malanson, G.P., N. Xiao, K. Alftine, M. Bekker, D.R. Butler, D.G. Brown, D.M. Cairns, D. Fagre, and S.J. Walsh. Abiotic and biotic controls of spatial pattern at alpine treeline.
At alpine treeline, trees and krummholz forms affect the environment in ways that increase their growth and reproduction. We assess the way in which these positive feedbacks combine in spatial patterns to alter the environment in the neighborhood of existing plants. The research is significant because areas of alpine tundra are susceptible to encroachment by woody species as climate changes. Moreover, understanding the general processes of plant invasion is important. The importance of spatial pattern has been recognized, but the spatial pattern of positive feedbacks per se has not been

explored in depth. We present a linked set of models of vegetation change at an alpine forest-tundra ecotone. Our aim is to create models that are as simple as possible in order to test specific hypotheses. We present results from a model of the resource averaging hypothesis and the positive feedback switch hypothesis of treelines. We compare the patterns generated by the models to patterns observed in fine scale remotely sensed data.

The resource averaging hypothesis holds that a treeline can be maintained where trees cannot maintain a carbon balance greater than zero when soil resources are too low – averaged over an area greater than needed to maintain non-woody individuals. We examine this hypothesis using a computer simulation model. The initial condition is a gradient of site quality in one direction on a grid of cells. Spatial variation and autocorrelation are added to the gradient, so there are spots of one or more cells that have higher or lower quality. In order for a tree to establish on a cell it must have a certain average level of site quality on that cell and a number of surrounding cells. For tundra to establish the quality must be above a certain level but on one cell only. Trees out-compete tundra. The model creates a variety of spatial patterns dependent on the initial abiotic pattern and the pattern of the surrounding cells that are averaged.

The positive feedback switch hypothesis holds that treeline is maintained as a relatively abrupt transition where the conditions created by trees improve tree establishment and growth while the conditions created by tundra limit tree establishment and growth. We derive a minimal set of neighborhood rules for use in a cellular automaton (CA) and a quasi (i.e., includes stochasticity) cellular automaton (QCA). The rules are derived from analyses of a forest biogeochemical cycling simulation parameterized for the alpine ecotone. Field measures used in the parameterization include wind monitoring, soil samples, and canopy leaf area and temperature profiles. The hybrid simulation is validated against a tree ring record for an area apparently invaded by trees immediately following the end of the Little Ice Age. The rules derived are related to whether or not neighboring trees make occupancy of a site more likely. The neighborhood rules are applied in the CA and QCA, which produce a variety of spatial patterns.

The spatial patterns generated are analyzed and compared to patterns observed in Glacier National Park, Montana. Metrics are generated for the simulated patterns as well as for patterns recorded at about 1 m spatial resolution by ADAR multispectral and CIR aerial photography.

We also present a methodology to use genetic programming to uncover the spatial patterns of feedback processes. A CA captures the processes as parsimoniously as possible as simple rules. Genetic programming will be used so that the rules change in response to how well the simulations produces patterns similar to observed patterns. Much of the analysis will compare the rules created in different conditions. Different patterns of abiotic (pre-feedback) site quality, static patterns of vegetation, changing rates of abiotic site quality (e.g., climate), and different scale relations will be examined through the rules created.

Keyword: climatic-change, ecotone, genetic-programming, positive-feedback, resource-averaging, simulation, spatial-pattern, treeline

<u>Binghampton Symposium on Geomorphology, Binghampton</u>

Walsh, S.J., Butler, D.R., Malanson, D.R., Crews-Meyer, K.A., Messina, J.P., and Xiao, N., 2000. Mapping, modeling, and visualization of the influences of geomorphic processes on the alpine treeline ecotone, Glacier National Park, Montana, USA. Binghamton Geomorphology Symposium on the Integration of Computer Modeling and Field Observations in Geomorphology, Binghamton, NY.

Spatially-explicit, digital technologies are integrated within a geographic information science (GISc) context to map, model, and visualize selected direct and indirect geomorphic processes that influence the spatial organization of the alpine treeline ecotone in Glacier National Park, Montana, USA. GISc is used to examine alpine treeline and its biotic and abiotic controls through the application of multi-resolution remote sensing systems, geospatial information and product derivatives, simulations of treeline spatial organization, and pattern metrics for quantifying the spatial structure of the ecotone. Space-time animations and other visualizations for characterizing variations in treeline expansion, constriction, and spatial pattern within a 3-D context show promise for analyzing relations between complex patterns and their causes in the future.

Keywords: Alpine treeline ecotone, Glacier National Park, biotic and abiotic controls, spatial representations, models and visualizations.

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