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A WATERSHED APPROACH TO ECOSYSTEM MONITORING IN DENALI NATIONAL PARK AND PRESERVE, ALASKA[1]

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ABSTRACT: The National Park Service and the National Biological Service initiated research in Denali National Park and Preserve, a 2.4 million-hectare park in southcentral Alaska, to develop ecological monitoring protocols for national parks in the Arctic/Subarctic biogeographic area. We are focusing pilot studies on design questions, on scaling issues and regionalization, ecosystem structure and function, indicator selection and evaluation, and monitoring technologies. Rock Creek, a headwater stream near Denali headquarters, is the ecological scale for initial testing of a watershed ecosystem approach. Our conceptual model embraces principles of the hydrological cycle, hypotheses of global climate change, and biological interactions of organisms occupying intermediate, but poorly studied, positions in Alaskan food webs. The field approach includes hydrological and depositional considerations and a suite of integrated measures linking key aquatic and terrestrial biota, environmental variables, or defined ecological processes, in order to establish ecological conditions and detect, track, and understand mechanisms of environmental change. Our sampling activities include corresponding measures of physical, chemical, and biological attributes in four Rock Creek habitats believed characteristic of the greater system diversity of Denali. This paper gives examples of data sets, program integration and scaling, and research needs.
(KEY TERMS: watershed management/wildland hydrology; watershed ecosystem; protocol; monitoring; environmental change; Alaska; Denali National Park.)

INTRODUCTION

In this paper we describe selected portions of pilot research in Denali National Park and Preserve (Denali) during 1992-1995. National Park Service policy (NPS Management Policy IV-2, 1988) requires provision of accurate scientific data for planning, development, and management of the parks. Realizing that few parks have met this policy, a National Inventory and Monitoring Program was established (Evison, 1987). The "Evison plan" described a 10-year program where natural resource inventories were to be completed and prototype monitoring designs developed and tested. Denali was selected to test a monitoring scheme for application in Alaska.

The large geographic scale of the Alaska national parks and their incomplete resource inventories provide a unique challenge for long-term monitoring. The 21.5 million hectares (53 million acres) comprising these parks are primarily wilderness with limited access. The parks range in size from small historic parks (< 10,000 ha) to more than 5.3 million hectares; Denali is 2.4 million-hectares. Parks of large size require the landscape be stratified into ecologically meaningful, yet manageable areas. A watershed approach was selected for this purpose because ecological processes such as insect outbreaks, fires, and disturbance occur at small scales, as low as first- or second-order catchments (10s to 1,000s ha; Natural Resources Council, 1995). Watersheds are appealing as their boundaries are defined by soil, vegetation, topographic, and hydrologic conditions. We recognize that not all ecosystem attributes are captured within watershed boundaries (e.g., atmospheric influences; see Allen and Hoekstra, 1990) and that transboundary issues exist for migratory populations and low-density, wide-ranging species whose habitats are not confined to a single catchment. We propose that monitoring within watersheds, representing Denali's aquatic and terrestrial resources, will capture the trends in temporal and spatial patterns for selected ecosystem attributes at the park level and at smaller

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levels of resolution. Cost considerations led to selection of a single watershed for development and testing of the conceptual design.

Terrestrial and aquatic ecosystems are connected by the common integrator – water – as it moves through air, land, and watershed compartments of the environment. In our conceptual model (Figure 1), we define catchment boundaries in classical terms including the storage of water in glaciers. Additional boundaries are determined by known physical disturbances, such as fire and flooding; unknown physical processes, such as contaminant transport; and biological constraints on ecosystem processes, including retention of allochthonous material in stream channels, animal dispersals and colonization processes, predator-prey relationships, and contaminant effects.

In Denali, we are testing an integrated approach for long-term monitoring (e.g., Champ *et al.*, 1993; Goez *et al.*, 1992; Herrmann and Stottlemyer, 1991) in a single watershed. Design research is delineating physical processes and interactions that we believe will be the best predictors of biotic distribution, abundance, and ecosystem condition. Conventional hydrological and geochemical measures are being linked to selected aquatic and terrestrial biota, key environmental variables, and defined ecological processes (Carpenter *et al.*, 1995; Van Cleve *et al.*, 1991). In time, the program will provide baselines for expanded ecosystem monitoring in additional watersheds, comparative reference points from a protected area, and critical input to existing paradigms of global and environmental change (e.g., Stohlgren *et al.*, 1995). Most importantly, it will provide an ability to diagnose normal and abnormal conditions and early warning signals for management action (Davis, 1989).

Research objectives are to establish ecosystem condition and trend, assist in selection and evaluation of indicators, and improve our understanding of causes and mechanisms of change. The monitoring we present has retrospective and predictive qualities (Natural Resources Council, 1995) providing a preliminary

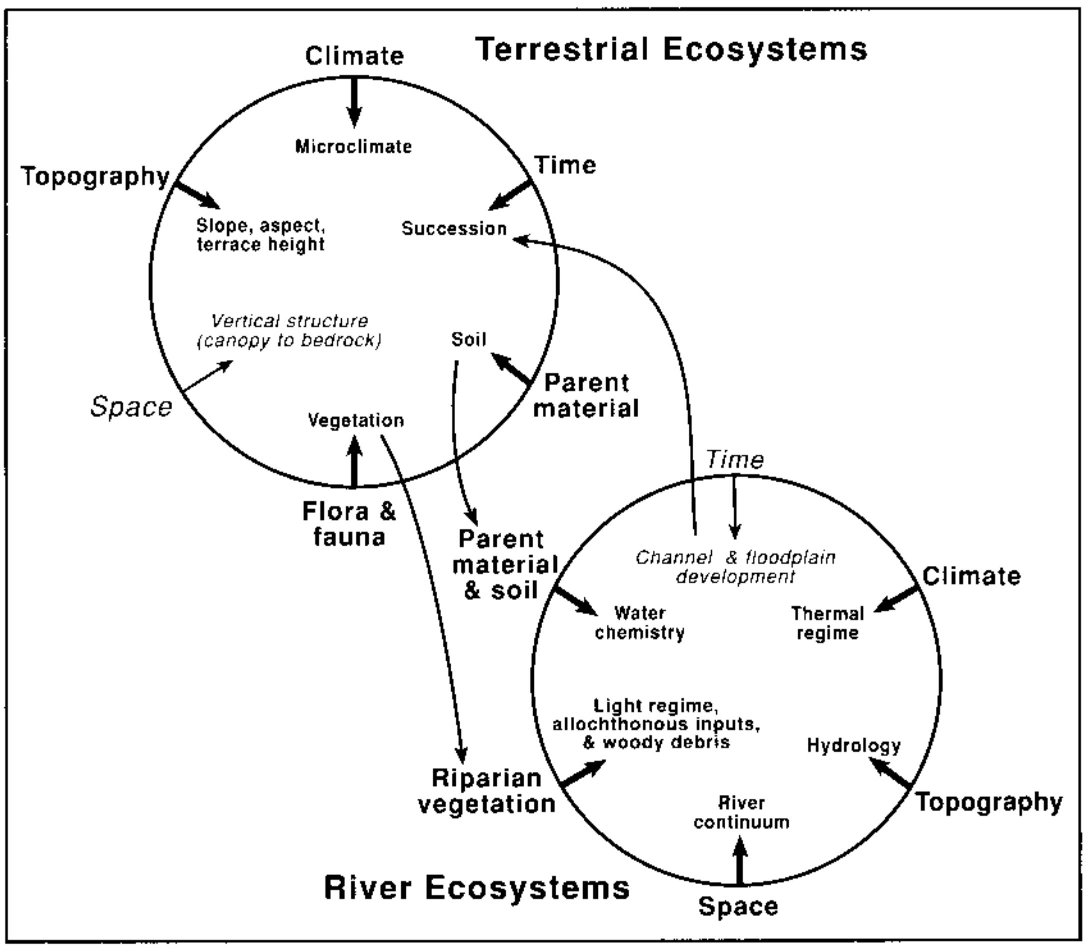

Figure 1. Conceptual Model of Watershed Ecosystem Interactions (with permission from M. Oswood and J. Irons, University of Alaska Fairbanks).

template and test for adaptive resource management in Denali.

STUDY AREA

Our selection of Rock Creek, a small headwater stream near Denali headquarters, considered local and regional knowledge (Figure 2). For example, in Alaska and the Yukon Territory, Canada, headwaters contribute substantially to the total regional runoff. Our review revealed that no Arctic or Subarctic watershed programs included a headwater component (Janowicz, 1993). We considered research and monitoring at Toolik and Bonanza Creek/Poker Flats Long Term Ecological Research (LTER) sites, MacKenzie River and Wolf Creek basins, and Copper-Susitna rivers, in our selection process. Thus, our selection of Rock Creek is important for comparisons in a geographic context.

