Biocomplexity associated with biogeochemical cycles in arctic frost-boil ecosystems

Principal Investigator:
Donald A. Walker
Institute of Arctic Biology and Department of Biology and Wildlife, University of Alaska Fairbanks, Fairbanks, Alaska 99775, 907-474-2460, ffdaw@uaf.edu

Senior Personnel:
Howard E. Epstein
Department of Environmental Science, University of Virginia, Clark Hall 207, Charlottesville, VA 22904-4123, 804-924-4308, hee2b@virginia.edu

William A. Gould
International Institut of Tropical Forestry, USDA Forest Service, P.O. Box 25000, San Juan, PR 00928-02500, 787-766-5335, iitf_coop@upr.edu

William B. Krantz
Department of Chemical Engineering, University of Cincinnati, Cincinnati, OH 45221-0171, 513-556-4021, bkrantz@alpha.che.uc.edu

Rorik Peterson
Geophysical Institute and Department of Geology and Geophysics, University of Alaska Fairbanks, Alaska, 99775, 907-474-7459, ffver@uaf.edu

Chien-Lu Ping
Palmer Research Center, University of Alaska Fairbanks, Palmer, AK 99645, 907-746-9462, pfclp@uaa.alaska.edu

Vladimir E. Romanovsky
Geophysical Institute and Department of Geology and Geophysics, University of Alaska Fairbanks, AK, 99775, 907-474-7459, ffver@uaf.edu

Marilyn D. Walker
Cooperative Forestry Resaerch Unit, University of Alaska Fairbanks, AK, 99775-6780, 907-474-2424, mwalker@nrm.salrm.uaf.edu

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BIOCOMPLEXITY ASSOCIATED WITH BIOGEOCHEMICAL CYCLES IN ARCTIC FROST-BOIL ECOSYSTEMS

A PROJECT SUMMARY

The central goal of this project is to understand the complex linkages between biogeochemical cycles, vegetation, disturbance, and climate across the full summer temperature gradient in the Arctic in order to better predict ecosystem responses to changing climate. We focus on frost-boils because: (1) The processes that are involved in the self-organization of these landforms drive biogeochemical cycling and vegetation succession of extensive arctic ecosystems. (2) These ecosystems contain perhaps the most diverse and ecologically important zonal ecosystems in the Arctic and are important to global carbon budgets. (3) The complex ecological relationships between patterned-ground formation, biogeochemical cycles, and vegetation and the significance of these relationships at multiple scales have not been studied. (4) The responses of the system to changes in temperature are likely to be nonlinear, but can be understood and modeled by examining the relative strengths of feedbacks between the components of the system at several sites along the natural arctic temperature gradient. We propose to examine disturbed and undisturbed patches associated with frost-boil ecosystems, from polar deserts of northern Canada to shrub tundra systems in Alaska. Frost boils are caused by soil heave in small, regularly spaced, circular highly disturbed patches, 1-3 m in diameter. The processes of frost-boil formation is currently poorly understood, so full knowledge of the biogeochemical system first requires a better understanding of the process of frost heave itself and how it is modified by interactions with climate and vegetation. A recent Differential-Frost-Heave (DFH) model by Peterson and Krantz provides considerable insight to the self-organization processes in frost boils. This physically based model can predict many phenomena associated with frost boils including the amount of heave, spacing and size of the boils. Early model results suggest that the ground-surface temperature is a primary control of frost-boil formation. Vegetation and/or snow cover can constrain the development of frost boils by insulating the soils. Climate and the level of disturbance caused by frost heave strongly influence the rate of organic-matter accumulation and biogeochemical cycles within the tundra soils. We will examine the full implications of this interaction by studying how frost heave affects nitrogen and carbon pools and rates of nitrogen mineralization along the climate gradient. We propose to answer six major questions related to the biocomplexity of frost-boil ecosystems: *(1) How does the self-organization associated with frost boils occur? (2) How does the frost heave affect the soil biogeochemical processes within and between the frost boils? (3) How do frost heave and biogeochemical processes affect plant communities? (4) How do the biological processes in turn feed back to control frost heave? (5) How do interactions between biogeochemistry, cryotrubation and vegetation change along the existing arctic climate gradient? (6) How do the complex patterns associated with frost boils affect the tundra systems in a hierarchy of spatial-temporal scales?* The response of the system to summer temperature is nonlinear. We propose to dissolve the complex system into linear models by examining the relationship between frost heave, carbon, nitrogen, and vegetation at a series of sites within five bioclimatic subzones along the temperature gradient. We will use ordination, path analysis, and information theory to examine the complex multivariate relationships between biogeochemistry, cryotrubation, vegetation, and the environment. We hypothesize that zonal sites in areas with intermediate summer warmth should have the highest measures of several key ecosystem functions (e.g., mineralization rates, nitrogen pools, biodiversity). In years 1 and 2, the field studies will focus along the Dalton Highway in northern Alaska. This region is well known and provides an exceptional opportunity because it has a particularly sharp boundary that demarcates essentially High-Arctic soils with abundant frost boils from Low Arctic soils with few frost boils. Extensive ecosystem, snow, and ground-temperature data are available from several sites in this region. In years 2, 3 and 4, we will extend the research into more remote areas in the Canadian Arctic where there are colder bioclimate subzones not represented in northern Alaska. To arrive at a predictive capability for biogeochemical response and plant community formation, we will use output from the DFH model to help parameterize a vegetation-change model (ArcVeg). The project has four research components: (1) Frost Boil Dynamics and Climate, (2) Soil and Biogeochemistry, (3) Vegetation, and (4) Modeling Nutrient and Vegetation Dynamics. We also propose a major educational component of the study. Students, as part of Dr. Bill Gould's Arctic Field Ecology course, will interact with the scientists. They will be actively engaged in the research activities as part of expeditions that will allow them to study biocomplexity in the Arctic. We are also proposing to host an arctic biocomplexity workshop early in the project and a synthesis workshop in Year 4.

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C PROJECT DESCRIPTION

C.1 RESULTS OF PRIOR NSF SUPPORT (SEE STARRED (*) REFERENCES SECTION D.1. FOR PUBLICATIONS RESULTING FROM THESE AWARDS)

1. Arctic Climate Change, Substrate, and Vegetation, OPP-9908829, $1,670,001, 7/1/99 - 6/30/03, D.A. Walker, PI, W.A. Gould and H. Epstein, Co-PIs

This project is part of the Land-Atmosphere-Ice Interactions (LAII) Arctic Transitions in the Land-Atmosphere System (ATLAS) study. The primary goal of the overall project is characterization of the fluxes of energy, water, and trace gases in the Arctic. Our component of these studies involve mapping the vegetation of the circumpolar Arctic (Gould et al. Submitted 2001; Markon and Walker 2000; Muller et al. 1999; Muller et al. 1998; Walker 1999; Walker 2000) and characterizing the vegetation, soil, and spectral reflectance patterns in relationship to zonal vegetation boundaries in the Arctic (Copass et al. 2000; Riedel et al. 2000; Walker et al. 1998; Walker et al. 2001b). The most significant finding was the large differences in many key ecosystem processes between moist nonacidic tundra (MNT) and moist acidic tundra (MAT) (Walker et al. 1998) (Table 1). Soils in moist nonacidic areas have about half the carbon storage and twice the depth of thaw of moist acidic areas (Ping et al. 1998). We and other investigators have found major differences in soil heat flux (Nelson et al. 1998), evapotranspiration, respiration, gross primary production and trace gas fluxes (Chapin et al. 2000; Fahnestock et al. 1998; Jones et al. 1998; Reeburgh et al. 1998; Walker et al. 1998), spectral properties (Jia et al. Submitted, 2001) cryoturbation (Bockheim and Tarnocai 1998), snow cover (Walker et al. 2001a), wildlife habitat (Walker et al. 2001b), and the effects of disturbance (Auerbach et al. 1997). These studies have direct relevance to the proposed work because of the discovery of the important role that frost boils play in these globally important ecosystems. The proposed research would examine the underlying physical, chemical, and biological processes associated with frost boils, which are thought to be one of the primary factors involved in maintaining high soil pH in MNT ecosystems.

TABLE 1. COMPARISON OF ECOSYSTEM PROPERTIES OF MNT AND MAT (Walker et al. 1998)

Ecosystem Property	MNT	MAT
pH of top mineral horizon	6.9	5.2
Number of vascular plant species	26	14
Average height of plant canopy (cm)	3.9	6.5
Leaf area index (m^2 m^{-2})	0.50	0.84
Moss cover (%)	65	79
NDVI	0.28	0.41
O-horizon thickness (cm)	11	21
Bare soil (% cover)	7.5	0.8
Soil heat flux (MJ m^{-2} d^{-1})	3.13	1.83
Thaw depth (cm)	52	39
Gross primary production (mg CO_2-C m^{-2} d^{-1})	940	1820
Net CO_2 uptake	670	950
Respiration loss	270	870
Methane emission (mg CH_4 cm^{-2} y^{-1})	69	449
Soil organic carbon to 1 m depth (kg C m^{-3})	40	88
Soil Ca in active layer (mol (+) m^{-2})	400	35

2. A framework for integrating field education, research, and traditional ecological knowledge (TEK) in undergraduate field courses in ecology. DGE-9906474, $51,000/yr, 9/1/99-8/21/01. W.A. Gould. PI.

This funding is a Postdoctoral Fellowship in Mathematics, Science, and Engineering Education specifically designed to develop innovative ways to integrate research, undergraduate education, and Inuit people in the Arctic. These are specific components that we hope to integrate with the research agenda of this proposal. The project involved six sections of field courses in ecology for the Canadian Arctic and the Caribbean. Two sections (1999-2000) involved teaching and research on the relationships of vegetation, topography and soil organisms and the involvement of local Inuit elders from the village of Umingmaktuuq. A third section (1999) integrated students in *Arctic Field Ecology* with scientists from the United States, Canada, Germany, Russia, and Norway on a 2000 mile transect along the complete climate gradient found in the Canadian Arctic. Fourth and fifth sections will be offered this upcoming summer (2001) with increased Inuit involvement. A sixth section will be offered (2001) integrating tropical research and local ecological knowledge in the Caribbean. Eight Inuit partners have been hired to assist in teaching, translation, and logistics for the Arctic field courses in Nunavut, Canada. Sixty undergraduate and graduate students have been involved between 1999 and 2001.

C.2 INTRODUCTION

We seek to understand the complex linkages between biogeochemical cycles, vegetation, disturbance, and climate across the full summer-temperature gradient in the Arctic in order to better predict ecosystem reponses to changing climate. We focus on frost-boils (Figure 1) because: (1) The processes that are involved in the self-organization of these landforms drive biogeochemical cycling and vegetation succession of extensive arctic ecosystems. (2) These ecosystems contain perhaps the most diverse and ecologically important zonal ecosystems in the Arctic and are important to global carbon budgets. (3) The complex ecological relationships between patterned-ground formation, biogeochemical cycles, and vegetation and the significance of these relationships at multiple scales have not been studied. (4) The responses of the system to changes in temperature are likely to be nonlinear, but can be understood and modeled by examining the relative strengths of feedbacks between the components of the system at several sites along the natural arctic temperature gradient.

