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ENVIRONMENTAL MODELING AND MONITORING AT THE NIWOT LTER SITE: AN OVERVIEW OF RECENT RESEARCH ACTIVITIES USING GIS

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ABSTRACT

Research at the Niwot Long-Term Ecological Research (LTER) site is concentrating on the ecological effects of altered snowpack and changes in precipitation and temperature regimes on alpine plant and animal communities. This is accomplished through the use of (1) a hierarchic geographic information system (HGIS); (2) a snow-fence experiment to examine altered patterns of snowpack, and (3) analysis of remotely sensed data. The HGIS database is helping us to study the links between species patterns at the level of plots, landscape patterns of plant communities, and regional patterns seen on satellite images. In this paper, an overview of ongoing research activities using the HGIS at the plot, landscape, and regional scale is given. Results obtained during recent satellite remote sensing investigations at the Niwot LTER are also highlighted. These studies consist of (1) determining the patterns of greenness as a function of regional climate, (2) evaluating the potential of multi-resolution remotely sensed data combined with ancillary topoclimatic data to map tundra vegetation, (3) monitoring and modeling the spatial distribution and temporal patterns of snow cover, and (4) modeling the radiation and energy balance in the alpine.

INTRODUCTION

Remote sensing imagery and ancillary data from geographic information systems (GIS) are important sources of information for input to ecological and climatic models of seasonal and long-term environmental change. One of the goals of the United States

Long-Term Ecological Research (LTER) program is the systematic monitoring and studying of patterns and controls within a variety of natural ecosystems at various spatial and temporal scales, with an underlying objective to monitor change at the Earth's surface resulting from natural and anthropogenic processes. Within that program, the integration of remote sensing and GIS data sets will be critical towards linking established and detailed ecological studies at plot and landscape level to regional scale interpretations through ecological simulation and modeling (Walker *et al.* 1993). Accordingly, all 18 LTER sites have full remote sensing data sets and GIS capabilities in place for these and other purposes.

These technologies are of particular interest at the Niwot LTER site in the Colorado Rocky Mountains. Alpine environments in general are remote, inaccessible and often possess complex and extreme environmental gradients which are highly sensitive to topographic and climatic controls. For example, in the alpine tundra ecosystem on Niwot Ridge, snow accumulation is an important and complex factor affecting the distribution of alpine vegetation communities. Snow cover insulates plants from severe winter temperatures, wind exposure and desiccation, but serves to shorten the growing season. Snow availability is affected by mountain precipitation regimes modified by strong prevailing westerly winds from the nearby Continental Divide which force snow removal, redistribution and accumulation based on topographic orientation. The Niwot LTER site has been the subject of numerous ecological and climatological studies. However, to monitor evidence of environmental change at different spatial and temporal scales within the Colorado alpine, it is also useful to capture pertinent information about vegetation, topography and climate from remotely sensed and ancillary information sources to enhance present knowledge and understanding of this complex environment.

A hierarchic geographic information system database has been developed to analyze the relationships between snow distribution and ecosystem patterns at the plot, landscape and regional scales in the Colorado alpine. In this paper, ongoing research activities using GIS at the Niwot LTER is presented. In particular, we focus our attention on recent remote sensing analysis and monitoring of complex interactions between vegetation and snowpack dynamics in order to provide critical surrogates for assessing the effects of environmental gradients and climatic variability at this mid-latitude alpine tundra site.

HIERARCHIC GEOGRAPHIC INFORMATION SYSTEM

The term hierarchic GIS, as used herein, corresponds to a nested set of GIS databases at several spatial scales. Long-term ecological studies often require data collected from a wide range of spatial domain so that, for example, changes observed in species distributions can be linked to changes in regional patterns of spectral reflectance as observed with Earth-orbiting satellites. The three primary goals for establishing the alpine HGIS are to provide accurate spatial frameworks for studies of ecosystem processes and geobotanical patterns at appropriate scales, develop baselines for long-term observations of natural and anthropogenic change, and provide geographically referenced data for models of ecosystem processes. The hierarchy of disturbances in the alpine ranges from soil heave caused by the formation of needle-ice crystals at spatial scales of 10^{-4}-10^{1} m^2 to the disturbance caused by glaciers, which currently cover areas as small as 10^4 m^2 but which covered areas as large as 10^8 m^2 in the Front Range during the Pleistocene (Outcalt and MacPhail, 1965; Figure 1). The databases are prepared to address questions related to disturbances at plot, landscape, and regional scales.