Other selection criteria for Rock Creek included: (1) the availability of meteorological data and other environmental information (e.g., Crock *et al.*, 1992; Oswood, 1989; Stottlemyer, 1992); (2) land use concerns including (a) it being a major freshwater source for human consumption in developed portions of the park, and (b) proximity to an external threat (< 10 km from Healy Clean Coal Project for power generation; see Department of Energy, 1993); (3) representation of the environmental-elevational gradient of Denali's vegetation and successional patterns; (4) existing monitoring infrastructure; and (5) accessibility and other logistic and cost factors.

Rock Creek is a snowmelt- and rainfall-dominated drainage in the northeastern section of Denali

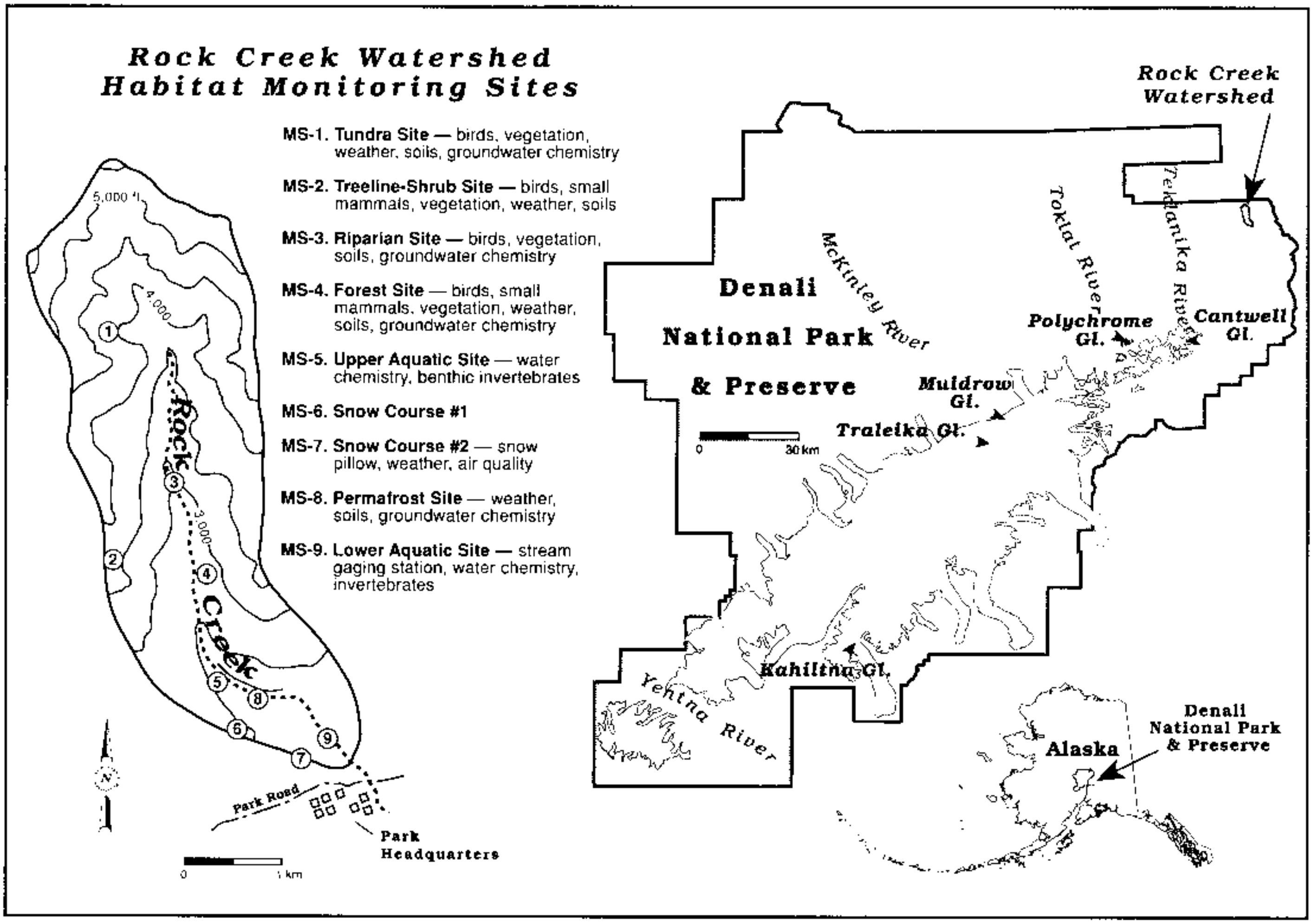

Figure 2. Study Area Location in Denali National Park and Preserve, Alaska, Glaciers Being Monitored, and Habitat Monitoring Sites in Rock Creek Watershed.

(63°44'N, 149°00'W). It has a south-southeast aspect and ranges in elevation from 625 m to 1,735 m. The stream channel is narrow (30 m) with a morphology characteristic of extreme flooding (i.e., steep gradient, straight flow, little pool formation, and boulder-strewn banks). It is a second-order stream flowing into Hines Creek, a tributary of the Nenana River. The watershed is 5.5 km long and 1.5 km wide, and drains 826 hectares from north to south. The site has documented fire and flooding histories. The vegetation is dominated by a mix of forest and upland tundra species.

Four terrestrial habitats in the Rock Creek watershed include: alpine tundra (627 ha), forest (143 ha), treeline-shrub (30 ha), and riparian (26 ha). Alpine tundra, comprising sparse vegetation dominated by white mountain-avens (*Dryas* spp.) and netleaf and arctic willows (*Salix reticulata* and *S. arctica*, respectively), occurs at the uppermost reaches. A mixed forest of white spruce (*Picea glauca*), quaking aspen (*Populus tremuloides*), and paper birch (*Betula papyrifera*) occurs at intermediate elevations in eastern portions of the watershed. This is a common forest type in interior Alaska, and is indicative of fire succession. Treeline-shrub habitat occurs mainly as white and black spruce (*Picea mariana*) forests with sphagnum moss and shrub understories in unburned areas to the west. Riparian vegetation, dominated by Sitka alder (*Alnus crispa*) and willow (*Salix* spp.), occurs in a narrow band along the stream corridor. Permafrost is common at intermediate elevations in the western portion of the watershed.

METHODS

Expert opinion from a series of review papers, technical workshops, and scientific conferences recommended ecosystem monitoring at the watershed scale for interior Alaska (Peale *et al.*, 1993). Further, research was needed to determine natural variability in the ecosystem parameters studied, methods development and testing (cf., Hinds, 1984), and protocol design. A completed protocol includes detailed information about every aspect of the monitoring element: goals and objectives, site selection, equipment description and setups, sampling frequency and intensity, analysis routines, and quality assurance/quality control procedures. The protocols are intended to provide comprehensive descriptions of sampling methods, data collections and management, and standardized reports. Each protocol is peer-reviewed and will become "standard operating procedure" when implemented. Typically, protocol development takes 3-5 years.

The protocol research in Denali is providing important, new baseline information about high elevation ecosystem attributes, indicators, and natural stressors in interior Alaska. We have selected data sets from 1992 through 1995 for presentation in this paper that emphasizes trends, interdisciplinary relationships, integration, and various scaling concerns in the design. Unless otherwise noted, the descriptive statistics we use are described by Zar (1984). Chi-square (χ^2) and Spearman rank correlation coefficient (r_s) analyses are significant at the 95 percent level of confidence. The summer period is May through September.

Climate and Air Quality

Seven meteorological stations, instrumented to electronically collect and record weather data, are located in the Rock Creek watershed at or near our habitat monitoring sites (MS) (Figure 2). Their number and placement reflect complementary objectives to describe regional and local weather conditions. Three stations equipped with 10-m towers are located in lower (MS-7), middle (MS-2), and upper (MS-1) elevations of the study area. Data collection at these sites provides mesoscale information (10s km) characteristic of eastern Denali. Four stations equipped with 2-m towers are located in, or near, permanent vegetation plots (MS-1, MS-2, and MS-4) and the permafrost site (MS-8). Data collection at these sites provides microscale information (10s m) characteristic of Rock Creek habitats. Standard measurements at each station include (see Greenland, 1986): air temperature (to the nearest 0.1°C), precipitation (1 mm), wind direction (1 degree) and speed (0.1 m/second), relative humidity (1 percent), barometric pressure (0.1 millibar), and solar radiation (5 percent W/hour). Denali is a participant in the National Atmospheric Deposition Program (NADP) and the Interagency Monitoring of Protected Visual Environments networks. Atmospheric deposition and ozone measurements (respectively) are taken at MS-7. Depositional data (mg/L) are accessed through the NADP/NTN Home Page (http://nadp.nrel.colostate.edu/sitelist.html). During winter (October to May) snow depth (1.0 inch) is continuously recorded at MS-1, MS-2, MS-7, and MS-8; snow water content (1 percent) at MS-7; and standard snow courses at MS-6 and MS-7 to supplement the electronic measures. Daily temperature (0.5°C) and precipitation (0.1 inch) are recorded at park headquarters. Pan evaporation measurements (1.0 inch) are made during summer at MS-7.