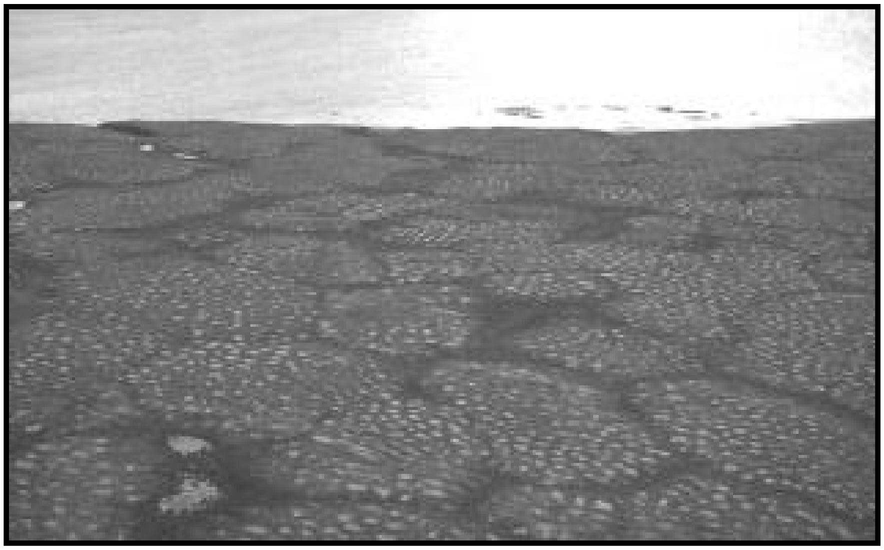


Figure1. (a) Aerial view of frost boils overlaid on a field of ice-wedge polygons on Howe Island, northern Alaska. Characteristic diameter of the ice-wedge polygons is 10-15 m, and diameter of the frost boils is 1-1.5 m. (b) Frost boil with garden-like vegetation consisting of *Saxifraga oppositifolia, Chrysanthemum integrifolia, and Bryum wrightii,* with Dr. Bill Steere collecting *Bryum wrightii,* a rare moss characteristic of frost boils. Note the relatively barren portion of the active frost boil, hummocky ring around the frost boil, and the well-vegetated inter-frost-boil area, all of which contribute to the diversity within frost-boil ecosystems.

A full understanding of biogecochemical processes in relation to substrate, climate, and vegetation is essential for accurate prediction of the response of global ecosystems to climate change. Arctic tundra ecosystems are thought to be particularly vulnerable to climate change (Everett and Fitzharris 1998). Understanding carbon and nitrogen cycling in relationship to climate, vegetation, and disturbance has been the focus of much arctic terrestrial ecosystem research because of the implications for vegetation change and consequences to trace-gas, energy, and water budgets (Chapin et al. 1997; Oechel et al. 1997; Rastetter and Shaver 1992; Shaver et al. 1992; Weller et al. 1995). There is growing consensus that the Arctic will experience marked changes in precipitation, temperature, and the timing of seasonal climate events (National Assessment Synthesis Team 2000). Because of a variety of feedback mechanisms, arctic ecosystems will likely respond rapidly and more severely than any other area on earth. Furthermore, the changes in Arctic climate will affect other parts of the world through changes in sea level, decreased oceanic heat transport and increased emissions of greenhouse gases from thawing permafrost (Everett and Fitzharris 1998). The magnitude and direction of changes to arctic terrestrial ecosystems are still far from clear, primarily because of uncertainty regarding magnitude and direction of hydrological changes and rate of decomposition of peat in response to temperature rise (Oechel, et al., 1997; Chapin, 1997; McKane, 1997).

As one moves from north to south along the arctic climate gradient, from the polar deserts to shrub tundra near treeline, the mean July temperature increases from about 2˚C to 12˚C, and the amount of carbon in the upper meter of soil on zonal sites increases by a factor of about 50 (Bockheim et al. 1996; Lacelle et al. 2000). Most ecosystem research in the United States has focused in the Low Arctic, the region south of about the 7˚C mean July isotherm.

Here, the soils have large stores of carbon and nutrients bound in the peat and frozen in permafrost. This carbon is of concern in studies of global climate because it represents a possible source of additional greenhouse gases to the atmosphere (McKane et al. 1997a; McKane et al. 1997b; Shaver et al. 1992). High arctic regions have received less attention because they are perceived to be of less concern with respect to possible sources of CO_2. However, they represent a large part of the Arctic, where there is relatively little information on soil processes. If climate warms sufficiently, the High Arctic could become a major sink for carbon as vegetation carpets expand and soil carbon reserves grow. The soil organic material is also a source of nitrogen, which is an essential nutrient for plant growth. Climate change could promote changes in the availability of nitrogen because of increases in heterotrophic respiration (Rastetter et al. 1991). If the availability of nitrogen increases in the soil, particularly in areas with extremely low soil nitrogen, plant growth would be promoted.

In this proposal we will focus on two aspects of arctic biogeochemical cycles that have received relatively little attention. (1) *Cryoturbation* is disturbance to the soil caused by ice formation. The effects of cryoturbation on biogeochemical cycles and ecosystem processes have not been studied. Frost boils are a common form of cryoturbation (Figure 1), and the ecosystems associated with these patterned-ground features offer a unique opportunity to study the complex interactions between biogeochemical cycles, climate, natural disturbances, and plant-community formation in extreme environments. (2) *The influence of the plant canopy on soil temperature* is critically important to cryoturbation and biogeochemical soil processes. Organic material in the soils and plants is complexly related to its own decomposition through the control it exerts on soil temperatures. Organic horizons insulate the soil, and lower the summer temperatures at rooting depths. Soil temperatures do not follow the same trend as air temperatures because of the influence of vegetation. Although air temperatures increase as one moves southward along the climate gradient, soil temperatures and active layers (the near-surface portion of the soil that is seasonally thawed) decrease in some parts of the same gradient. This is caused by the insulating influence of organic material (soil and moss), and also the shading caused by taller, more-dense plant canopies (Nelson et al. 1998). In frost-boil ecosystems, the contrast between barren, nearly unvegetated, frost boils and the vegetated areas between the frost boils provides an opportunity to examine the complex interactions between the vegetation canopy, soil temperature, cryoturbation, and biogeochemical cycles.

C.2.1 Overview of the study design, project components, and organization of this proposal

We will examine the following key questions: ***(1) How does the self-organization associated with frost boils occur? (2) How does frost heave affect soil biogeochemical processes within and between the frost boils? (3) How do frost heave and biogeochemical processes affect plant communities? (4) How do the vegetation and biogeochemical cycles in turn feed back to control frost heave? (5) How do biogeochemistry, cryoturbation, and vegetation change along the existing arctic climate gradient? (6) How do the complex patterns associated with frost boils affect tundra systems in a hierarchy of spatial-temporal scales?*** The project is divided into six components, four research components, an education component, and a coordination and data management component. Table 2 summarizes the components, investigators, major questions, and the approaches that will be used to address the questions. We first present an overview of the three main biocomplexity issues that will be addressed: (1) self-organization of frost boils, (2) interactions between biogeochemical cycles, cryoturbation, vegetation and climate, and (3) biocomplexity across spatial temporal scales. We then discuss the global significance of the research. Finally, we describe each of the components of the project in more detail.

Table 1. Project Components, Questions, and Approaches.

Component (Investigators)	Questions	Approach
I. Frost-boil dynamics and climate (Peterson, Krantz, Romanovsky)	1. How does the self-organization associated with frost boils occur? 2. How do the biological processes and climate change feed back to control the formation of frost boils?	1a. Develop the Differential Frost Heave (DFH) Model based on field observations. 1b. Test and validate the DFH model using laboratory frost-heave experiments. 2a Parameterize the DFH model using different soil surface temperatures and climates. 2b. Validate the model with field experiments (removal of vegetation mat and snow-fence experiment).
II. Soils and Biogeochemistry (Ping, Epstein, Michaelson, Romanovsky)	3. How does frost heave affect biogeochemical processes within and between the frost boils?	3a. Examine soil physical and biogeochemical characteristics along gradients of frost-heave activity and climate. 3b. Examine vertical and horizontal gradients of geochemical trends within frost boils. 3c. Paleo-analysis of frost-boil and inter-frost-boil organic layers.
III. Vegetation (D. Walker, Epstein, Gould, Knudson,	4. How do biogeochemisty and cryoturbation affect plant communities?	4a. Classify the plant communities within and between frost boils along the arctic climate gradient using the Braun-Blanquet approach. 4b. Perform ordination analyses relating stands, plant functional types (PFTs) and

Raynolds, M. Walker)	5. How do the complex patterns associated with frost boils affect the tundra systems in a hierarchy of spatial-temporal scales?	species to site factors. 5a. Map plants, plant communities, and plant-community complexes in a hierarchy of spatial scales (individual frost boils, frost-boil complexes, and regional landscapes). 5b. Examine measures of total ecosystem function (e.g., biomass, leaf-area index, and Normalized Difference Vegetation Index) along the climate gradient.
IV.Modeling nutrient and vegetation dynamics (H. Epstein, M. Walker)	6. How do these patterns and processes change along the existing climate gradient as the pool of available species and plant functional types (PFTs) changes?	6. Use the ArcVeg model to examine the effects of different nutrient pools, PFTs, climate, and disturbance regimes.
V. Education (Gould)	7. Questions will be developed by the classes.	7. Class projects will be developed during the Arctic Field Ecology course.
VI. Coordination and Data Management (Walker, Knudson, Maier)	None	8a. Central data management at NEAML with metadata and data archived through JOSS and ADCC. 8b. Spatial data managed through NEAML. 3c. Arctic tundra biocomplexity workshops.

C.2.2 Biocomplexity of frost-boil ecosystems

Although frost boils have been studied extensively by geomorphologists and permafrost scientists, the process of their formation is still not known, and their role in ecosystem dynamics has not been studied to any significant extent. We will examine threee aspects of biocomplexity associated with frost-boil ecosystems:

C.2.2.1 Complexity associated with self-organization in frost boils

Full knowledge of the biogeochemical cycles within frost-boil ecosystems first requires a better understanding of the process of frost heave itself and how it is modified by interactions with climate and vegetation. Ice lenses are responsible for the process of *frost heave.* A recent Differential-Frost-Heave (DFH) model (Peterson and Krantz 1998) provides considerable insight to how ice-lens formation leads to the self-organization of frost boils. The DFH model is a physically based model that can predict many phenomena associated with frost boils, including the amount of heave, spacing, and size of the boils. Early model results suggest that ground-surface temperature is a primary control of frost-boil formation. We will model how self-organization occurs within the frost boils themselves and how this creates the circular frost boils and the patterned-ground mosaics that are so common in the Arctic. We will use the DFH model to examine the process of frost-boil formation (see Section C.3, Component I, Frost Boil Dynamics, Climate and Permafrost). One of our major foci will be the role of soil surface temperature in constraining the frost-heave process. Soil surface temperature is only partially a product of the regional climate. It is also strongly influenced by the vegetation mat and/or snow cover, both of which can decrease the heat flux to the soil surface and buffer the process of frost heave.