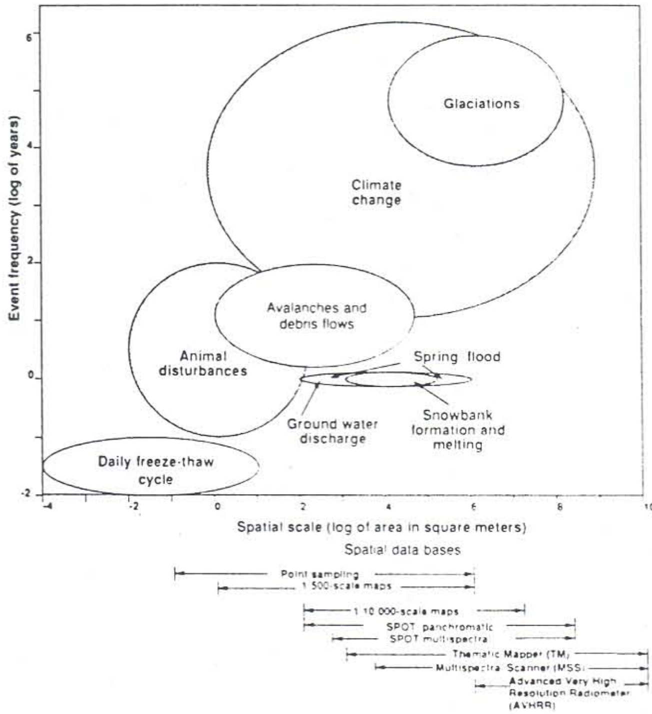

Figure 1. Spatial and temporal domains for natural disturbances at the Niwot LTER site. The shaded ellipses represent disturbance types that are major focuses of study at the site. The available data types for examining various scales of disturbance are shown at the bottom of the figure (Walker *et al.*, 1993).

A conceptual diagram of the HGIS (Figure 2) summarizes its tiers, the major topics of research at each scale, the themes that provided the linkage between tiers, and models that provide conceptual integration. A suite of standardized mapping methods makes this approach useful for multiscale and intersite comparisons (see Walker *et al.*, 1993 for a complete description).

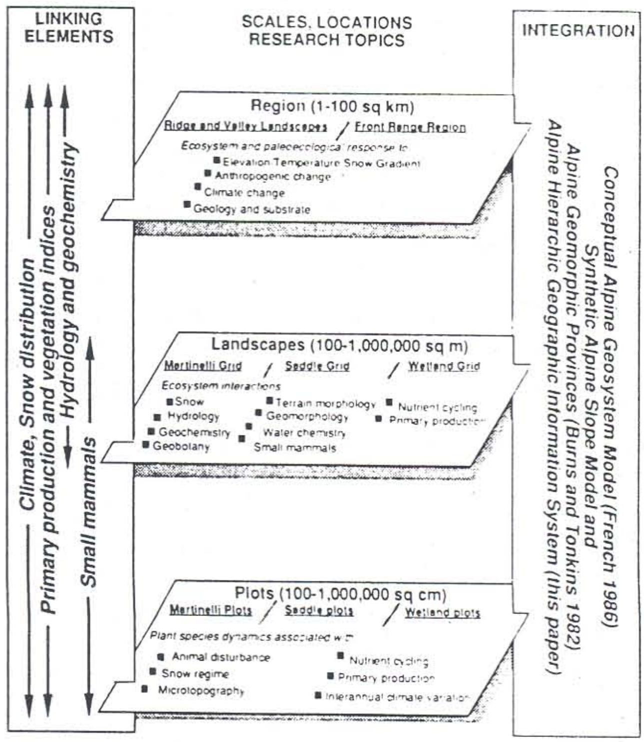

Figure 2. Conceptual framework for the Niwot hierarchic GIS.

MULTI-SCALE STUDIES OF SNOW-VEGETATION INTERACTIONS

Plot-scale studies

At plot-level scales (10^{-2}-10^{2} m^2), the main hypothesis is that plant species react to changes in snowpack in a manner that is predictable from their present-day distribution along snow-depth gradients. We are interested in the plant species dynamics associated with snow distribution. Snowpack indirectly controls the distribution of many plant species by limiting the length of the growing season. Wind-exposed sites have extremely low winter soil temperatures and high moisture stress. The distribution of pocket gophers (*Thomomys talpoides*) is also strongly controlled by snow patterns. Gophers are largely responsible for the fine-scale mosaic of many plant communities; they maintain species diversity by creating gaps in the plant canopy, redistributing nutrients and soil and suppressing species that would otherwise dominate.