Soils

The National Resources Conservation Service (NRCS) Wet Soil Monitoring Project protocol is being applied at Denali. This standardization brings regional, national, and global context to Denali's monitoring (Ping, 1994). Other Alaskan sites include Prudhoe Bay, Fairbanks, Gulkana, and Kenai Peninsula. In 1992, soil profiles were developed at sites characteristic of Rock Creek watershed (MS-2, MS-3, MS-4, and MS-8) and the major vegetation types of the park (Moore, 1993; Figure 2). Tundra (MS-1), treeline-shrub (MS-2), and forest (MS-4) habitats, and the permafrost site (MS-8) are equipped with 2-m weather towers to monitor standard climate variables, and ambient temperatures near ground level and at four soil horizons between 0 and 70 cm of depth. At each site we are measuring water availability (with soil moisture blocks), oxidation-reduction state (redox probes), and water level (tensiometers), and we are collecting nutrient samples (piezometers).

Water Resources

Total runoff, including surface and subsurface discharge, is calculated using standard techniques at the lower end of Rock Creek at the catchment gaging station (Carter and Davidian, 1968; Linsley *et al.*, 1982). Two sites, MS-5 and MS-9, were monumented for cross-section and longitudinal surveys (Figure 2). Stream bed and bank materials were characterized at each site (Harrelson *et al.*, 1994). Suspended sediment, turbidity, pH, conductivity, and major ions and nutrients are measured monthly between May and September using standard procedures (e.g., American Public Health Association, 1985). A Microtox® screen for heavy metal contamination was tested in 1992 (Microbiotics Corporation, 1992). Annual sampling for *Giardia lamblia* and *Escherichia coli* is included within the water quality protocol.

Rapid bioassessment procedures are being used to assess aquatic macroinvertebrate community structure and succession in Rock Creek and other Denali streams (Plafkin *et al.*, 1989; Milner and Oswood, 1995). Structural indices include standard metrics for population density, species richness and diversity, and indicator taxa (Milner and Roberts, 1996). Functional attributes relate dominant feeding morphology to stream development and order (Merritt and Cummins, 1978). Invertebrates are sampled just prior to ice breakup (late May-early June), midsummer (late July), and autumn (early September). The biological sampling is conducted at MS-5 and MS-9 (Figure 2) and is accompanied by (1) standard in-stream measures for temperature (°C), conductivity (S), pH, flow (cm/second), substrate embeddedness, and algal growth; and (2) water samples for chlorophyll *a*, major ions (e.g., Ca, Mg, Cl, Fe), and nutrients (e.g., N, Ph, K, Si). During the midsummer sampling, dissolved oxygen is monitored hourly (24-hour period) at MS-5 to obtain a surrogate measure of algal productivity. Annual leaf retention studies provide an additional index of habitat stability and stream development (Milner and Roberts, 1996).

We postulate that standing stock indices of primary production will provide early signals of change in the terrestrial environment. Previously, Stottlemyer (1992) reported high riparian contributions of N from nitrogen-fixing vegetation into Rock Creek suggesting P limitation on algal growth. During the summer of 1994, three in-stream experiments were conducted at the Rock Creek aquatic monitoring sites (two experiments at the lower site and one at the upper; Figure 2). Each experiment consisted of the random placement of sixteen 250-ml clay flower pots filled with a 2 percent nutrient-diffusing agar and four nutrient treatments. Experimental replicates included one set of four pots with no nutrient additions as controls; one set with 0.1 M K_3PO_3 additions; one set with 0.1 M NH_4NO_3 additions; and one set with 0.1 M K_3PO_3/NH_4NO_3 additions. The pots diffused either no nutrient, P, N, or both P and N depending on treatment. After four weeks, a 3-cm^2 area of each pot was sampled for chlorophyll *a* analysis.

Vegetation

The vegetation component of the terrestrial ecosystem is central to the experimental design. All other biotic measures relate to the vegetation types. Protocol objectives are to: (1) monitor composition and structure in plant communities in Rock Creek habitats; (2) design and test methods to provide landscape information about plant diversity, production, and phenology; and (3) determine abiotic influences on growth and reproduction of white spruce, a dominant treeline species. Three replicate plots were established in forest (MS-4), treeline-shrub (MS-2), riparian (MS-3), and tundra (MS-1) sites (Figure 2). The basic design consists of an inner plot centrally nested within an outer plot, a scheme patterned after that described by Van Cleve and Martin (1991) to monitor watershed-level changes at the northern treeline (Starfield and Chapin, 1996). A line intercept method is being tested to investigate changes in species composition at the habitat level (Helm and Mayer, 1985).

The permanent vegetation plots at MS-2 and MS-4 measure 50 m x 50 m (0.25-ha outer plots) and 25 m x 25 m (0.06-ha inner plots). The plots at MS-1 measure

20 m x 20 m (0.04-ha outer plots) and 10 m x 10 m (0.01-ha inner plots). At MS-3, the size and shape of the plots reflect a narrow, dynamic riparian corridor, and research focuses on stream-vegetation interactions. Riparian outer plots measure 10 m x 10 m (0.01 ha) and have an inner plot size of 5 m x 10 m (0.005 ha). One 5-m side is adjacent to the creek. At every site, smaller (0.75-4.0 m^2) subplots are nested within the inner plots to establish measures of vegetation cover and berry production (Bonham, 1989; Husch *et al.*, 1982). Similarly, standard methods were used to conduct inventories, estimate cover, and map and establish the condition of white spruce trees at the time of initial site surveys. Annual growth (in inches) of white spruce is measured with dendrometer bands. Cone crop values for white spruce are based on mean counts of cones per half-tree on five trees per plot. Phenological status of the dominant trees, shrubs, and herbaceous plants is determined weekly (Molau, 1993).

Ground Water

Quantification of the nutrient dynamics in the soil-plant-water system establishes an ecological linkage between watershed, terrestrial, and aquatic ecosystems and to primary and secondary production therein. Piezometer arrays, in transects extending downslope from higher elevation sites to the stream channel, were located in or near MS-1, MS-3, MS-4, and MS-8 in 1995 (Figure 2). In 1995, water samples were collected biweekly in July and August. Soil water samples were collected at transect endpoints (with suction lysimeters) and at six sites in Rock Creek (distributed between and including MS-5 and MS-9). On site, the samples were analyzed for pH, conductivity, and hardness. Soil water samples (1/lysimeter) were analyzed for dissolved organic and inorganic carbon (DOC and DIC), ions (Ca, Mg, K, and Na), and major nutrients (PO_4, NO_3, and NH_4) using standard analytical techniques (Popovics *et al.*, 1996). Soil water flow rate was determined using piezometers and Darcy's Law (Wilson *et al.*, 1995). Replicate stream water samples were analyzed for major ions, and nutrients (PO_4 and NO_3). Stream flow was estimated using standard methods as above.

Birds

Standard point counts (Ralph *et al.*, 1993) of land birds are being conducted at a watershed and larger coverage. The avian research is focusing on analytical procedures, including frequency of occurrence observations as the basis of trend detection. A constant-effort mist netting program focuses on avian population dynamics (international Monitoring Avian Productivity and Survivorship [MAPS] program; DeSante *et al.*, 1993). MAPS is to provide annual regional indices and estimates of adult population size, post-fledgling productivity, adult survivorship, and recruitment into the adult population for land-bird species. Catch-per-unit-effort (CPUE) indices and mark-recapture methods are used to estimate population recruitment and survival in numerous bird species occurring in dominant park habitats, including the Rock Creek monitoring site (Figure 2).