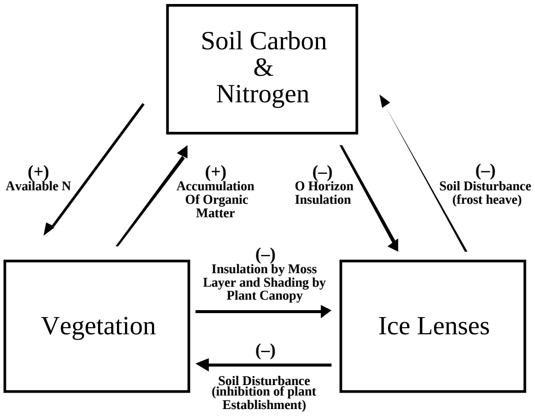
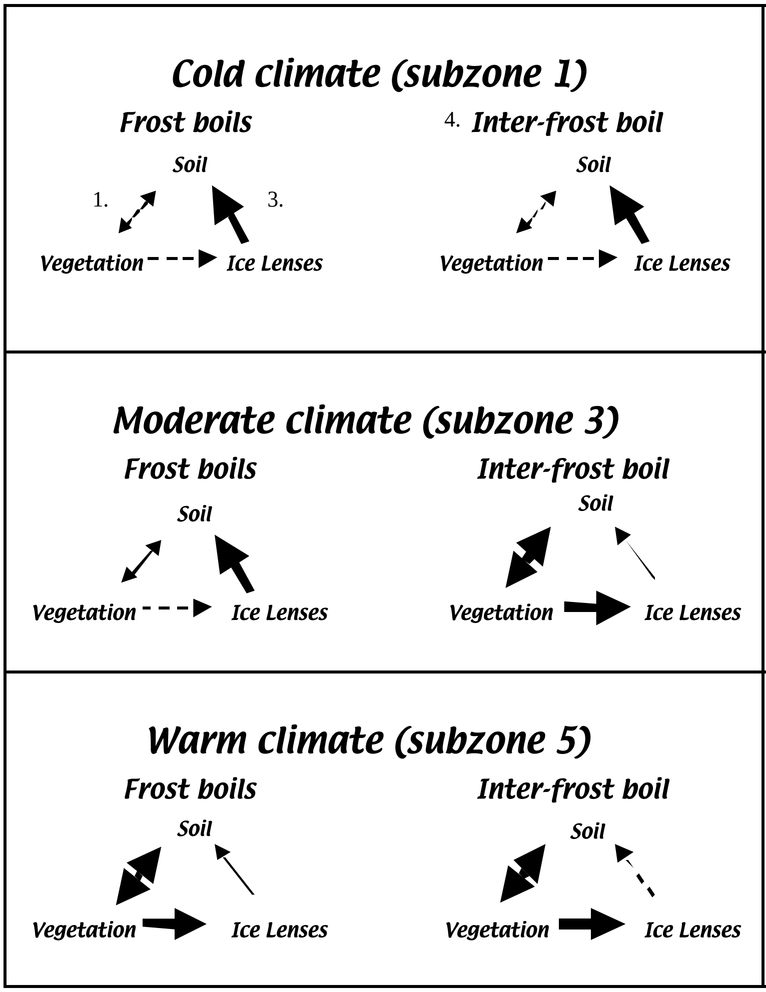


Figure 2. Interactions between key components of the frost boil ecosystem. Each subsystem is closely linked to the others, with either positive or negative effects (as indicated). The soil carbon and nitrogen are negatively influenced by ice-lens formation, which disturbs the soil, aerates it, promotes decomposition and limits the buildup of organic matter in the soil. Soil carbon, mainly in the form of thick organic horizons, negatively affects ice-lens formation through insulation of the soil. Soil carbon pools are positively influenced by the development of a vegetative mat because this is the primary source of carbon. There is a positive feedback promoting development of the vegetation mat through mineralization of organic matter to form available nitrogen, an essential plant nutrient. The vegetation negatively influences the formation of ice lenses through insulation provided by the moss layer and shading by the plant canopy, and ice lens formation has a negative influence on vegetation by inhibition of seedling

C.2.2.2 Complexity associated with interactions between biogeochemical cycles, cryoturbation , and vegetation

We will examine interactions between three major subcomponents of the frost-boil system: soil (focusing on the C and N cycles), vegetation, and ice. A simple triangular diagram summarizes the major linkages between these components (**Figures 2)**. We are interested in how the interactions between these subcomponents vary along a climate gradient from the coldest parts of the Arctic to the arctic treeline **(Figure 3)**. *We hypothesize that the best developed frost-boil systems should occur in intermediate areas of the climate gradient (i.e., Subzone 3, the typical tundra subzone of the Russian literature* (Chernov and Matveyeva 1997)*)*. In this region, summer warmth is sufficient to develop deep active layers on barren frost boils, but there is also sufficient vegetative activity to develop diverse closed mats of vegetation between the frost boils. This combination maximizes the contrast between the



Explanation

1. Little or no soil organic matter build up and no real plant succession.
2. Cold dry climate allows few plant species to form complex plant communities, so vegetation places few constraints on heat flux.
3. Cold climate allows only moderate active layer development and frost heave.
4. Little contrast between frost boils and inter-frost boil areas.

1. Incipient soil formation in frost boils, with high disturbance, low nutrient pools, and very slow or no vegetation succession. Inter-frost-boil areas have thick organic layers and large nutrient pools.
2. Moderate climate allows larger pool of plant species, but vegetation places few constraints on heat flux in scars. Larger constraints in inter-frost-boil areas where soils are stable.
3. Maximum development of frost heave in frost boils, but low levels of heave in inter-boil areas.
4. Maximum contrast between frost boils and inter-boil areas.

1. Maximum organic layer development, and well-developed plant canopies, but cold wet soils limit annual production.
2. Warm climate allows complex plant communities to form on frost boils and inter-frost-boil areas, constraining heat flux in both sites.
3. Limited frost heave in both frost boils and inter-frost boil areas.
4. Little contrast between frost boils and inter-frost boil areas.

Figure 3. Hypothesized strength of interactions between subsystems of frost-boil ecosystems along the arctic climate gradient in three of the five subzones (Walker 2000). Explanation of numbers in top diagram: (1) The interactions between soil and vegetation are mainly feedbacks involving disturbance regimes and organic-matter buildup and development of nutrient pools. (2) The interaction between vegetation and ice lenses are mainly constraints on heat flux due to the insulating vegetation mat. (3) The interaction between the ice lenses and soil represents frost heave. (4) Contrasts between the frost-boil and inter-frost-boil areas vary along the climate gradient and are maximum in the intermediate climate of Subzone 3. Only three subzones are shown. The project will analyze five subzones. Note that physical processes (between ice and soil) dominate in the colder subsone, whereas biological interactions (those involving vegetation) are dominant in the the warmest subzone.

frost boils and the areas between the boils, and forms diverse landscapes with high biodiversity. In very cold regions of the temperature gradient, we should see a dominance of the physical components of the system, with sparse vegetation on both the frost boils and inter-frost-boil areas, and little contrast in the heat-flux properties, and hence poorly developed patterns of frost boils. At the other extreme, in the warmest areas of the Arctic, there is also little contrast in heat flux between the frost boils and the areas between the frost boils. But here the biological component is dominant. The abundant vegetation insulates the frost boils and effectively shuts off frost heave. We also should see maximum nitrogen mineralization in the intermediate areas because the soils are sufficiently warm to promote active biological activity. Further south the insulating moss carpet cools the soils and limits mineralization. Further north, there is insufficient soil organic matter to provide a substrate for significant heterotrophic respiration (See **Figure 3** for more details of this hypothesis).

C.2.2.3 Biocomplexity across spatial-temporal scales

An explicit consideration of scale is critical to developing an adequate concept of how frost-boil ecosystems function internally and as part of larger systems (Allen and Hoekstra 1990; Allen and Starr 1982; Maurer 1999; O'Neill et al. 1989; Urban et al. 1987; Walker and Walker 1991; Walker 1996). **Figure 4** shows the spatial-temporal scale of the frost-boil systems operating at different process rates in relationship to the domain of DFH

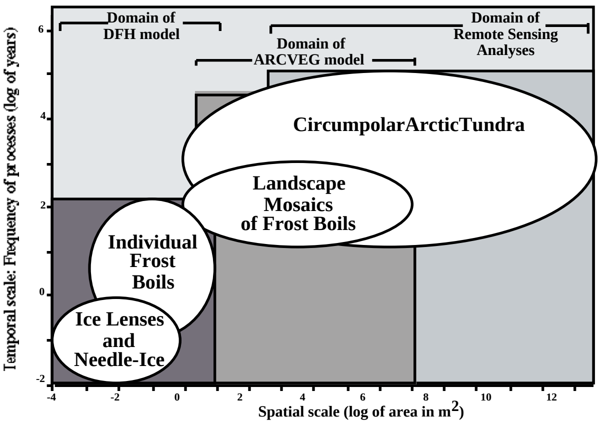


Figure 4. Spatial-temporal scales of frost-boil-related systems operating at different process rates.

and ArcVeg models and the remote sensing studies. Integrated measures of total ecosystem function (total system parameters of O'Neill et al. 1989) have proved useful for examining processes across a wide range of spatial and temporal scales. Examples include the measurement of atmospheric CO_2 fluxes at multiple scales (Oechel et al. 1998), stream flow and watershed chemistry (Likens et al. 1970), and high resolution studies of trace gases and airborne chemicals in ice cores (Alley et al. 1996; Mayewski et al. 1997). One of the most promising methods to detect change in biological systems across a broad range of spatial scales is the use of Earth orbiting satellites to collect time series of spectral reflectance data (Myneni et al. 1997). The vegetation greenness during summer can be measured using a variety of vegetation indices. The Normalized Difference Vegetation Index (NDVI[1]) has been the most widely applied index and has been correlated with a variety of biophysical parameters, including biomass, leaf-area index (LAI), intercepted photosynthetically active radiation (IPAR), and fluxes of trace gases (Shippert 1997; Stow et al. 1998). We will study spectral reflectance and biophysical properties over large areas commensurate with drainage systems or atmospheric systems. This builds on our earlier research in the Low Arctic of northern Alaska. We found a clear correspondence between total available summer warmth, NDVI, LAI, and biomass on zonal sites (Copass et al. 2000; Jia et al. 2000; Riedel et al. 2000; Walker et al. 1995a; Walker et al. 2000). Here, we propose to extend the transect into the High Arctic with three additional sites in Canada. We will use NDVI as a surrogate for total ecosystem function in combination with ground studies of biomass and leaf area index.

C.2.3 Significance of frost-boil ecosystems to the circumpolar Arctic and global system

Small-scale physical processes associated with ice-lens formation have complex biogeochemical consequences at plot, landscape, regional, and global scales (**Figure 5**). Recent studies in the Kuparuk River Basin of Alaska show that frost boils in this region are positively associated with vegetation types that occur on soils with relatively high soil pH (Bockheim et al. 1996; Nelson et al. 1998; Walker et al. 1998). In Russia, the term “spotty tundra” is sometimes used to characterize the Arctic bioclimatic subzone where frost boils are dominant. This name is derived from the abundant “spots” or disturbed patches caused by frost boils that dot the landscapes (see Figure 1) (Alexandrova 1980). Cryoturbation is thought to be largely responsible for maintaining high soil pH because it continually refreshes the soil surface with nutrient-rich subsoils. In the absence of cryoturbation, soils tend to become wet and

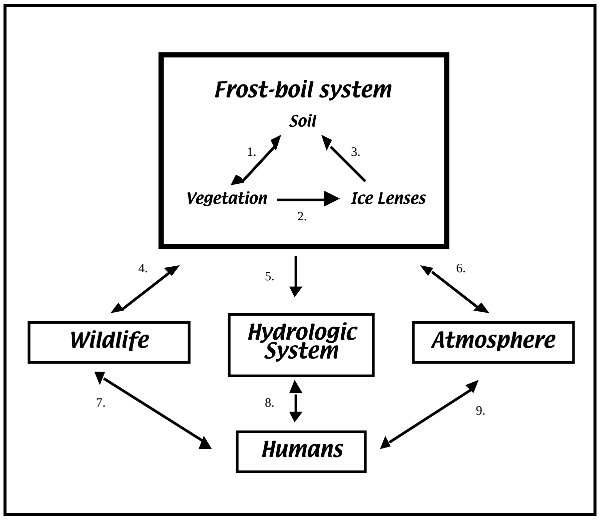


Figure 5. Linkages between the frost-boil system and key elements of the greater arctic ecosystem and biosphere. Arrows showing the linkages between subsystem components *within* the frost-boil system represent: (1) Interactions between soil and vegetation, consisting primarily of feedbacks involving disturbance regimes, organic-matter buildup and development of nutrient pools; (2) Interactions between vegetation and ice lenses, consisting primarily of constraints on heat flux due to the insulating vegetation mat; (3) Interactions between ice lenses and soil, resulting in frost heave. The linkages with the greater arctic system are: (4) effects on forage quality and wildlife habitat, (5) effects on water flux and water quality, and (6) fluxes of energy and trace gases to the atmosphere. These components have important interactions with humans through their effects on: (7) availability of game, (8) fish and water resources, and (9) air quality and feedbacks to the atmosphere influencing climate change.