To monitor changes in species composition, we are using a grid of 88 permanent plots that span the snow gradient from windblown sites to areas with over 6 m of maximum winter snowpack. This is the most detailed level of the HGIS. Data at this level allow for detailed examination of the controls of microscale environmental variation because the data are spatially referenced to the UTM coordinate system, both with respect to the 350 x 500-meter Saddle grid and the 1 x 1-meter permanent plots. An examination of the distribution of plant species along a snow gradient indicate that most species are found in relatively narrow ranges of snow depth; but a few cosmopolitan species such as *Acomastylis rossii*, occur in a broad range of winter snow regimes with its optimal occurrence in 1-2 m of snow.

Landscape-scale studies

At the landscape scale (10^2-10^6 m^2), the main long-term research hypothesis is that shifts in snowpack regimes should cause changes to vegetation-community boundaries that are predictable from present-day vegetation-snow relationships. We are examining the patterns of vegetation communities, primary production, and small-mammal distribution associated with hill-slope toposequences, and snow gradients from wind-blown sites to deep snow patches. Our main study site is the Niwot Ridge Saddle Grid, where we prepared a detailed vegetation map at 1:500 scale and analyzed the vegetation patterns in relation to mean maximum snow depth, slope and aspect (Walker *et al.* 1993). At this level of the hierarchy, vegetation is mapped using the Braun-Blanquet approach (Komárková and Webber 1978) and six different soil-plant communities (noda) (Webber and May 1977).

The control of snow on the distribution of the dominant alpine species is apparent at the plant-community level. For example, the primary vegetation types on west-facing slopes are either fellfield associations (*Trifolietum dasyphylli* and *Sileno-Paronychieum*) or dry sedge meadow associations (*Selaginello densae-Kobresietum myosuroidis*). In contrast, east-facing slopes have a predominance of deep snow accumulation areas and snowbed associations. Plant communities associated with either windblown sites or snow patches cover a total of 78.6 percent of the Saddle Grid and 77.9 percent of the alpine area of Niwot Ridge mapped by Komárková and Webber (1978), an indication of the importance of wind and snow cover in this windy alpine landscape (Walker *et al.* 1993).

Regional-scale studies

At the regional scale associated with the entire City of Boulder Watershed or the Front Range (10^6-10^8 m^2), remotely sensed data provide an efficient means to examine regional patterns of greenness. The main hypothesis at this scale is that primary production is broadly controlled by gradients associated with changing elevation, but also influenced by smaller scale topographic interactions with wind and snow. Currently we are using SPOT HRV and Landsat TM satellite images to examine patterns of greenness along elevation gradients. We are also building a database at a scale of 1:10,000 that covers the City of Boulder Watershed and the entire Niwot LTER site. In addition to remotely sensed data, this database includes vegetation maps (Braun-Blanquet vegetation associations and vegetation noda) and digital elevation models. Surficial geology and surficial geomorphology maps will be added in the future to the analysis of NDVI (Normalized Difference Vegetation Index) in relation to geobotanical features and terrain information.

In addition to linking ground-level observations to remotely sensed imagery through the utilization of NDVI, we are also investigating the use of SPOT MLA as well as Landsat TM and MSS for long-term monitoring and modeling experiments within the alpine tundra zone of Niwot Ridge. In particular, we are conducting studies aimed at 1) evaluating the potential of multi-resolution remotely sensed data combined with ancillary topoclimatic data to map tundra vegetation; 2) monitoring and modeling the spatial distribution and temporal patterns of snow cover, and 3) modeling the radiation and energy balance within the alpine. These studies provide some of the building blocks necessary for improving simulation experiments of the response of alpine tundra to climatic change. Results of our most recent remote sensing investigations are briefly described next.

REMOTE-SENSING STUDIES

Spatial patterns of green biomass

Our early studies relating patterns of green biomass to elevation in the Front Range using SPOT HRV (20 m ; 4 September 1988) indicate that the fine-scale patterns associated with snow distribution at plot and landscape scales do have an influence on regional patterns of primary production (Walker *et al.* 1993). NDVI generally showed a strong negative correlation with elevation in the Front Range, which is logical because of colder temperatures and longer periods of snow cover at higher elevations. However, this relationship is also affected by strong winds which are responsible for the redistribution of snow. West-facing slopes east of the Continental Divide showed no relationship between elevation and NDVI, an indication of the strong control of wind on production at all elevations.