Small Mammals

Small mammals are a significant component of the diet of many predatory birds and mammals in Denali (Cook and Rexstad, 1992). Live trapping for microtines and other small mammals was conducted on 100-m x 100-m grids (1 ha; 100 Sherman traps/grid) at MS-2 and MS-4 (2 grids/habitat) during 1992-1994 (Furtsch, 1995; Figure 2). Sampling began in early July and consisted of five- to six-day sessions every other week until early September. Baited traps were sampled three times daily (0600, 1300, 2000 hours). Live-captured mammals were injected with passive integrated transponder (PIT) tags in mark-recapture testing of a habitat-based method for monitoring population dynamics and seasonal abundance of microtines (Furtsch, 1995). Retained specimens were frozen in liquid nitrogen and archived at the University of Alaska for determination of heavy metal, pesticide, and radionuclide levels. Animal fecal samples were collected for information on diets and fungal spores.

RESULTS AND DISCUSSION

Ecosystem monitoring within watershed boundaries in Alaska's national parks offers a natural environmental partitioning in the absence of detailed natural resource inventories. Research at Denali is testing the premise that a program of integrated long-term monitoring in representative watersheds can develop broad-scale information needed to describe ecosytem status and trend. The initial research at Denali addresses program design, including, but not limited to, indicator selections, integration, methods development and documentation, landscape scaling, and demonstrated execution, in a single watershed.

Underlying this is the unstated but concurrent need to develop ecosystem knowledge in a remote environment where existing data are limited.

Summer air quality, as indicated by wet deposition measurements at the Rock Creek NADP station (MS-7), may be the least polluted in Alaska (Figure 3). It most closely represents "pristine" conditions for the Arctic today. For those studying Arctic haze and acidification, this 16-year baseline provides key background with respect to Arctic contamination. Summer precipitation weighted means for the 1980-1995 interval indicate low depositions for NO_3 (0.13 mg/L), SO_4 (0.29 mg/L), and Ca (0.12 mg/L), and slightly acidic rainfall (mean pH = 5.4). These values compare to mean values for NO_3 (0.8 mg/L), SO_4 (4.0 mg/L), Ca (0.76 mg/L), and pH (8.2) on Alaska's North Slope (unpublished data, University of Alaska Fairbanks, Geophysical Institute). Thus, the record provides a regional and local diagnostic measure of acidification (synoptic scale of 10^3 km; Shaw and Benner, 1996) and depositional measures for geochemical budgeting (e.g., Baron, 1992). Ionic composition of the snow pack requires further investigation.

The 70-year weather record from Denali headquarters shows an annual mean temperature of -2.6°C with a ±3°C range of variability (Figure 4). Precipitation varies from 20 to 70 cm per year. Previously, Patric and Black (1968) calculated a potential evapotranspiration index (PET) of 14.61 inches for Denali, a value they related to tundra/scrub tree vegetation conditions. The mixed forest stand in Rock Creek suggests a different hydrological regime and a smaller-scale successional pattern reflective of aspect, slope, and disturbance history than might be indicated by a PET value of less than 16 inches. After five years monitoring in Rock Creek, we will recalculate the moisture indices described by Patric and Black (1968) and test their proposed relationships between water availability and elevation in our study area.

The Rock Creek hydrograph for 1993 (Figure 5) shows a peak discharge in May of about 270 cfs. Following the early peak, stream discharge drops to 10-20 cfs. It remains at these low levels through the summer except for brief torrents following rainstorms. Efforts are underway to develop a water budget for Rock Creek in order to assess the accuracy of our discharge estimates. Preliminary water budget analyses indicate that the total volume exported may be grossly underestimated by our present method, which employs continuous stage and instantaneous discharge measurements to develop a stage-discharge rating curve. Underestimation could be due to the unstable nature of the stream bed during periods of high discharge and/or to under flow.

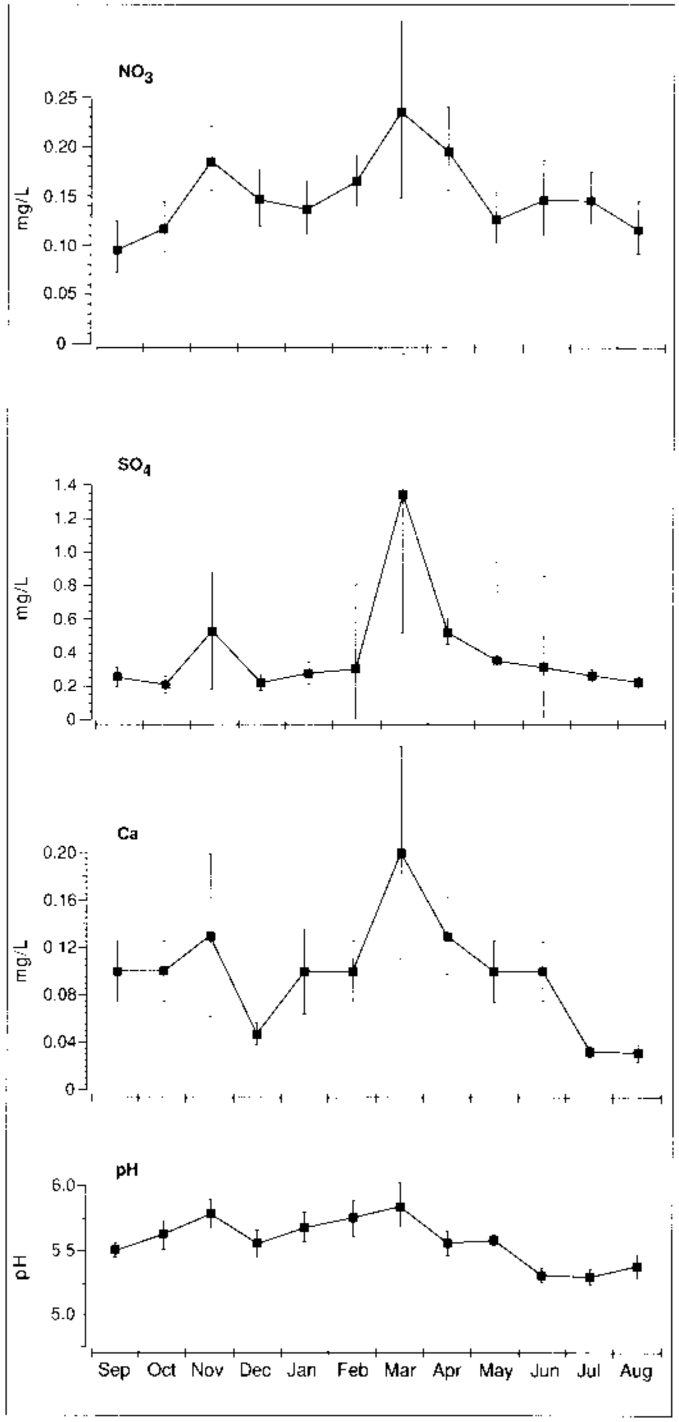

Figure 3. Long-Term (1980-1995) Trends in Wet Deposition at the Rock Creek National Atmospheric Deposition Program Study Site (Monthly Precipitation Weighted Mean ± SE).

The dominance of Mg (mean ± SD = 97.23 ± 8.4 mg/L), Ca (48.88 ± 1.84 mg/L), and $S0_4$ (467.89 ± 78.07 mg/L) in stream water and its high pH (summer mean = 8.51, N = 78, range = 8.2-8.83) are a consequence of the bedrock geochemistry. High $HC0_3$

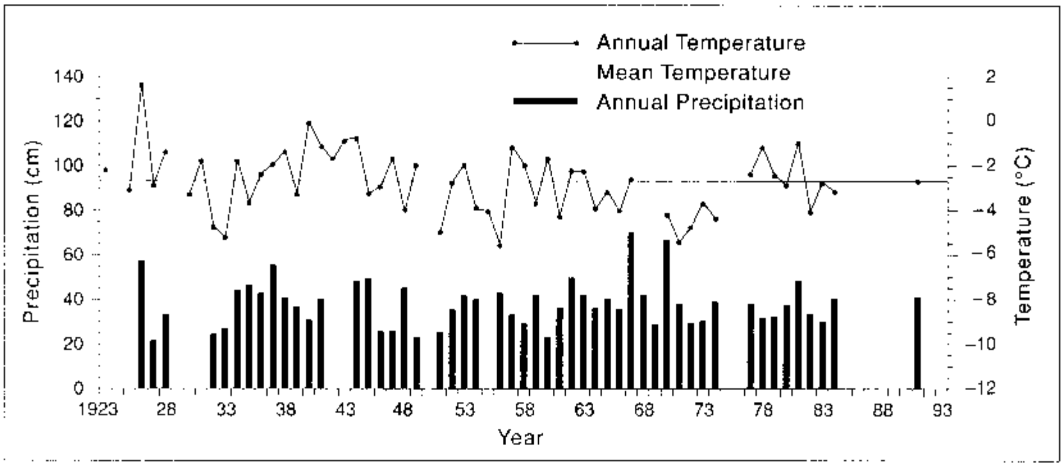

Figure 4. Seventy-Year Record of Temperature and Precipitation Near Rock Creek at Park Headquarters, Denali National Park and Preserve, 1923-1993.

concentrations (353.64 ± 29.93 mg/L) reflect biological activity in the soils. Mean concentrations of NO_3 were low at all sites (1.06 ± 0.07 mg/L) although midstream concentrations were higher due to NH_4 contributions from ground water at MS-4. The inverse relationship between ionic concentration and stream flow indicates the ground water discharge component into Rock Creek.