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[1] NDVI = (NIR - R)/(NIR + R), where NIR is the spectral reflectance in the near-infrared (0.725 to 1.1 µm), where light scattering from the canopy dominates, and R is the reflectance in the red chlorophyll-absorbing portion of the spectrum (0.58 to 0.68 µm). The NDVI varies between -1 and 1, and is related to the amount of chlorophyll in the plant canopy with minimized contribution from background sources. Globally, it is considered a surrogate of green biomass (Goward et al., 1985).

acidify under the influence of organic-matter accumulation and leaching. Furthermore, the physical movement of soils involved with forming frost boils disrupts the accumulation of mosses and organic material. The development of thick organic layers, particularly moss accumulation, apparently shuts off frost-boil formation. Once this happens, the soils are much colder during the summer months and warmer during the winter months because of the insulative organic mat.

Climate is generally perceived to be the major determinant of global and arctic vegetation structure and composition. However, soil factors affect estimates of regional productivity of arctic regions by factors of four in some cases (Gilmanov 1997). This is greater than estimated effects due to anticipated climate change scenarios. Regionally, geology, substrate, and soils play very large roles in ecosystem response (Esser et al. 1982). The control exerted by the underlying geological substrates and periglacial landforms, and the effects these have on key biogeochemical cycles are key to understanding regional ecosystem response to climate change (Walker 2000). Two of the most extensive vegetation types in the Arctic are moist acidic tundra (MAT) and moist nonacidic tundra (MNT). These two types dominate much of the well-vegetated portion of the Low Arctic, but they have very different biophysical properties that are important to global carbon and trace gas budgets (Walker et al. 1998) (see Section C.1, Results of Prior Support). There is not a clear understanding of the cause of their different properties. There are also no maps of the global distribution of these types; nor is there an understanding of the consequences to patterns of production and biomass. Frost boils are thought to be a primary factor controlling the high soil pH in most MNT ecosystems (Bockheim et al. 1998; Walker et al. 1998). So in order to extrapolate the results of the new information regionally and globally, a clearer understanding of the underlying causes of frost boils and their ecosystem consequences is needed.

C.3 Component I: Frost-boil dynamics and climate (Rorik Peterson, Bill Krantz, Vladimir Romanovsky)

C.3.1 Introduction

Frost boils are a form of patterned ground that is due to a type of self organization that occurs in seasonally frozen soils. *Frost heave* causes the self-organization process. Frost heave is caused by *ice lenses* (closely spaced thin, 1-3 mm, layers of ice) that form in soils with high unfrozen-water content (Miller 1980, Nixon 1991). The orientation of the ice lenses and the related direction of ground heaving are controlled by the temperature field within the freezing and frozen soil. A model for differential frost heave (DFH) that includes the necessary mass, momentum, and energy balance equations has previously been developed (Peterson 1999; Peterson and Krantz 1998). The reader is referred to key references for further explanation, history, and validation of the model (Fowler and Krantz 1994; Fowler and Noon 1993; Krantz and Adams 1996). A key aspect of the DFH model is that *all DFH-model parameters can be measured and quantified in the field or laboratory. This characteristic of the DFH model sets it apart from conceptually based models that use probability functions to determine the direction and degree of frost heave. Existing models that attempt to describe the genesis of some types of patterned ground are limited by the use of empirical parameters that lack physically measurable analogs* (e.g., *Kessler et al. 2001 in press).*

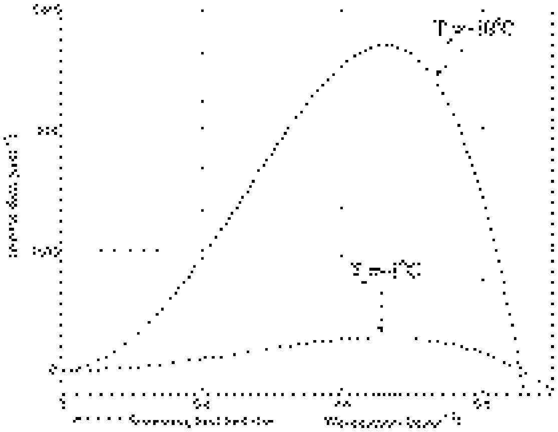

Figure 6: DFH model prediction of frost-boil growth rate as a function of the wavenumber and frost boil size. Frost boil diameter is characterized by showing the effect of ground-surface temperature; larger growth rate values imply more rapid development of frost boils; smaller wave number values imply larger diameter frost boils.

One of the more influential DFH-model parameters is the thermal condition at the ground surface during freezing. As an illustration, the DFH model predicts that colder ground-surface temperatures result in patterns with greater frost heave, as shown in **Figure 6**. *This suggests that frost heave and frost boils are quite sensitive to ground surface temperature and hence to vegetation and snow cover*. The DFH model can predict the effect of the plant canopy, snow cover, mean annual temperature, soil type, as well as other ecosystem variables on the formation and characteristics of frost boils. Hence, in principle this model can provide the quantitative link between measurable dynamic landform characteristics and ecosystem variables. As such, this model has the potential to permit using dynamic landform characteristics as ecological indicators. However, this model needs to be refined and validated in depth via both carefully controlled laboratory and field-scale studies.

C.3.2 Integration of DFH model with the vegetation model (ArcVeg) and biogeochemistry

The ArcVeg model describes plant community and ecosystem development in arctic ecosystems (Epstein et al. 2000) (See Section C.6). Coupling the DFH model with ArcVeg will provide an important link between the physical processes in recurrently frozen soils and the ecosystem. The degree of ground-surface disturbance due to frost heave is an important input parameter that can effect the disappearance and emergence of different plant functional types. In addition, ArcVeg feeds back into the DFH model information about changing ground-surface thermal conditions due to evolving vegetative ground cover (**Figure 7**). The ArcVeg model describes ecosystem development on a spatial scale of hundreds to thousands of m^2 and changes that occur over time periods of tens to hundreds of years. These scales are larger and longer than those associated with the DFH model. However, the occurrence and degree of frost-boil activity predicted by the DFH model are necessary input parameters to the ArcVeg model, and ground-surface vegetation is a necessary parameter for the DFH model. This dependency forms an important link between these two models that operate on different spatial and temporal scales (**Figure 4**).

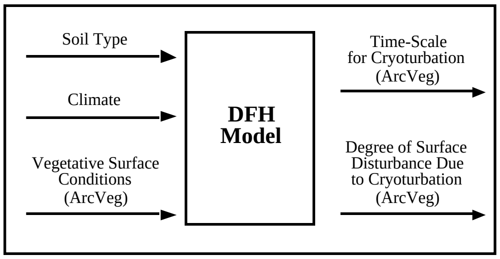

Figure 7: DFH model inputs and outputs to the ArcVeg model.

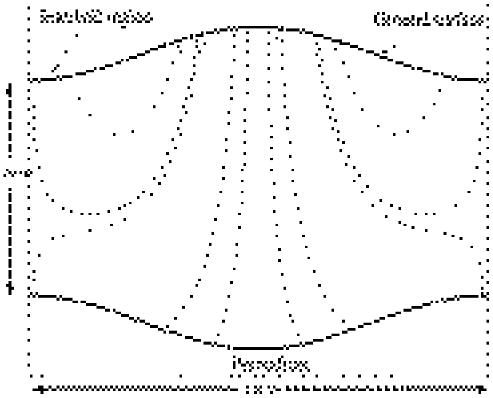

Figure 8. Soil movement as a result of differential frost heave within a frost boil, as predicted by the DFH model (Peterson and Krantz, 1998). Arrows indicate direction of soil movement, with a net soil migration to the boil surface.

The cryoturbation predicted by the DFH model has important implications for parameterizing nutrient cycling in larger-scale ecosystem models. The DFH model is capable of predicting direction and velocity of the soil matrix within the active layer during differential frost heaving. The cyclic motion of soil during cryoturbation can have profound effects on nutrient cycling (**Figures 8 and 9**). Cryoturbation is believed to greatly increase the rate of nitrogen mineralization and subsequent plant uptake. The ArcVeg model is nutrient-based and accounts for the cyclic movement of nitrogen through the active layer, plant community, and atmosphere. Velocities predicted by the DFH model indicate an active-layer cycle time of 50-200 years. This cycle time agrees with the time scale for cryoturbation theorized by several field investigators.

C.3.3 Further Refinement of the DFH Model for Periglacial Landform Dynamics

An important feature of the DFH model is how one describes the resistance of the frozen soil layer to deformation. Thus far, the frozen soil has been described either as a Hookian *solid* or as a Newtonian *fluid.* A more realistic model would describe it as a *viscoelastic* medium (*i.e.*, having both elastic and flow properties). We propose to explore a model of this type to ascertain how sensitive the DFH model predictions are to the frozen soil rheology. The present DFH model assumes that either the temperature or heat flux at the ground surface remains constant. As such, this does not allow for seasonal or diurnal changes. We propose to incorporate cyclic changes of the ground-surface boundary condition into the model to improve its accuracy. The DFH model should predict the characteristics of frost boils reasonably well since seasonal climate changes occur on a relatively long time scale compared to the heat transfer and water permeation that control frost-boil dynamics. The DFH model describes the inception and initial growth of patterned ground landforms. It appears that many of the important characteristics of frost boils such as their diameter are established early in their development. However, it is important to explore the long-term evolution of the frost-boil dynamics. Hence, we propose to solve the evolution equations that describe the subsequent development of frost boils. This will take the form of a weakly nonlinear stability analysis and/or a numerical finite element simulation. Validation of the model will be done using field measurements of frost-boil parameters from the field sites (active layer depth, size and spacing of the frost boils, and amount of heave) plus soil characteristic information and information on the ice lenses (size and spacing).

C.3.4 Controlled Laboratory Studies of Patterned Ground

Krantz and his co-workers have also constructed a novel apparatus for ‘growing’ patterned ground in the laboratory. This apparatus permits controlled cycling of the ambient temperature to cause recurrent freezing and thawing of the test soils. Provision is made for subsurface water flow via cryostatic suction during ice-lens formation, which is pivotal for inducing the differential frost heave that causes the formation of patterned ground. To the best of our knowledge this is the first demonstration that landforms of this type can be ‘grown’ in the laboratory. An initial experiment was successful because we used the DFH model to determine the conditions necessary to promote the formation of these nonsorted circles in the laboratory. These laboratory experiments, in combination with the model predictions for the Kuparuk River Basin frost boils, strongly support this proposed research and provide confidence that we can relate measurable dynamic landform characteristics to ecosystem variables and thereby establish their utility as ecosystem indicators. To further validate the modeling studies, we will continue the controlled laboratory studies of the initiation and growth of small-scale nonsorted circles that were described above. We propose to study soil samples taken from both the MNT and MAT regions of the Kuparuk River Basin field site in northern Alaska. These laboratory studies offer the advantages of maintaining controlled environmental conditions and accelerating the ‘seasonal’ temperature variables by cycling the temperature diurnally. In this manner we are able to develop nonsorted circles on a much shorter time scale than possible under field conditions. These studies will be carried out in a computer-controlled laboratory freezer that we have constructed expressly to simulate patterned-ground formation. This laboratory freezer can be programmed to carry out a prescribed daily temperature variation. It also has provision for a simulated subterranean water supply, which is essential for the ice-lens formation that is associated with significant frost heave. In these studies we seek to assess whether we can predict the conditions necessary for the formation of frost boils and whether we can predict the characteristic diameters of the resulting patterns.