Based on the preliminary results with SPOT, we are currently investigating the relationship (correlation) between NDVI values derived from Landsat TM (30 m ; 6 August 1986) and several topographic and topoclimatic variables for Niwot Ridge alone. One objective of this study is to develop an empirical model of NDVI based on a simple set of topographic/topoclimatic variables. The six topographic variables describe elevation (DEM), slope (SLP), relief (REL), down-slope convexity (DSC), cross-slope convexity (CSC), and angle of incidence (INC), and the five topoclimatic variables correspond to an orogenic precipitation index (OPI), growing degree days (GDD), slope-aspect index (SAI), insolation index (INS), and snow probability (PS). The topoclimatic indices are derived from a 16 year Landsat data archive, geomorphometry from a DEM, and meteorological station data. The procedure used to derive these indices is described in a recent paper by Peddle *et al.* (1993).

Briefly, we define OPI as altitude/distance from the Continental Divide. Higher OPI values indicate greater likelihood for higher relative precipitation amounts and consequently, greater moisture availability potential for plant growth. GDD refer to the magnitude a given temperature measure exceeds a temperature (5°C) at which plant growth is inhibited. We compute cumulative GDD totals throughout the growing season to gain insight into the total amount of energy available for plant growth. SAI enables to distinguish between terrain orientations likely to contain ample soil moisture due to snow redistribution versus those that would be exposed, wind-blown, and dry. High values of SAI are found on steep, leeward (east-facing) slopes where snow accumulation is great and moisture is readily available. INS gives a measure of instantaneous global insolation computed in terms of global transmission, extra-terrestrial solar radiation corrected for the angle of incidence, diffuse sky radiation, and angles of direct beam incidence to sloping and horizontal surfaces. Finally, PS is derived from co-registered Landsat MSS images acquired in different years and at different times in the growing season to capture relevant information pertaining to both the seasonal and annual variability of snow cover patterns.

Correlations between NDVI and the 11 topographic/topoclimatic variables were computed for Niwot Ridge at various levels of stratification of slope and aspect classes (table not shown). Only the results which involved stratification into east-facing (67.5-112.5°) and west-facing slopes (247.5-292.5°) with gradients 3-10° are discussed herein. For east-facing slopes, NDVI is highly correlated with OPI (r=0.77), GDD (r=-0.75) and DEM (r=0.75). Correlations are below $\pm$0.27 for all other variables. In the case of west-facing slopes, NDVI is also highly correlated with OPI (r=0.78) but only moderately with GDD (r=-0.47) and DEM (r=0.51). In contrast to east-facing slopes, PS (r=0.50) and DSC (r=-0.51) for west-facing slopes are moderately correlated with NDVI. All other correlation coefficients are below $\pm$0.18 for these slopes. One possible explanation for the moderate correlations between NDVI and the variables PS and DSC is that some of the west-facing slopes (most probably concave) that are covered by snow during the winter months provide moister soil conditions for plant growth (i.e. snowpatch communities). These preliminary results should, however, be interpreted with some caution since the relationships between NDVI and the topographic/topoclimatic variables have been derived from a dataset at 30-m resolution. For example, fine-scale topographic variations associated with the presence of features such as turf-banked terraces and lobes and their associated drainageways, which occur mainly on the upper part of Niwot Ridge, may be best captured at spatial resolutions of the order of 2 to 5 m.

Tundra vegetation mapping

Remote sensing investigations into mapping alpine tundra vegetation in the Saddle area of Niwot Ridge have been carried out with some degree of success using digitized colour infrared 1:50,000-scale aerial photography with indicators of topographic context (slope, aspect) (Frank and Thorn 1985) and topoclimatic index values (Frank and Isard 1986). We recently complemented and built on these studies by exploring the development of a spectral, topographic and climatic digital data set to test our hypothesis that classification accuracy and precision can be increased by incorporating ancillary climate indices into satellite image analysis of vegetation patterns within the complex alpine tundra ecosystem on Niwot Ridge.