Soluble carbon dominates the soil water chemistry in Rock Creek watershed soils (Popovics *et al.*, 1996). The high average value of DOC in 1995 (mean ± SD = 19.2 ± 1.05 mg/L) is indicative of a slow decomposition rate in permafrost soils (MS-8). Conversely, a more rapid decomposition rate is suggested by the relatively high DIC concentrations in soil waters sampled in tundra (MS-1: 65.03 ± 12.65 mg/L), forest (MS-4: 54.70 ± 11.87 mg/L), and riparian (MS-3: 55.80 ± 12.51 mg/L) habitats. The most dominant ion in all soils was Ca, with concentrations close to 2.0 mg/L. Soil nutrient levels, NO_3 and PO_4, were low at 0.1 mg/L.

The Rock Creek headwater is characteristic of mountainous terrain and early stages of stream ecosystem development in an unstable regime. Microtox® bioassays indicate clean sediments with no toxic substances. However, less than 10 percent of leaves released were retained in the system and invertebrate counts (< 1,000 organisms/m^2) and species diversity were low. Low Ephemeroptera/Plecoptera/Trichoptera (EPT) ratios compared to number of chironomids indicate degraded water quality, but in this instance, a system in early stages of colonization. Impaired retentive capability and possible diminished primary productivity due to low nutrient values, stream instability, and high spring flows, contribute to overall habitat condition, stream succession, and productivity in the invertebrate community.

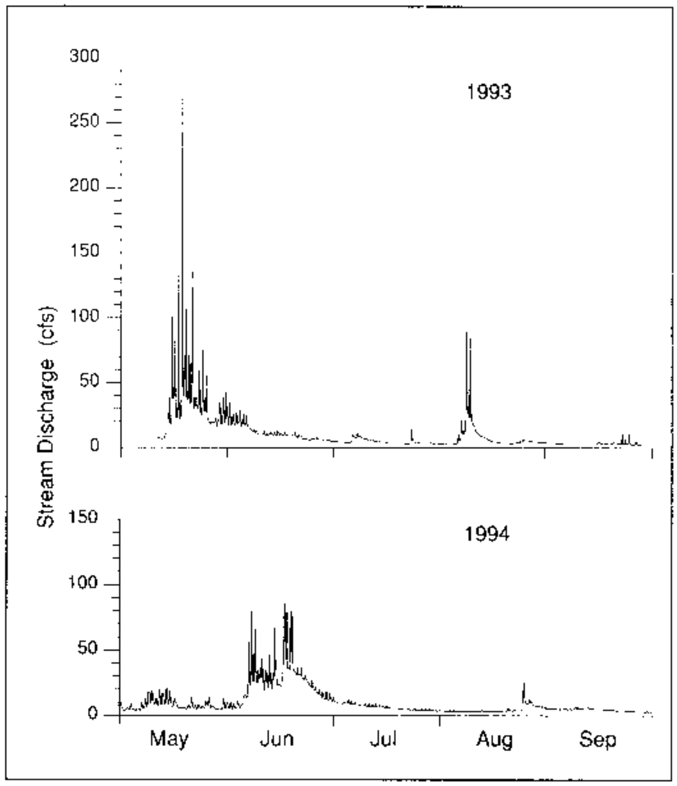

Figure 5. Rock Creek Hydrographs for May-September 1993 and 1994 (data from Ken Karle, this study).

The NRCS surveys in Rock Creek identified four landscape units in the Rock Creek watershed – alpine tundra, glaciated uplands with permafrost, forest, and stream terrace sites – characteristic of much of Denali. As a first step, they provided baselines about soil origins, their productivity, permeability, and plant cover; critical information in our selection of monitoring sites. Knowing that soil temperature and water relationships control vegetation pattern, productivity, and soil mass stability, we proposed that, within a given habitat, the soils-climate-plant relationships derived from Rock Creek could be extrapolated to other landscapes. In Denali, remote landscapes require more costly sampling, but extrapolation from Rock Creek can achieve desired power and confidence in the monitored attributes (e.g., Muttlak and McDonald, 1990).

Alpine tundra soils (MS-1) are thin and have a fragile organic surface. The soil morphology is influenced more by physical properties and by permafrost at depth, frost sorting, and solifluction, than by chemical action (Moore, 1993). Climate and anthropogenic effects such as trampling of alpine vegetation decrease soil stability if surface cover, rooting depth, and root density decrease, while an increase in surface cover and rooting activity stabilizes the soil and increases chemical weathering. Soils are saturated during snowmelt (Figure 6), a time when solifluction lobes migrate the greatest distances. Comparison of the summer soil water matrix decrease and precipitation provides information about how much evapotranspiration combined with gravitational effects on soil water exceeds rainfall during this period (Figure 6). The water matrix and pan evaporation data from Rock Creek suggest the importance of evaporation throughout the summer months. Autumn rains and freeze-up result in decreased evapotranspiration and, combined with precipitation, saturated soils. Once freeze-up occurs, soil water is drawn to the freezing front, thus decreasing soil water matrix potential (Kane and Stein, 1983). After freezing, solifluction lobes become active again, through frost action, although this is less active compared to spring saturated soils.

Redox potentials in the alpine tundra soils vary with soil depth (Figure 7). At 15 cm the soil contains more organic matter, and thus holds more water than at other depths. At 40 cm less organic matter is present, and during spring, ice and the saturation from spring thaw result in a reduced state. At seasonal (frost) melt, water percolates from the soil and the oxidation level increases.

The treeline-shrub (MS-2) is a transitional habitat between alpine tundra and forest zones, and ecotonal shifts in the plant community may relate to earlier subtle changes in soil and climate. Treeline-shrub soils are thin and well drained, resulting in drier soils (Figure 7). The slope is relatively steep and south-southeast facing. It is therefore warmer and, due to winds, has less snow accumulation. Treeline-shrub was the only Rock Creek habitat where soils were not saturated during spring melt in 1994. Early spring water levels were lower due to frost depth. During May through October 1994, redox potentials (corrected to pH 7) were always above the 270-millivolt reference. Values dropped temporarily following rainfall, and recovered to higher levels as the soils dried.

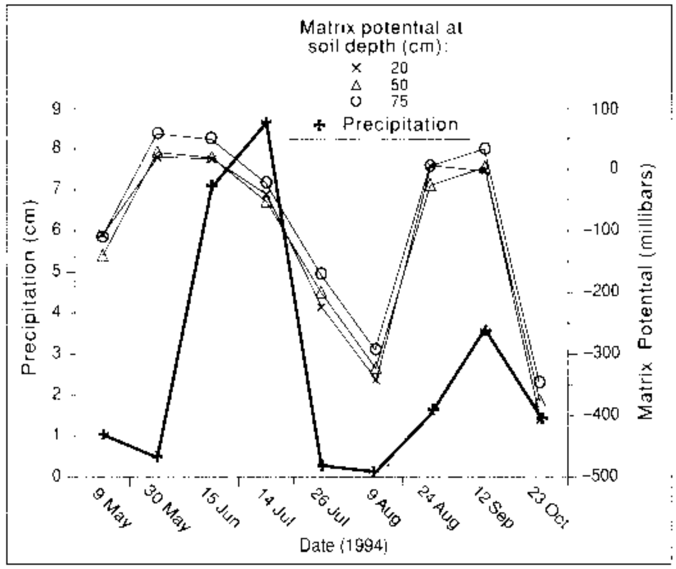

Figure 6. Precipitation and Water Matrix Potential in Alpine Tundra Habitat, Rock Creek Watershed, 1994 (data from Chien-Lu Ping and Greg Probst, this study).

Rock Creek forest soils (MS-4) are of moderate permeability and possess high runoff potential. Soils are saturated during spring melt, and continue to dry through evapotranspiration and groundwater movement throughout the summer even in the presence of precipitation (Figure 7). The soil water matrix drops at the 20-cm depth due to percolation and evapotranspiration. It continues to drop in fall periods of increased precipitation due to gravity effects on soil water and evapotranspiration from conifers. The high runoff potential of forest soils coupled with the relatively thin nature of this habitat's organic mat suggests a heightened vulnerability of these soils to erosion processes.