C.4 COMPONENT II: SOILS AND BIOGEOCHEMISTRY (CHIEN-LU PING, HOWIE EPSTEIN, GARY MICHAELSON, AND VLADIMIR ROMANOVSKY)

C.4.1 Physical and geochemical analyses

In order to apply the DFH model, numerous geophysical, thermal and hydraulic properties of the frost-boil soils are required, all of which we will measure either in the field or on laboratory samples. The required soil properties include the following: density, thermal conductivity (frozen and unfrozen), heat capacity (frozen and unfrozen), water content, and porosity. We also must determine the hydraulic conductivity and freezing temperature of the soils as a function of unfrozen water content. Control sites will be instrumented in both the MNT and MAT soil regions. The instrumentation will monitor soil temperatures, soil moisture, and cryoturbation activity. Romanovsky has designed ground-surface-heave instruments (heavometers) to monitor frost heave. Snow depth, wind, air temperature, and precipitation will also be measured. We will also need to determine the thermal conductivity and heat capacity of the snow and the convective heat transfer coefficient that characterizes the energy exchange with the ambient air. Standard techniques are available to determine these properties and parameters.

We will describe the soil color, organic-horizon distribution pattern, redoximorphic features, rooting distributions, soil boundary, cryogenic structures in the non-frost boils vs. the frost-boil profiles. Detailed morphological study will be performed on profiles exposed along the dissected frost boils and associated soils. These morphological properties are indicative of the physical processes (Hoefle and Ping 1996; Ping et al. 1998). Soil samples will be taken from the genetic horizons or soil zones from the paired profiles. Characterization analysis will be performed on these samples according to the USDA National Soil Survey Center procedures (USDA 1996). The analyses include bulk density, water content, electric conductivity, particle size distribution, mineralogy, pH, inorganic and organic carbon, total nitrogen, extractable cations including Ca^{+2}, Mg^{+2}, K^{+}, Na^{+}, and anions including sulfate and phosphate, active iron and aluminium extracted by dithionite-citrate, pyrophosphate and acidic oxalate, acidity and cation exchange capacity.

The manner in which ice-lens formation affects soil development is not likely to be simple, and we expect that one explanation will not apply to all frost boils. For example the strong sorting that has been noted in high-arctic frost boils (Kessler et al. 2001 in press), does not occur in the fine-grained soils along the Sagavanirktok River because of the lack of coarse grained sediments. In other frost boils, the presence of low-density, ice-rich materials near the permafrost table can lead to inversions and involutions of the soil horizons (diapirism) (Swanson et al. 1999), but this has not been noted in the frost-boil soils along the Sagavanirktok River. The effects of ice-lens formation on soil physical and chemical properties will be examined in detail by taking cores in winter when the ice-lenses are present. These cores will be frozen and examined in a cold room. The density, size, and water quality of the ice lenses will be measured. We will look at variation with depth and also horizontal variation across the soil profile. We will be particularly interested in the biogeochemistry of the very thin surface horizons which often support cryptogamic crusts or have salt crusts that could affect colonization by plants.

C.4.2 Biogeochemical cycling

We will focus primarily on nitrogen and carbon pools and transformations (**Figure 9**). In conjuction with the vegetation sample sites (See Component III, Section C.5), we will set up several microtransects emanating from the center of frost boils that include adjacent areas without heaving. At various distances along these transects, we will measure a variety of ecosystem variables related to the C and N cycles, including the depth of the active layer, and using 50-cm soil cores, soil organic N, C:N ratios, ammonium, nitrate, and net N mineralization at different soil depths. In the surface soil layers (top 10 cm) we will estimate *in situ* rates of net N mineralization using paired cores with ion exchange resin technique (Raison et al. 1987), and rates of N_2 fixation using acetylene reduction (Stewart et al. 1967). Plants will be sampled and analyzed for N concentrations in foliage, stems, and roots, and an evaluation of ∂^{15}N of plant samples will provide an integrated assessment of the sources of reactive N (i.e., atmosphere or internal organic cycling) (Evans and Ehleringer 1993; Evans and Ehleringer 1994). Intensive carbon and nitrogen sampling will be conducted in Year 1 of the study at the MAT-MNT boundary near Sagwon. Plant and nutrient sampling will be conducted at peak of the growing season (mid July) at the Sagwon sites. This site is of particular interest because it is the major transition between areas with and without abundant frost boils. Plant and nutrient sampling will be conducted every 30 days from mid June through mid August (3 sampling dates). In the second year of the project, sampling will be conducted once at the peak of the growing season at the Sagwon sites. In Year 3, the intensive sampling will be conducted on Bathhurst Island in northern Canada, with a peak season sampling again in Year 4. In addition to gaining insight into the biogeochemical processes occurring at this scale, these data will also be used to parameterize the ArcVeg model.

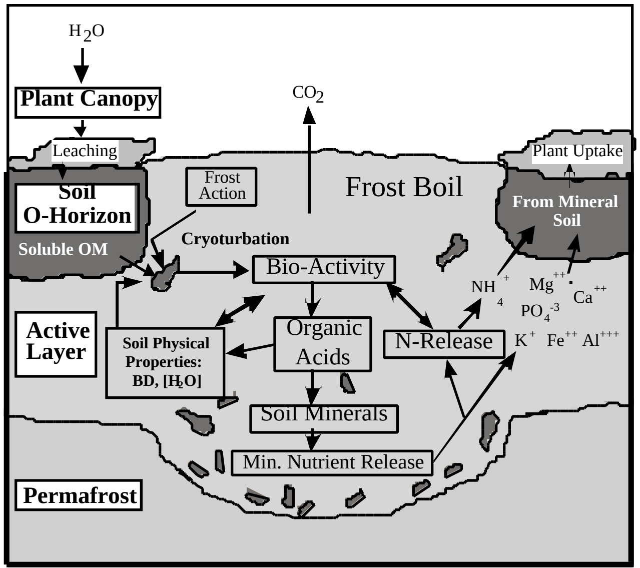

Figure 9. Generalized biogeochemical cycle within frost-boil soils, emphasizing the effect of frost heave on the process of decomposition of organic matter and subsequent uptake of nutrients by the plants.

C.4.3 Paleo-analyses

The history of frost boil development in arctic Alaska is a matter of great interest for the paleoecological history of Beringia. Are the present-day frost boils very old features or does the pattern of frost boils shift with time? We will use accelerator mass spectrometry C_{14} analysis of *in situ* organic material to date organic horizons that occur in conjunction with frost boils. We will also do a detailed analysis of a 10 x 10-m area in the MAT region of the Sagwon Hills, where it appears that tussock tundra has formed over a field of old frost scars. This could give us insights into how the transition from MNT to MAT occurs. We will successively strip off the moss layer, organic horizons and finally the mineral horizon down to the permafrost table and make a detailed topographic map of each layer that we strip off. This should reveal the distribution of old frost boils that have since been covered by tussock tundra vegetation.

C.5 COMPONENT III: VEGETATION (SKIP WALKER, HOWIE EPSTEIN, BILL GOULD, MARTHA RAYNOLDS, AND MARILYN WALKER)

C.5.1 Introduction

Vegetation is another self-organizing system that occurs on and between frost boils and that integrates the physical and biogeochemical components of the landscape. The presence and abundance of frost boils play a key role in determining the patterns of tundra vegetation across scales ranging from patches to landscapes to regional climate gradients (Walker et al. 1998; Walker et al. 2001b). Vegetation strongly influences the heat regimes of the soil and hence biogeochemical cycles and cryoturbation. Cryoturbation strongly influences plant colonization, and thus there is a strong feedback system present. The nitrogen limited nature of arctic tundra (Chapin et al. 1995; Shaver et al. 1996) and the presence of nitrogen-fixing species on frost scars suggests that nitrogen may play a key role in the dynamics of tundra ecosystems. Arft et al. (1999) found that the responses of tundra plants to experimental warming were more strongly related to nitrogen pools than to temperature per se, and modeling results suggest that the biomass pools as well as the specific nutrient-use strategies of species within a community strongly control response to warming (Epstein et al. 2000). Data from Devon Island, Canada show that N_2-fixation rates are no higher on frost boils than in nearby sedge or grass meadows, but the quantity of N fixed per unit of plant biomass is likely much greater on the frost boil (Chapin and Bledsoe 1992). By considering vegetation to be an *interference pattern* (sensu Allen and Hoekstra 1992) between physical and biogeochemical processes, we can use vegetation patterns and response as a strong indicator of the interactions between these other components.

The vegetation studies combine field sampling and analysis, remote sensing, and experiments in order to understand and describe how patterns of vegetation relate to biogeochemical and physical patterns in frost boil systems. Combined with the ArcVeg modeling (Section C.6), the vegetation sampling and analysis will extend across multiple time and space scales. First we will analyze the zonal and frost-boil plant communities along the full arctic temperature gradient. In order to build a consistent vegetation framework across the arctic we will build on the vegetation classification and mapping framework initiated in earlier studies (Gonzalez et al. 2000; Schickhoff et al. submitted; Walker et al. 1994b, Walker, 1996). This work will provide important input to the ArcVeg model in form of cover and of plant species and plant functional types. Second, we will develop arctic-wide relationships between biomass, leaf area index (LAI), and satellite-derived information. This will allow us to extrapolate the results of our research across the full temperature gradient, and provide key variables to the ArcVeg model (plant biomass, soil and plant nitrogen, and carbon). Finally, we will perform experimental studies to directly examine the interactions between vegetation and cryoturbation, while holding the soil biogeochemistry environment constant. The experiments will allow us to look at the surface-temperature effects of disturbance (by removing the vegetation mat) and altered snow cover (through the use of snow fences).

C.5.2 Vegetation analyses

We will sample and analyze natural vegetation of frost boil and inter-frost-boil areas. Approximately 10 relevés (vegetation and soil samples) will be collected from frost boil and intra-frost boil areas at the 10 sites along the temperature gradient (approximately 200 total relevés). Special attention will be paid to cryptogamic crust communities, since these are the pioneer communities that first form on frost boils. These communities change the summer heat flux and begin the process of nitrogen fixation and stabilization of the barren soils (Gold 1998). Careful attention will also be paid to microhabitats within the frost boils such as barren soils, partially stabilized areas, earth-hummock rings surrounding the frost boils, and the areas between the frost boils (see Figure 1). Soils will be collected and analyzed for physical and chemical properties (See Section C.4, Soils and Biogeochemistry). Students from Gould’s Arctic Ecology course will be actively involved in the sampling and analysis of this component (Section C.6, Education).

The vegetation analysis will seek to place the vegetation into a global framework and to quantitatively examine the interactions of vegetation and environment. The communities will be classified using the Braun-Blanquet approach (Dierschke 1994; Westhoff and van der Maarel 1978), which has been used extensively in Russia (Matveyeva 1994), Svalbard (Elvebakk 1994), and Greenland (Daniëls 1994). Applications in the North American Arctic have been done in the Toolik Lake region (Walker et al. 1994b) and to riparian willow communities (Schickhoff et al. Submitted). A reinforced application of the Braun Blanquet approach in North America would be highly desirable in order to lay the foundation for a circumpolar arctic vegetation classification (Walker et al. 1994a).