The five topoclimatic indices described in the previous section were tested individually and together with a Landsat TM image and topographic measures from a DEM to assess their significance for increasing the accuracy and precision of maximum likelihood landcover classification with respect to the hierarchical Braun-Blanquet vegetation classification system. Growing Degree Days and Orogenic Precipitation index had the highest classification accuracies among individual topoclimatic indices, with the highest accuracies obtained using all five indices together with several TM bands (74% to 83% at the highest and lowest levels of precision tested, respectively). Experiments showed good correspondence between digital classifications and a vegetation field map at the Class and Order levels of aggregation of the Braun-Blanquet system. However, greater accuracy and precision might be expected at the Alliance and Association levels using a higher resolution remote sensing (i.e. airborne imaging spectrometers) and DEM data sets together with more sophisticated classification algorithms (e.g. evidential reasoning).

Snow cover variability

As shown earlier in this paper, snow is one of the principal factors controlling alpine vegetation at all levels of investigation. For example, an increase in snowfall affects plant processes in several ways, the most important effect being to shorten the growing season, so reducing the time available for photosynthesis and reproductive development. Under a climate scenario of increased winter snowfall on Niwot Ridge, dry exposed ridges would receive little, if any, additional snow, whereas traditional snowbed sites would be more susceptible to impact. Over several decades, weather modification resulting in an increase or decrease in winter snowfall would most probably alter the proportional composition of alpine community classes. Satellite remotely sensing provides the capabilities necessary for monitoring changes in the spatial/temporal patterns of snow cover. In addition, when combined to a DEM and climate data, remote sensing imagery may be used to estimate snow depth, an important input parameter to runoff forecasting.

Snow covered areas, expressed as a percentage of the total area of Niwot Ridge, have been extracted from a Landsat MSS image archive (1973-present) and correlated to temperature and precipitation records from two climate stations on the Ridge to see if snow cover can be utilized as one of the many indicators of climate variability/change at the Niwot LTER. Preliminary results show a good correspondence between snow covered area derived from Landsat MSS during the major period of seasonal runoff and climate conditions (average monthly temperatures and total snowfall calculated from October through May). Long-term monitoring of seasonal snow cover with Landsat MSS (and higher resolution sensors) will complement another experiment in which we are artificially altering winter snow regimes with a large snow fence (100-year snow-fence experiment, starting in summer of 1993). Because alpine plant species are long-lived perennials, we expect that many ecosystem responses will be slow. We, therefore, are planning to continue the experiment until we no longer see changes in species patterns or soil properties. The experiment is likely to provide many insights to the ecosystem consequences of climate-altered snowpack regimes.

Radiation and energy balance modeling

The accurate determination of the net radiation flux at the earth's surface is an important objective in climate related research on all spatial and temporal scales. Net radiation is a fundamental measure of the energy available at the earth-atmosphere interface since it regulates evapotranspiration, sensible heat flux, soil heat flux, and photosynthesis. A knowledge of the spatial distribution of net radiation is therefore of considerable importance to geoecological research on Niwot Ridge. We have recently proposed a model to estimate the radiation balance over alpine snow fields under clear-sky conditions (Duguay, 1993) and presented an approach to derive surface albedo from Landsat TM imagery and digital terrain data (Duguay and LeDrew, 1992). Results were in good agreement with data acquired during field measurement campaigns. We now plan to use the approach of Duguay and LeDrew (1992) to monitor changes in surface albedo at the Niwot LTER on an ongoing basis. In addition, the net radiation model is currently being revised to consider cloudy conditions and provide further capabilities to estimate both the radiation balance and evapotranspiration over the alpine tundra zone of Niwot Ridge. Field data acquired this past summer will enable us to validate and improve our model.

CONCLUSIONS

In this paper, we have presented an overview of ongoing research using a hierarchic geographic information system database at the Niwot LTER site. Thus far, much of our efforts have been directed at examining the relationships between patterns and processes at a variety of spatial scales. The hierarchic analysis of alpine vegetation patterns has demonstrated that plant species, community, and green-biomass patterns are largely controlled by snow distribution, which varies greatly with topography and wind patterns. Environmental monitoring and modeling experiments within the alpine tundra zone of Niwot Ridge have mostly been conducted at the regional scale using remotely sensed imagery and ancillary GIS data.

In the future, high-resolution remote sensing and digital elevation data should be acquired in order to address more fully the question of scale. With respect to the development of an empirical model of NDVI or a model of snow accumulation and distribution, there is a need to collect high-resolution data (2-5 m) to capture fine-scale topographic variations that control snow redistribution. Finally, high-resolution sensors could provide some important land-surface parameters for initializing and validating alpine tundra simulation models, such as the one recently presented by Grant and French (1990).

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