The Rock Creek permafrost site (MS-8) is unique, as it is the only permafrost area being studied by the National Park Service. The band of shallow permafrost is frozen (-1 to 0°C) within 10 cm of the soil surface. The relatively high temperature near the soil surface makes the site extremely sensitive to climate or other environmental change. The resulting possible slope instability is of special interest. Disturbance of the thick moss organic surface, which is also a carbon sink, will affect soil temperatures, thickness of the

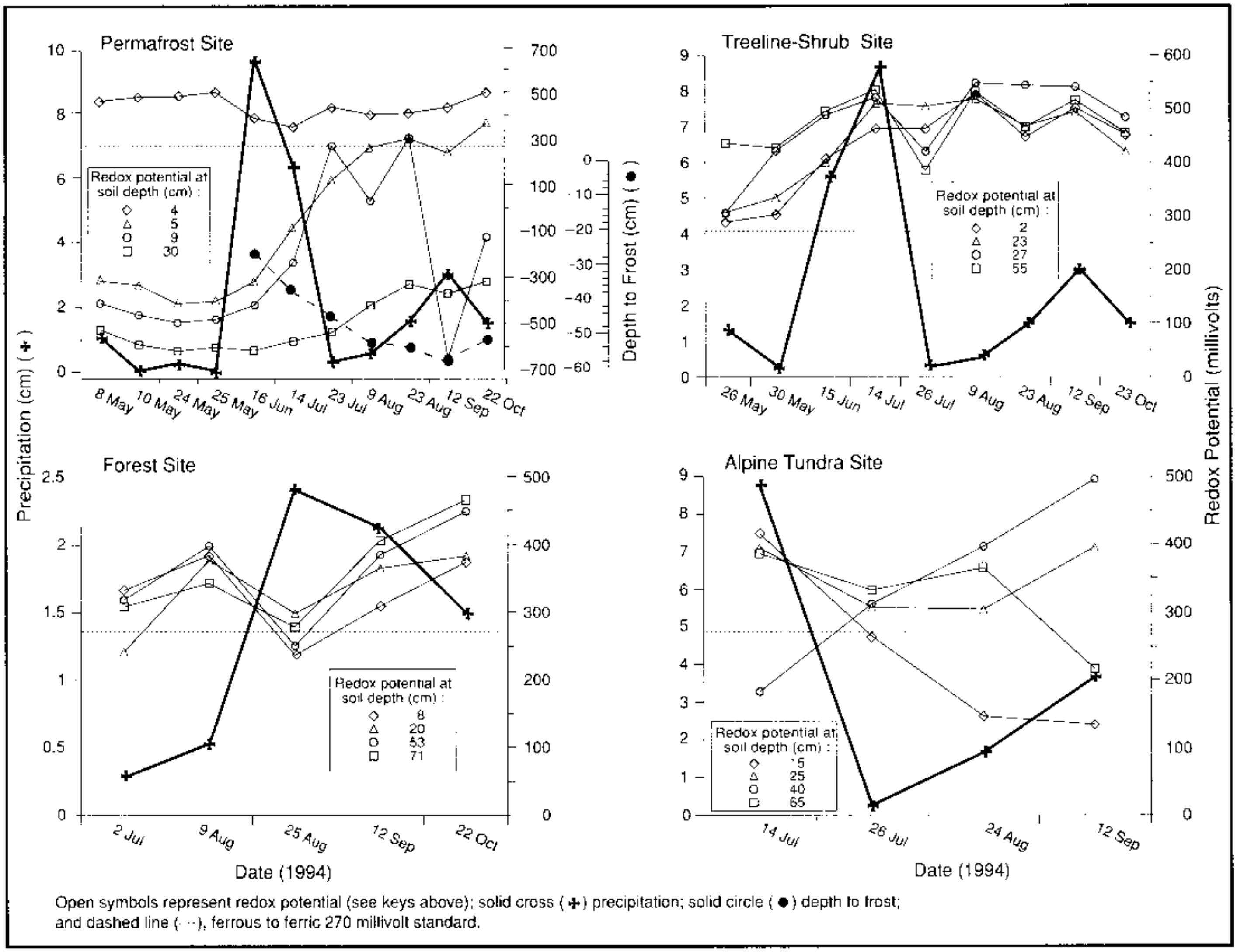

Figure 7. Precipitation and Reduction-Oxidation Potential Records from Rock Creek Monitoring Sites, 1994: Permafrost, Treeline-Shrub, Forest, and Alpine Tundra Habitats (data from Chien-Lu Ping and Greg Probst, this study).

active layer, physical and chemical hydrological properties, and vegetative cover.

Saturation due to perching of the water table above the permafrost creates a reducing environment that controls vegetation type, favoring hydrophilic species (Figure 7). Air penetrates the organic matter, causing an oxidized state on the soil surface. Summer warming increases the permafrost active layer by as much as 30 cm (Figure 7). As depth to permafrost increases, the soil at 5 cm becomes aerated and redox potential changes from 500 millivolts to approximately 300 millivolts. At 20 cm the pattern is similar but less pronounced. Soil heterogeneity and fluctuating soil water level lead to an erratic redox response at 9 cm, indicating greater sampling replication at this depth is necessary.

Our plant inventory for Rock Creek includes 26 species of trees and shrubs, 17 species of grasses, 68 forbs, and 59 species of cryptogams (34 lichens, 25 mosses). These numbers reflect the low plant species diversity of Denali. White spruce growth was 15 percent greater on the forest site compared to the treeline site in 1994 (0.07 ± 0.01 inches/year versus 0.06 ± 0.00 inches/year, respectively). The forest site produced a mean of 182, 214, and 66 cones per white spruce tree, respectively, for the years 1992, 1993, and 1994. The treeline site produced 132, 112, and 22 cones, respectively, for the same years. Forest cone production was 27 percent and 76 percent greater than cone production in the treeline site during the three years. None of the shrubs – blueberry (*Vaccinium uliginosum*), lowbush cranberry (*V. vitis-idaea*), crowberry (*Empetrum nigrum*), bearberry (*Arctostaphylos rubra*), bunchberry (*Cornus canadensis*), and *Geocaulon lividum* – produced more than five berries per plot on the forest site through 1994. Blueberry produced 24 berries per plot on the treeline site, and crowberry produced 93 berries per plot on the tundra site. Crowberry produced less than one and two berries per plot on the forest and treeline sites, respectively. Thus, these data illustrate variation in berry production between shrub species and site.

Twenty-four bird species were sampled at the five MAPS stations (DeSante and Walker, 1994). Capture rates of adult birds, as an index of adult population size, was higher at the less heavily forested stations dominated by willow scrub and lower at the more heavily forested stations dominated by white spruce or riparian alder forest. Percentage of young, as an index of post-fledgling productivity, tended to be inversely correlated with adult population size. Indices of adult population size derived from capture data were significantly correlated with indices of adult population size derived from point count data at four of the five stations.

Understanding the effects of interannual and population irruption of microtine species is only beginning (Emanuelsson, 1984; Pruitt, 1968). Three years of small mammal trapping in Rock Creek habitats indicates high interannual and spatial variability in population densities and productivities, and a general trend for population growth from spring lows to autumn highs (Figure 8). Three species, *Clethrionomys rutilus, Microtus oeconomus,* and *M. miurus* are the most dominant each year. Small mammals were more abundant in 1993 than 1994 in all habitats sampled. Small mammal densities in 1993 were five-seven times greater during early summer to autumn sampling periods in treeline-shrub habitats and eight times greater throughout the research season in forest habitat. Densities remained below 10 animals/hectare throughout 1994. Investigators speculate that above-normal snow pack during the winter of 1992, an early spring breakup in 1993, and good overwinter survival may have contributed to the higher densities observed in 1993. The colder spring in 1994 (Table 1) coupled with heavy rain in June probably affected breeding and subsequent survival of young that year.

CONCLUSIONS

Scaling to Denali's 2.4 million hectares will eventually require the inclusion of other watersheds in the program design. This will occur in combination with a park-wide network of soil and climate monitoring stations, landscape mapping incorporating satellite imagery, and extrapolations from quantitative ecological models in the decision-making process. Our ecosystem monitoring will eventually include higher trophic levels and considerations outside the watershed context. Glacial forces exerted on north-facing landforms of the Alaska Range and Denali landscapes are extreme; thus, expanding the monitoring program to include a larger, glacier-fed watershed would enhance environmental representation and integration. At the small scale, temporal considerations already vary from minutes (temperature) to hundreds of years (carbon cycling). Spatial scales range from centimeters (site-specific) to hundreds of kilometers (climate) to thousands of kilometers (neotropical migratory birds). Clearly, the Denali monitoring program has park, regional, and global components.