The relationships that lead to the self-organized systems of frost boils and ecosystems are non-linear and have multiple feedbacks, but their *state* at a given time and climate regime can be described through linear methods by considering each climate regime (zone) individually. Attempting to analyze all samples simultaneously would likely result in a confusing picture, because we expect the relationships to change in strength and nature along the gradient. Relationships between environmental variables (soil factors, climate, disturbance regimes, etc.) and vegetation will be analyzed using detrended and canonical correspondence analysis ordination methods (Hill and Gauch 1980) (ter Braak 1987). Our hypothesis predicts that the vegetation of the northernmost parts of the transect will be relatively poorly organized and show strong physical control, with little difference between frost boil and inter-frost-boil samples. The southernmost samples will be strongly organized but will also show minimal difference. We predict that in the middle of the gradient there will be maximum difference in plant communities between the frost boils and the inter-frost-boil areas. We will examine the complex controls of temperature and cryoturbation on vegetation through the use of path analysis (Li 1975). This approach has been used to analyze effects of interannual climate variation on the biomass, phenology, and growth of alpine plants (Walker et al. 1995b, Walker et al., 1994). Path analysis requires that the variables have linear relationships. Although the interactions among components in the frost boil system are nonlinear over long time scales, we can dissolve the complex system into linear models by examining the relationships between heave, carbon, nitrogen, plant functional types, and plant species at a series of discrete sites along the temperature gradient. Although the nonlinearities in the system must be explicitly considered in any dynamic model, we essentially examine a series of static systems that have arisen through nonlinear dynamic interactions to a quasi-stable state that can be described through linear functions.

C.5.3 Regional studies: biomass/LAI/NDVI relationships

We will develop a hierarchical set of map and remote sensing products in order to examine vegetation-landscape relationships across a spectrum of spatial scales. A Landsat-derived land-cover map already exists for the Kuparuk River region (Muller et al. 1998). More detailed vegetation maps are not available for any of the proposed study sites. We will map individual frost boils, mosaics of frost boils within the 10 x 10-m grids, and patterns of MNT vegetation within larger landscapes. Landscape-scale field investigations will involve the acquisition of aerial photography at 50 to 1000 meters above the ground surface to map vegetation and microsite patterns. At coarser scales we will use existing 1:60,000-scale color-infrared imagery and satellite images. Spatial analysis of these maps using a variety of diversity indices will be performed (Milne 1988). Regional-scale analyses will utilize the field-collected data, including aerial photography, to ground-truth satellite imagery. This imagery will then be used for analyses of large-scale frost-boil patterning across the Arctic landscape to determine its effects on and associations with large scale patterns of climatology, hydrology, and wildlife use of these landscapes. We will also use spectral data as a surrogate for total ecosystem function through the use of the normalized difference vegetation index (NDVI) (Shippert et al. 1997; Stow et al. 1998). We will quantify biomass (clip harvests, and soil cores), leaf area index (LAI), and the normalized difference vegetation index (NDVI) within and between the frost boils. Studies of the relationships between biomass, LAI and NDVI will follow the procedures used during the FLUX and ATLAS studies (Jia et al. Submitted, 2001; Riedel et al. 2000; Walker et al. 2000).

C.5.4 Experimental studies to alter cryoturbation regimes

We will experimentally alter vegetation cover and winter ground-surface temperature to test directly our hypotheses about the interactions among variables in Figure 2. By removing the vegetation from 5x5-m areas of soil in MAT region, we will decrease the summer insulative mat and thereby increase summer ground-surface temperatures, increase the active-layer depth, and correspondingly increase the frost-boil activity and characteristic diameter. Doing the same within the MNT region should increase frost-boil formation where it already occurs. By using a snow fence to increase the snow depth in the MNT region, we will increase the winter ground-surface temperature, and thereby suppress frost-boil activity. A snow fence experiment is already available as part of the International Tundra Experiment (ITEX) at a MAT site on the Arctic LTER (Long-Term Ecological Research) field site at Toolik Lake. The vegetation properties and history of the site are well known as are the snow drift characteristics (Walker et al. 1999). A similar snow fence will be built at an MNT site to examine the effects of increased snowpack on the diameter and density of frost boils. These field experiments will permit us to assess whether the DFH model can predict the occurrence and properties of existing frost boils. They also will allow us to assess whether it can predict the ecosystem conditions required to either promote or suppress frost-boil formation and the effect of these conditions on observable frost-boil characteristics such as their diameter, spacing, and maximum frost heave.

C.6 COMPONENT 4, MODELING VEGETATION AND NUTRIENT DYNAMICS (HOWIE EPSTEIN AND MARILYN WALKER)

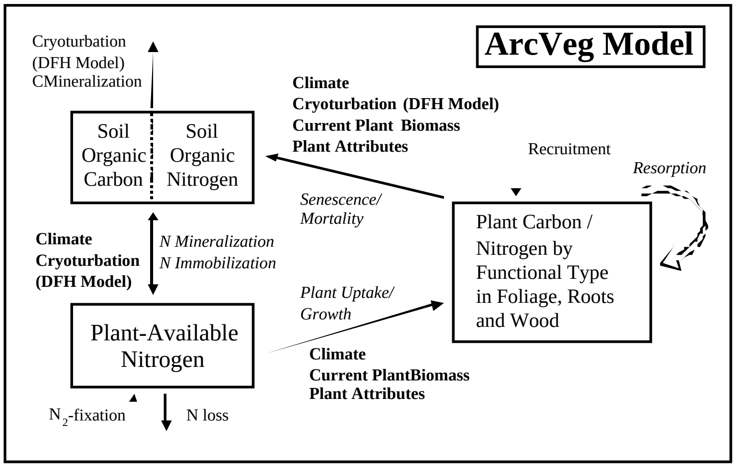

Figure 10. Flow diagram for the ArcVeg model (Epstein et al. 2000, Epstein et al. 2001), demonstrating links with the DFH model. Italicized terms represent processes that are dynamic within the model, and bold terms represent factors that affect the dynamics (i.e., controlling factors). Each plant type in the current version of ArcVeg is parameterized for six traits: (1) mean biomass:nitrogen ratio for the whole plant (g biomass / g N), (2) proportion of biomass senescing at the end of the growing season (g / g), (3) annual probability of establishment of new individuals, (4) nitrogen uptake efficiency (g N taken up / g biomass), (5) timing of growth and cold-tolerance (6) capability for N_2-fixation. Together these attributes represent a variety of strategies for plant growth and survival. ArcVeg runs on an annual time step to simulate transient dynamics, and it can be run for up to 100 independent patches of vegetated or bare soil (1 m^2 each) to represent spatial heterogeneity of a landscape.

A major challenge of this research program is to explicitly link the processes of biogeochemical cycling, species and vegetation change, and ice lens formation and deformation. The vegetation and ecosystem-modeling component will allow us to examine the differences in system dynamics and interactions among these components across time scales of decades and centuries. Empirical hierarchical field and remote sensing studies of vegetation and soils allow us to examine a gradient of climate at multiple scales, but they give only very short time-scale information on dynamics. We infer longer time scale dynamics through studies of pattern. Modeling allows us to explicitly examine feedbacks and their consequences in ways that are not possible with linear descriptions of system state. We will use an interannual tundra ecosystem model, ArcVeg, to examine long-term interactions of climate and ecosystem processes key to this study (vegetation patterns and carbon and nitrogen cycling). ArcVeg was developed to simulate changes in typical acidic ecosystems on the North Slope of Alaska as a result of climate warming (**Figure 10**; Epstein et al. 2000; Epstein et al. 2001 in press). Epstein et al. (2000) provide a complete description of the model. ArcVeg simulates the interannual dynamics of tundra ecosystems consisting of about twenty plant types found in various arctic plant communities throughout the North Slope. Because arctic ecosystems are generally nitrogen-limited, and plants compete for available nitrogen and respond rather quickly to additions of nitrogen (Shaver, 1992; Shaver, 1995; Schimel and Chapin 1996), the model is structured around nitrogen mass balance. Therefore, there is an explicit link between a detailed plant community and biogeochemical cycling (in this case nitrogen and carbon). Fine-scale disturbances, such as frost heave, and the establishment of new individuals, are processes that are stochastic at the patch level within the model. Each execution of ArcVeg explicitly represents a 10 m X 10 m plot, but we have primarily used the model to simulate “regionally typical,” or average, plant communities for a given vegetation type. Spatial heterogeneity of climate, disturbance regime, and initial soil nutrient status within a vegetation type can be expressed with multiple runs.

What sets ArcVeg apart from other ecosystem models, such as TEM (Rastetter 1991), and makes it particularly appropriate for this research, is that it allows species to explicitly compete with one another for nitrogen in a context of both temperature and disturbance, both of which affect ecosystem and individual-scale uptake. Each species in the model also responds differently according to climate, so that a different mix of species in a different climate regime will change model outcomes. This is particularly important in this study because the pool of plant species and plant functional types changes substantially from bioclimate subzone 1 to subzone 5, and this will be key to understanding the different successional patterns along the gradient. Other models deal with carbon and nitrogen without explicit consideration of species. Our results from ArcVeg indicate that the mix of species present is at least as important as the total pools in understanding long- and moderate-term responses to change (Epstein et al. 2001 in press). Also, the ability to modify disturbance regime within ArcVeg will allow us to directly import results from the DFH model into ArcVeg and to look at how various levels of surface disturbance affect biogeochemistry and vegetation. Using ArcVeg for this study will require a new parameterization based on the frost boil communities. Since there is little or no information on species and biomass on frost boils available in the literature, we will require new data to do this. The vegetation data described in Section C.5 and the microtransect-biogeochemical data described in Section C.4 will be used for this parameterization.

C.7 COMPONENT V: EDUCATION (BILL GOULD)

One of the fundamental goals of our national science policy is to better integrate research and education. There is strong national interest to improve this integration at the graduate and undergraduate levels, with the general public, and (in the Arctic in particular) with indigenous people. Funding agencies and academic institutions promote undergraduate field research opportunities but in reality these can be difficult to arrange and fund. Innovative research and education opportunities are often small-scale, unique in nature, and "fall between the cracks" of larger research and education agendas. We propose here a project integrating well-defined research goals, an established field education program, and experienced personnel willing to create this unique educational opportunity.

Our goal is to link the biocomplexity research agenda with an ongoing field studies program, *Arctic Field Ecology* (University of Minnesota EEB 4842). This program has a history of integrating research, undergraduate education, and indigenous people (Gould 1999; Gould 2000). In 1999 we successfully developed a course that involved 5 students and a group of 6 scientists from the circumpolar region in a research expedition from treeline to the northernmost area of the Canadian Arctic (Gould et al. Submitted 2001). We propose to create a similar framework linking *Arctic Field Ecology* with the field studies proposed here for the Alaskan and Canadian Arctic. The coursework and student involvement will be directed by Dr. Gould, who has 15 years of experience in combining research expeditions to the Arctic with undergraduate education.

We will develop a curriculum that focuses on current themes and findings in Arctic ecology, with a focus on issues of biocomplexity. The specific research questions addressed each field season in this study will include skills for conducting field sampling, and opportunities to interact with participating research scientists and Inuit representatives. Specifically, we propose the following. (1) Organize a four-week field ecology class that will overlap with the summer field activities related to the research agenda of this study. (2) Develop a curriculum and research agenda for this course that addresses variation in vegetation along the climatic gradient to be investigated, in particular the complex interaction of climate, biogeochemistry, vegetation, and cryoturbation. Biodiversity of ecosystems will be a likely focus of the student research. (3) Facilitate the interaction of Inuit with students involved in the course by creating series of meetings where students have a chance to learn from Inuit about local land use, land management, and landscape change issues from Inuit perspectives. (4) Foster continued learning and working relationships between students and scientists involved in the study in part through the development of a web-based clearinghouse of information related to the field course and cryoturbation study. (5) Offer students and Inuit participants an opportunity to attend annual workshops related the proposed study. (6) Organize a workshop in the final year of the study in which students and Inuit participants can present the impact of their involvement in the project on their own lives and careers. These impacts will be summarized for inclusion in a publication on the results of the integration effort.