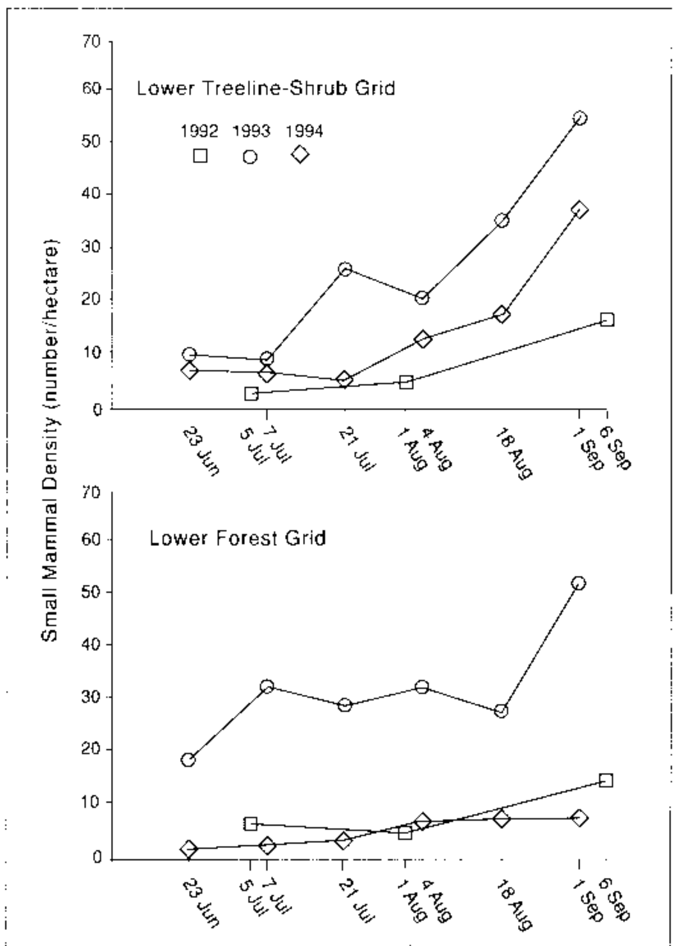

Figure 8. Estimate of Small Mammal Densities in Treeline-Shrub and Forest Habitats of Rock Creek Watershed, 1992-1994 (data from Eric Rexstad and Pamela Furtsch, this study).

TABLE 1. Temperature and Precipitation from May through September 1949-1990 Recorded Near Rock Creek at Denali Park Headquarters, and 1993 and 1994 Recorded at Rock Creek Monitoring Stations.

	Temperature (°C)									Mean Precipitation (cm)		
	1949-1990[1]			1993[2]			1994[2]					
Month	Mean	Min.	Max.	Mean	Min.	Max.	Mean	Min.	Max.	1949-1990[1]	1993[2]	1994[2]
May	5.1	-1.6	11.8	12.5	5.3	15.5	7.5	0.9	14.1	2.0	0.2	0.5
June	10.8	3.9	17.7	11.5	5.3	17.6	11.2	4.8	17.6	6.1	3.3	13.0
July	12.4	5.8	18.9	14.9	8.2	21.6	14.4	7.5	21.2	7.9	6.8	1.9
August	10.4	4.2	16.6	11.0	6.5	15.4	12.6	6.6	18.5	6.0	6.8	4.2
September	4.9	-0.8	10.8	4.5	-0.3	9.3	5.6	0.8	10.4	3.6	9.4	1.0

1. Data provided by U.S. Department of Agriculture, Natural Resources Conservation Service Central Forecasting Service, Portland, Oregon.
2. Data summarized from Denali National Park records.

The research design links data sets from the monitoring program and provides insights into causal mechanisms. For example, the timing of peak stream discharge corresponds to the sum of environmental factors (cloud cover, temperature, precipitation, and sunlight), thus integrating conditions within the catchment. The timing of biological events such as plant green-up, bud burst, bird nesting, and small mammal reproduction is synchronized with spring conditions in the Subarctic. We suggest that spring chronology in Denali can be measured against peak stream discharge, and thus specific dates, not generalized "early," "average," or "late" temporal qualifiers, can be used to "set the clock" and characterize interannual variability in vernal seasonality for Arctic and Subarctic systems.

For example, comparison of the 1993 and 1994 hydrographs (Figure 5) and monthly temperatures and precipitation (Table 1) provides illustration. Local observers considered the spring of 1994 cold, rainy, and late. The hydrographs show peak stream discharge was one month later in 1994 than 1993. Peak flows occurred on May 17 in 1993 (268 cfs) compared to June 19 in 1994 (102 cfs). This corresponds with the mean maximum temperature for May being 1.1°C higher in 1993 than in 1994, and the mean minimum temperature 4.4°C higher. June temperatures were similar in 1993 and 1994.

Precipitation amounts were similar in 1993 and 1994 in May and August, but different in each of the other months (Table 1). Thus, with respect to peak stream discharge, the difference in the hydrographs between the two years was a result of warmer temperatures and earlier snowmelt in spring 1993 compared to the colder temperatures and lack of snowmelt in May 1994, and of greater rainfall and snowmelt in June 1994. Unfortunately, on-site maintenance problems prevented collection of snow pillow measurements for May 1994. Weather and weather observer records indicated the 1993 peak-stream discharge was associated with snowmelt and the 1994 peak to a combination of snowmelt and precipitation.

The contrast between 1993 and 1994 temperatures and precipitation in Rock Creek supports the concept of "late" year in 1994. A closer comparison of weather data in light of the longer historical record from Denali headquarters indicates notable departures from mean temperatures in May 1993 and, to a lesser extent, May 1994 (Table 1). Other months were nearer the long-term average but 1-2°C warmer. Early summer in 1993 was dry, followed by two months of normal rainfall and an extremely wet autumn. May 1994 was dry, followed by almost twice the normal rainfall in June; the rest of the summer was drier than normal.

Preliminary data indicate significant declines in the nesting success of many bird species at Denali in 1994 (DeSante and Walker, 1994). Significant decreases in the CPUE of young-of-the-year birds, an index of annual productivity, were especially notable in ground-nesting species whose nests may have been susceptible to June weather conditions. The productivity of nine of ten ground-nesting species declined from 1993 to 1994, whereas productivity of only three of 13 above-ground-nesting species decreased (X^2 = 7.64, df = 1, P = 0.006). In 1994, the mean date of first capture of young was July 11, and in 1993 it was July 5. DeSante and Walker (1994) suggested a "late" breeding season as a partial explanation for the reduced overall productivity in 1994 (from 71 percent in 1993 to 62 percent in 1994), supporting our observation.

If the timing of peak flow provides an accurate index of initial spring conditions it should be reflected in the timing of key biological events. The relationship is not direct. For example, the date of first nest fledgling, an index of avian reproductive timing, occurred one week, rather than one month, later in 1994 than 1993. However, in the seasonal view, annual estimates showed reduced population survival in 1994, possibly reflecting the poorer environmental quality and corresponding population functional response expected in a "late" year (Figure 9). Further inspection of this data suggests an inverse relationship developing between the timing of peak flow and survival of young birds (r_s = -1.000, $P < 0.0001$, N = 3). Other indices of phenology, such as those for "greenness" derived from on-site measurements and satellite-derived data (e.g., Normal Difference Vegetation Index) will eventually be included in our reference.

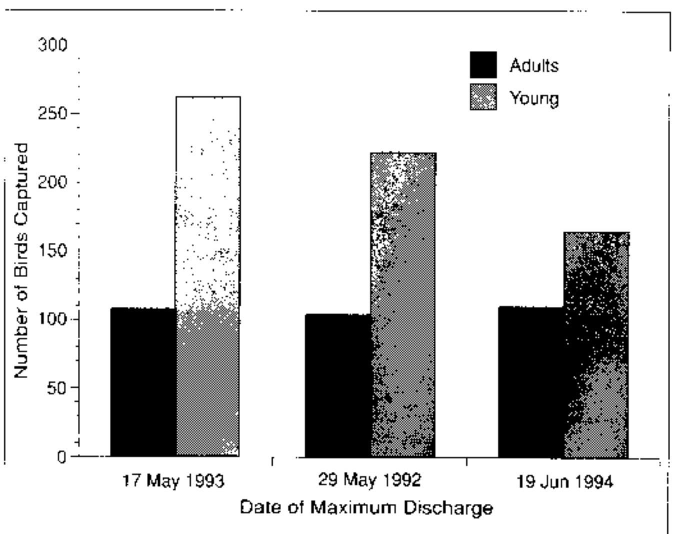

Figure 9. Relationship Between Date of Maximum Rock Creek Discharge and Numbers of Adult and Young Birds Captured in Constant-Effort Mist Netting, 1992-1994 (data from Ken Karle, this study; DeSante *et al.*, 1993; DeSante and Walker, 1994).