The primary motivation in integrating research and education in this way is that the effect of combining the expertise of the scientists with the enthusiasm of the students and the organizational framework of the *Arctic Field Ecology* class is beneficial to all components. It is impossible to offer a field course at such a variety of remote locations and with such a range of scientific expertise without the logistic support of the research. Likewise, a well-integrated educational component cannot be developed without the support of well-planned teaching agenda and students with adequate background knowledge of the subject. The field component of the integration of research and education will be conducted over each of the first four years of this study. All student and Inuit participants will then be invited to a final (5th) year synthesis workshop to present the short and long-term impact of the experience on their lives and careers. Field activities will be accomplished in two stages: (1) An initial meeting (1-2 weeks) of the instructor and assistants with enrolled students at one of the field sites of interest to the present study. Here students will gain familiarity with the landscape, learn about the research plan, learn sampling techniques to be used later in the course, and discuss topics in Arctic natural history and current issues in Arctic ecology. We will also cover safety skills for travel in remote regions and meet with Inuit residents. (2) A field campaign of 2 to 3 weeks in which students join with the research scientists and assistants as they visit a series of sites along the climatic transect being investigated. At each site we will conduct sampling related to the research and course agenda. Students will assist in sampling related to the proposed research (primarily substrate and cryoturbation related measures). They will meet formally and informally with scientists involved in this study, and continue to discuss what they learn in light of the proposed research questions and the Inuit perspectives gained earlier in the course. Finally, students and scientists will be encouraged to continue learning and working relationships generated during the field course as these relationships are often crucial in shaping a students future direction in science and life.

C.8 COMPONENT VI: COORDINATION AND DATA MANAGEMENT (SKIP WALKER, JULIE KNUDSON, HILMAR MAIER)

The project will have an integrated design, whereby the project collaborators will all work at the same research sites along a climatic transect from Happy Valley, Alaska, to Amund Rignes Island in northern Canada. Along this transect we have already established five research sites in northern Alaska as part of a previous project. We are proposing to establish two more sites in northern Alaska, and three sites in Canada. The objective is to have a series of sites in all five bioclimatic subzones of the Arctic (Walker 2000). In order to characterize significant differences and similarities of frost-boil ecosystems within and across the Arctic climate gradient, this project has been organized to look at characteristics associated with frost-boils at a variety of scales, ranging from the individual frost boil scale up to the plot, landscape, and regional scales.

Extensive data from the NSF-sponsored FLUX (Kane and Reeburgh 1998) studies are already available for soil composition and type, active-layer depth, snow cover, plant canopy composition, canopy structure, biomass, ground surface temperature, air temperature, and prevailing winds along the gradient in northern Alaska (Romanovsky and Osterkamp 1997, 1998). We will assess these data for their usefulness in relating the size and density of frost boils, and structure and composition of the vegetation, to climate gradients of depth and ground-surface temperature. These data plus the new data we collect then will be used in the DFH and ArcVeg models to predict the formation and characteristics of frost boils and the response of the vegetation.

The research areas would all be located on zonal sites with fine-grained (silt or silt-loam) parent materials. At each site, we will have a climate station, a 10x10-m grid where we will characterize and map vegetation, soils, and active-layer depth in detail. We will also have several 50-m transects to characterize the spacing and size of the frost boils, and other sites to monitor frost heave, and soil temperatures within and between frost boils. At most sites, we will also dig trenches to examine the subsurface characteristics of the frost-boil networks and to characterize the soils. Field investigations associated with ice formation and soil heave will require the collection of mid-to-late winter soil cores and the installation of devices measuring soil heave in both frost boil and inter-frost boil areas. Soil trenches will also be excavated through frost boils at each site to characterize the complete profile of soil layers and activity, with C_{14} dating of particular layers of interest within the profile. Most subterranean data will be collected through continuously-recording instrumentation installed at each research site, with additional measurements of active layer depth performed with steel probes during each field visit. Climatological data collection will capture air temperature, relative humidity, wind speed, wind direction, and snow depth. Continuously-recording tower-mounted instrumentation will be used to collect most of the climatological data, with some additional snow data collected using hand-held equipment during mid to late winter field visits. Collection of the climatological and subterranean data is particularly useful for calibration and simulation runs using the DFH model.

C.8.1 Data and product archiving

Data will be centrally managed at UAF. A project coordinator will facilitate day-to-day activities and be the data manager of the project. She will also develop a web page for the project. A GIS manager will handle the GIS and Remote Sensing needs of the project. Data will be made available to the wider science community through the Joint Office for Science Support (JOSS) as soon as it becomes available and is quality checked. Final archiving will be done through the Arctic Data Coordination Center. All data management and archiving will follow protocols established by the ARCSS Data Management Committee.

C.8.2 Workshops

This project involves personnel from four universities and two federal agencies, and integrates information from many disciplines and scales. The project will also involve close coordination with other projects within ARCSS including the International Tundra Experiment (ITEX) for the snow fence experiment, and also other ARCSS and Canadian investigators for the Canadian transect. Integration and synthesis will be a major challenge. We propose to hold two workshops. The first is a workshop on Arctic Tundra Biocomplexity in Year 2. To assist with the biocomplexity aspects of the synthesis, we would invite some of the key people in biocomplexity research, such as members of the Santa Fe Institute and the Institute for the Study of Coherence and Emergence, where many of the approaches to biocomplexity issues have been developed. In Year 4 of the project we would have a workshop that would bring together all of the members of the project for a week-long synthesis effort. The final year of the project will be devoted primarily to synthesis.

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E BIOGRAPHICAL SKETCHES

E.1 DONALD A.(SKIP) WALKER

University of Alaska, Institute of Arctic Biology and Department of Biology and Wildlife, University of Alaska Fairbanks, Fairbanks, AK, USA 99707, Present Telephone: 907 474 2460, Facsimile: 907 474 7666, Internet: ffdaw@uaf.edu.

Personal Data

Date of Birth: 16 April 1945, Denver, Colorado
Military Experience: U.S. Air Force, 1963-1969
Social security number: 522-60-7573

Education

1964-1967 U.S. Air Force Academy - Mechanical Engineering, Astronautics
1972 B.A. Environmental Biology, University of Colorado, Boulder
1977 M.A. Environmental Biology, University of Colorado, Boulder
1981 Ph.D. Environmental Biology, University of Colorado, Boulder

Areas of Specialization

Geobotany, Tundra Ecology, Vegetation Mapping, Quantitative Ecology Methods, Vegetation of Northern Alaska, Geographic Information Systems and Remote Sensing, Snow Ecology, Soil-Vegetation Interactions, Disturbance Ecology, Paleo-vegetation of northern Alaska

Positions

Professor, Department of Biology and Wildlife, University of Alaska Fairbanks 1999-
Fellow, Institute of Arctic and Alpine Research, University of Colorado 1986-1999
Co-Director, Tundra Ecosystem Analysis and Mapping Laboratoryn 1986-1999
Assistant Professor (1986-1994), Associate Professor (1994-1998), and Professor (1998-1999) Attendant-Rank, Department of Environmental Population and Organismic Biology, University of Colorado

5 most relevant publications: (Total list includes 1 edited book, 7 book chapters, 52 journal articles, 38 other publications including refereed government reports, 8 book reviews, 47 conference papers and lectures (14 invited), 39 conference posters, 49 reports and maps to government agencies and consulting firms, 2 theses)

Bockheim, J.G., D.A. Walker, and L.R. Everett. 1997. Soil carbon distribution in nonacidic and acidic tundra of Arctic Alaska. In: Lal, R., J.M. Kimble, R.F. Follett, and B.A. Stewart (eds.). Soil Processes and the Carbon Cycle. Boca Raton, Fla.: CRC Press, pp. 143-155.

Nelson, F.E., N.I. Shiklomanov, G.R. Mueller, K.M. Hinkel, D.A. Walker and J.G. Bockheim. (1997, in press). Estimating active-layer thickness over large regions: Kuparuk River Basin, Alaska. Submitted to Arctic and Alpine Research.

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Walker, D.A. and M.D. Walker. 1991. History and pattern of disturbance in Alaskan arctic ecosystems: a hierarchical approach to analyzing landscape change. Journal of Applied Ecology, 28:244-276.

5 other publications:

Walker, D.A., J.G. Bockheim, F.S. Chapin, F.E. Nelson, and C.L. Ping. 2001. Calcium-rich tundra, wildlife, and the Mammoth Steppe. Quaternary Science Reviews, 20: 149-163.

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Walker, D.A., J.C. Halfpenny, M.D. Walker, and C.A. Wessman. 1993. Long-term studies of snow-vegetation interactions. BioScience, 43:287-301.

Collaborators in the past two years: Terry Chapin, University of California, Berkeley; Bill Reeburgh, University of California, Irvine; Chien-Lu Ping, University of Alaska; Fritz Nelson, New York University, Albany; Doug Stow, San Diego State University; Allan Hope, San Diego State University; Jim Bockheim, University of Wisconsin.

E.2 HOWARD E. EPSTEIN

University of Virginia, Department of Environmental Sciences, Charlottesville, VA USA 22903,

Telephone: 804 924 4308, Facsimile: 804 982 2137, Internet: hee2b@virginia.edu

Personal Data

Date of Birth: 23 October 1964, Brooklyn, NY

Social Security Number: 137-70-9368

Education

1986	B.A. Computer Science, Cornell University, Ithaca, NY
1995	M.S. Rangeland Ecosystem Science, Colorado State University, Fort Collins, CO
1997	Ph.D. Ecology, Colorado State University, Fort Collins, CO

Areas of Specialization

Grassland, Shrubland and Tundra Ecology, Plant Community Ecology, Ecosystem Ecology, Plant-Soil Interactions, Climate-Vegetation Relationships, Climate Change, Geographic Information Systems, Remote Sensing, Simulation Modeling

Current Position

Assistant Professor, Department of Environmental Sciences, University of Virginia, Charlottesville, Virginia.

Publications: (1 book chapter, 10 journal articles, 5 conference papers, 4 conference posters, and 2 theses)

Paruelo, J.M., W.K. Lauenroth, H.E. Epstein, I.C. Burke, M.R. Aguiar and O.E. Sala. 1995. Regional climatic similarities in the temperate zones of North and South America. Journal of Biogeography 22:915-925.

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Collaborators in past two years: All co-authors listed above and R.E. Davis, J.D. Fuentes, G.H.R. Henry, G.V. Jones, P.J. Michaels, A.L. Mills, S.F. Oberbauer, K.E. Schwaegerle, G.R. Shaver, P.J. Webber, J.M. Welker

E.2.1 William A. Gould

University of Colorado – Institute of Arctic and Alpine Research and Department of EPO Biology. University of Colorado, Boulder, CO, USA, 80309-0450. Telephone 303-492-8250, Facsimile: 303-492-6388, Email: gouldw@taimyr.colorado.edu, Internet: http://muskox.com.