The small mammal community of interior Alaska is poorly known. The large numbers and biomass, and high population turnover characteristic of microtines, suggest the tremendous herbivorous influence on the plant community mosaic and high relative importance in predator-prey dynamics. Such relationships have not been adequately described and basic information about population cycling, seasonal dispersals and migrations, habitat use, and social interactions is needed. As an example, Emanuelsson (1984) described microtine grazing on Swedish reindeer ranges in peak years as being under the snow. Crust formation in the snow 5-10 cm above the soil surface causes the rodents to graze only the lower parts of plants, leaving the upper parts frozen into the snow, killing more dwarf-shrubs than were consumed, thus affecting plant species composition. Elsewhere, Pruitt (1968) found the relationship between *M. oeconomus* and the flowering of *Eriophorum* as being similar to that reported for *Lemmus obensus* and *Eriophorum* in the Taimyr Peninsula, Russia. Further, by relating his work to that of Lent (1968), on caribou movements in search of *Eriophorum* flowers, he suggests one could speculate on the effect microtine highs and lows might have on caribou movements. To this speculation, we add the possibility of an effect microtines might have on the population crashes of caribou, a species of tremendous subsistence, sport, and recreational value in the Arctic.

Rainfall quickly results in increased stream discharge, showing the flashy nature of Rock Creek (Figure 10). Water quality data indicate that most ions decrease with increasing stream flow. An exception is nitrogen. Nitrate concentrations increase during storms, suggesting precipitation effects via increased runoff (Figure 11). Our analysis also shows that nitrate concentrations were higher at the upper stream monitoring station adjacent to extensive riparian habitats. We hypothesize that riparian influences, specifically nitrogen-fixing alders, enhance terrestrial inputs of nitrogen during precipitation. This relationship between runoff, stream productivity, and soil water chemistry is currently being investigated. As ground water seeps through alpine tundra, treeline-shrub, and riparian zones, varying quantities of dissolved nutrients are transported into Rock Creek. Soil solution flow rates, nitrogen and phosphorus content, and in-stream algal response are being measured and evaluated by in situ experimentation.

Natural disturbances are the major agents of change in Denali landscapes. Fire and flood frequently have transformed the Rock Creek area to early secondary successional stages. Volcanic ash from Mt. Spurr (about 650 km to the south) dusted the watershed in 1992. Flooding effects on aquatic habitats and processes have been dramatic. The stream, as presently configured, is subject to flash flooding and has poor retentive capabilities for nutrients and organic matter. Primary production is low (100 mg $0_2/m^2$ per day in fall 1993, 1994, and 1995) and appears to be limited by nitrogen and phosphorus (e.g., the greatest algal growth was observed on the clay pots diffusing both P and N) even though riparian contributions of nitrate are significant (Stottlemyer, 1992). The channel bed is poorly colonized (< 1,000 organisms/m^2) and the invertebrate fauna is dominated by chironomids and baetid mayflies. Fish are presently absent from the stream, whereas one resident species (slimy sculpin, *Cottus cognatus*) and two transient species (Arctic char, *Salvelinus alpinus*; and Arctic grayling, *Thymallus arcticus*) were present a decade ago (Miller, 1981).

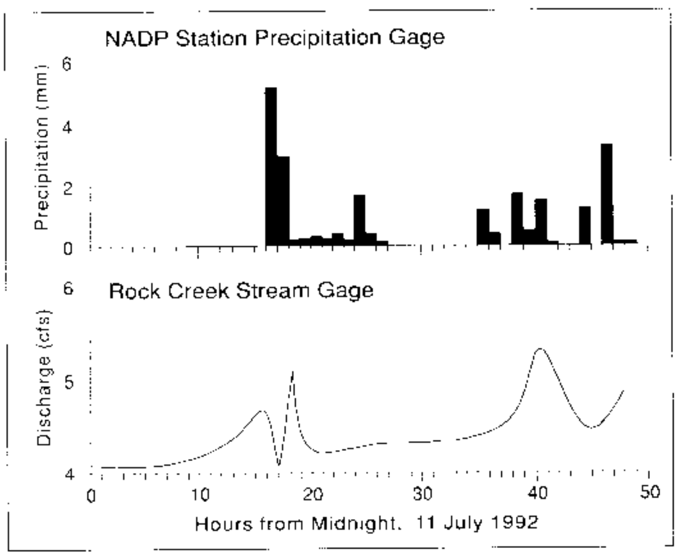

Figure 10. Stream Discharge Response to a Rainstorm on July 11, 1992 at Rock Creek (data from Ken Karle, this study).

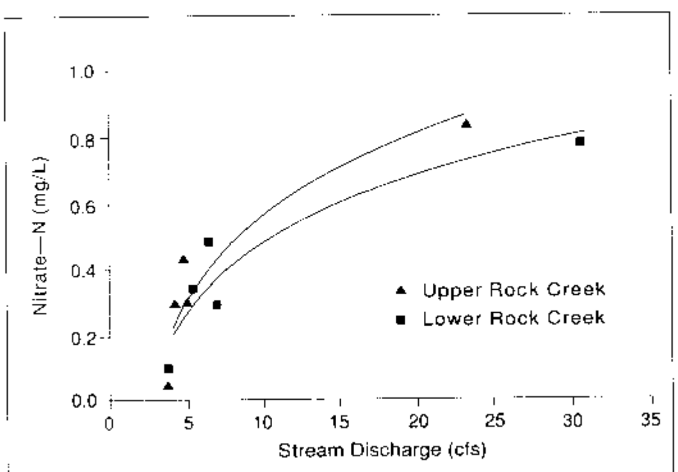

Figure 11. Increase in Streamwater Concentrations of Nitrogen Following the July 11, 1992 Rainstorm at Rock Creek (data from Ken Karle, this study).

In most instances the habitat patterns of the Rock Creek terrain mirror the elevation and moisture gradients of the greater Denali environment. Thus, these habitats play a key role in establishing environmental relationships, designing and testing of methods, and determining the sampling requirements for expansions in landscape coverage. As an example, in addition to MAPS participation, off-road census methods are being developed to evaluate large-scale trends in bird abundance in Denali. Our objective is to conduct enough sampling to have a 90 percent chance of detecting a 2 percent decline in a species' abundance over 25 years. In 1992, a pilot study in Rock Creek watershed provided enough data to evaluate the sampling required to achieve this power in a single watershed, and at a larger scale, in multiple forests located in watersheds along the park road (about 150 km). The power model indicated that increasing spatial scale would require a redistribution of effort, but not a change in total stations occupied. Field sampling in 1993 and 1994 supported this result. By increasing the size of our study area, we increased the diversity of species observed, and the total number of "abundant" species included in the subsequent trend analysis.

FURTHER RESEARCH

Monitoring in a single watershed addresses a limited, but linked, number of ecosystem parameters and attributes including a small portion of the trophic spectrum. Protocol research is aimed at what we believe are the major physical controls on the aquatic, vegetation, land bird, and small mammal community systems we are studying. As this program is implemented in additional watersheds, other wildlife research (e.g., life history, habitat, population dynamics), conducted outside this effort targeting valued natural resources, may eventually lend itself to an expanded application of our design. In Denali the possibilities include gray wolf (*Canis lupus*), grizzly bear (*Ursus arctos*), moose (*Alces alces*), caribou (*Rangifer tarandus*), Dall sheep (*Ovis dalli*), and various birds of prey.

An estimated 17 percent of Denali is covered by glacier ice, an important force in the physical environment of Denali. Glaciers influence hydrological cycles, and are prevalent at the headwaters of many Alaska streams. Oswood *et al.* (1992) estimated that 35 percent of the total runoff in Alaska rivers is from glaciers. These authors, and others (e.g., Mayo, 1991; Mayo *et al.*, 1992), hypothesize that glacial advances and retreats are reliable indicators and "early warning signals" of global climate change. A high priority in our expansion to additional monitoring sites in Denali will be inclusion of a watershed with glacial headwaters. Possible selections include Muldrow, Kahiltna, Traleika, Cantwell, and Polychrome glaciers, where long-term studies of glacier movements are already underway (Figure 2).

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