Personal Data

Date of Birth: February 12, 1956
Social Security Number: 468-72-5277

Education

Ph.D. EPO Biology, University of Colorado–Boulder 1998
M.S. Plant Biology, University of Minnesota 1992
B.S. Biology, University of Minnesota 1988

Areas of interest

Arctic ecology, quantitative plant ecological methods, field teaching, remote sensing image analysis, vegetation mapping, central Canadian Arctic vegetation, riparian vegetation and ecology.

Positions

Director, Institute for Advanced Field Education, Ltd. 1994–present
Teaching Assistant, University of Colorado 1992–present
Graduate Research Assistant, University of Colorado 1996–1997
Instructor, INSTAAR Arctic field courses 1987–1994
Teaching Assistant, University of Minnesota 1988–1992
Interpreter, Bell Museum of Natural History 1986–1988
Field Assistant, Cedar Cr. Natural History Area (LTER site) 1986

Publications

Refereed papers

Gould, W.A. and M.D. Walker 1997. Landscape scale patterns in plant species richness along an Arctic river. Canadian Journal of Botany. In press.

Gould, W.A. and M.D. Walker 1997. Plant communities of the Hood River riparian corridor, Northwest Territories, Canada. In prep.

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Theses

Gould, W.A. expected 1998. *Biodiversity of an Arctic Riparian Ecosystem*. Ph.D. Thesis, University of Colorado, Department of Environmental, Population, and Organismic Biology.

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Published abstracts and posters

Gould, W.A., M.D. Walker, D.A. Walker, T. Edmands, M. Dornfeld, N. Auerbach, T. Nettleton, and S. Muller. 1997. Decade-scale changes in vegetation in the Brooks Range Southern Alaska Foothills. Poster presented at the ARCSS Workshop, Seattle, Washington. March, 1997.

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Gould, W.A. 1995. Biodiversity of an arctic riparian ecosystem. *The Journal of the Colorado-Wyoming Academy of Science.* 27:24.

Reports and maps

Gould, W.A. 1997. Sensitive sites in the vicinity of the Ulu mining project, the Hood River drainage, and surrounding areas, Nunavut, Canada. Echo Bay Mines, Edmonton, Alberta, Canada. April, 1997.

Gould, W.A. 1997. Vegetation and soils in the vicinity of the Ulu mining project and the Hood River riparian corridor. Echo Bay Mines, Edmonton, Alberta, Canada. April, 1997

Gould, W.A. 1997. Baseline description of the water chemistry of the Hood River, Nunavut, Canada. Echo Bay Mines, Edmonton, Alberta, Canada. July 1997.

Grants and Awards

National Science Foundation Dissertation Improvement Award	1995–1997
Science Institute of the NWT Research Assistance Support Program	1995
Canadian Studies Graduate Student Fellowship	1994
University of Colorado Museum Award/Walker van Riper Fund	1993, 1994
Dean's Small Grant Award	1993, 1994
John W. Marr Ecology Fund	1993, 1994
Dayton Natural History Fund	1990, 1991
James W. Wilkie Fund for Natural History	1990, 1991
Carolyn M. Crosby Fellowship	1990, 1991

Graduate advisors

Dr. Marilyn Walker (Ph.D.), INSTAAR, CB 450, University of Colorado, Boulder, CO, 80309-0450. Tel. 303-492-5276, email: mwalker@taimyr.colorado.edu

Dr. Harvey Nichols (Ph.D.), EPO Biology Department, CB 334, University of Colorado, Boulder, CO, 80309-0334. Tel.: 303-492-5652, email: nicholsh@stripe.colorado.edu

Dr. Clifford M. Wetmore (M.Sc.), University of Minnesota, Department of Plant Biology, 220 BSC, 1445 Gortner Avenue, St. Paul, MN, 55108. Tel.: 612-625-6292, email: wetmore@VZ.CIS.UMN.EDU

BIOGRAPHICAL SKETCH

Name: Chien-Lu Ping

Address: University of Alaska Fairbanks
Agricultural and Forestry Experiment Station

Palmer, Alaska 99645
Phone: (907) 746-9462 FAX: (907) 746-2677
E-mail: pfclp@acad2.alaska.edu

Education:	Chung-Hsing University, Taiwan	1965 B.S. Agriculture Chemistry
	Washington State University	1972 M.S. Soils
	Washington State University	1976 Ph.D. Soils

Experience:

1976-1977 Forest Soil Specialist, Washington State Department of Natural Resources
1977-1982 Natural Resource Scientist II, Washington State Department of Natural Resources
1982-1989 Assistant Professor of Agronomy, University of Alaska Fairbanks, Palmer Research Center, Agricultural and Forestry Experiment Station
1989-93 Associate Professor of Soil Science, University of Alaska Fairbanks Palmer Research Center, Agricultural and Forestry Experiment Station
1993-present Professor of Soil Science, University of Alaska Fairbanks, Palmer Research Center, Agricultural and Forestry Experiment Station

Selected Activities:

Executive Secretary, International Permafrost Association Cryosol Working Group, 1993-1998
Coordinator, Joint US-Russia Seminar on Cryopedology and Global Change, Moscow, 1992
Coordinator, US-Russian exchange in Cryosol study, NE Russia-Alaska, 1992; 1994
Coordinator, Joint US-China soils study in the Lhasa Region, Tibet, China, 1995
Coordinator, Joint international Cryosol study in the Qinghai-Tibet Plateau, 1999
Visiting Professor to National Chung-Hsing University, Taiwan, Feb.-June, 2000
Visiting Senior Scholar to the Cold and Arid Regions Environment and Engineering Research Institute, Chinese Academy of Sciences, Lanzhou, China, June- Sept. 2000
Member of the US Commission to the International Permafrost Association, 2000-

Relevant Journal Publications:

Dai X.Y., C.L. Ping, R. Candler, L. Haumaier and W. Zech. 2001. Characterization of Soil Organic Matter Fractions of Tundra Soils in Arctic Alaska. Soil Sci. Soc. Am. J. 65:87-93.
Dai X.Y., D. White, and C.L. Ping. 2001. Evaluation of soil organic matter composition and bioavailability by pyrolysis-gas chromatography/mass spectrometry. J. Anal. Appl. Pyrolysis. (in press)
Ping, C.L., J.G. Bockheim, J.M. Kimble, G.J. Michaelson, and D.A. Walker. 1998 Characteristics of cryogenic soils along a latitudinal transect in arctic Alaska. J. Geophy. Res. 103:28,917-28,928.
Michaelson, G.J., C.L. Ping, G.W. Kling, and J.E. Hobbie. 1998. The character and bioactivity of

dissolved organic matter at thaw and in the spring runoff waters of the arctic tundra north slope, Alaska. J. Geophy. Res. 103:28,939-28,946.

Walker, D.A., N.A. Auerbach, J.G. Backheim, F.S. Chapin III, W. Eugester, J.Y. King, J.P. Mcfadden, G.J. Michaelson, F.E. Nelson, W.C. Oechel, C.L. Ping, W.S. Reeburg, S. Regli, N.I. Shiklomanov and G.L. Vourlitis. 1998. Energy and trace-gas fluxes across a soil pH boundary in the Arctic. Nature 394:469-472.

Hoefle, C.M., C.L. Ping, and J.M. Kimble. 1998. Properties of permafrost soils on the Northern Seward Peninsula, Northwest Alaska. Soil Sci. Soc. Am. J. 62:1629-1639.

Ping, C.L., G.J. Michaelson, and J.M. Kimble. 1997. Carbon storage along a latitudinal transact in Alaska. Nutrient Cycling in Agroecosystems, 49:235-242.

Michaelson, G.J., C.L. Ping and J.M. Kimble. 1996. Carbon storage and distribution in tundra soils of Arctic Alaska, USA. Arctic Alp. Res. 28:414-424.

Hoefle, C.M., and C.L. Ping. 1996. Properties and soil development of late-Pleistocene paleosols from Seward Peninsula, northwest Alaska. Geoderma, 71:219-243.

Book Chapters:

Ping, C.L. G.J. Michaelson, J.M. Kimble, and L. Everett. 2001. Soil organic carbon stores in Alaska. In R.Lal, J.M. Kimble, and R. Follet (eds.) *Agricultural practices and policies of carbon sequestration in soils*. CRC Lewis Publishers, Boca Raton. (in press)

Ping, C.L., G.J. Michaelson, X.Y. Dai, and R.J. Candler. 2001. Chapter 18. Characterization of Soil Organic Matter. p. 273-283. *In* R. Lal, J.M. Kimble, R.F. Follett and B. Stewart (eds.) *Assessment methods for soil carbon*. Lewis Publishers, Boca Raton.

Michaelson, G.J., C.L. Ping and J.M. Kimble. 2001. Chapter 23. Effects of soil morphological and physical properties on estimation of carbon storage in arctic soils. p.339-347. *In* R. Lal, J.M. Kimble, R.F. Follett and B.A. Stewart (eds.) *Assessment methods for soil carbon*. Lewis Publishers, Boca Raton.

Dai, X.D., C.L. Ping, and G.J. Michaelson.2000. Chapter 2. Bioavailability of organic matter in tundra soils. p.29-38. *In* R.Lal and J.M. Kimble (eds.) *In* R.Lal, J.M. Kimble, C. Tarnocai, and H. Eswaran (eds.) *Global environmental change and soils of the cold ecoregions.* Lewis Publishers, Boca Raton.

Graduate Student Advisors:

Marcus Clark
Xiaoyan Dai
Wendy Loya
Lisa Popovics

Graduate Student Advisees:

Michelle Weston
Claudi Hoefle
Paul Overdiun
John Shaw

Recent US Collaborators Other than Co-authors Above and PIs Here:

Larry Hinzman, Univ. Alaska;
Kenji Yoshikawa, Univ. Alaska
T.J. Zhang, Univ. Colorado;
C.A. Stiles, Univ. Tennessee
R.F. Paetzold, USDA-NRCS
V.E. Romanovsky, Univ. Alaska

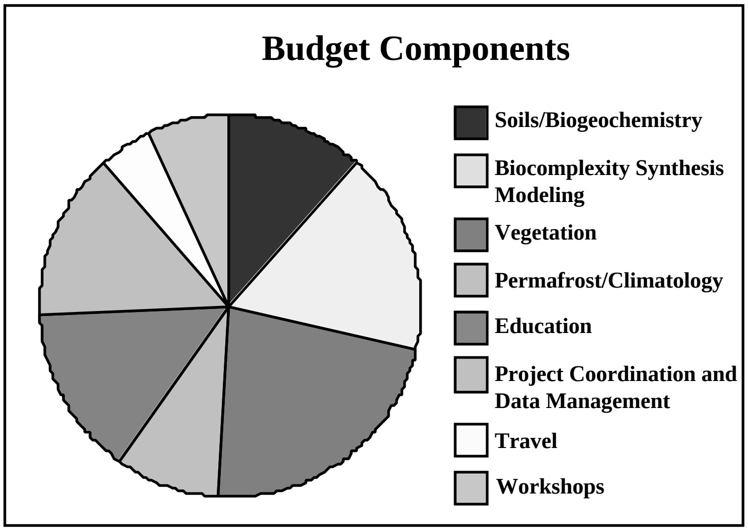
J.P. Schimel, UC Santa Barbara D.K. Swanson, NPS, Alaska

F SUMMARY PROPOSAL BUDGET

F.1 BUDGET JUSTIFICATION

F.1.1 Budget breakdown by project components

The approximate percentages of the budget devoted to the major components of the research are as follows: Soils and biogeochemistry 12%, Biocomplexity and synthesis 17%, Vegetation 23%, Permafrost and climatology 9%, Education 14%, Coordination and data management 14%, Travel 5%, Workshops 7%.



F.1.2 Personnel and salaries

The project PI will be Dr. D.A. Walker, who will lead the project and the vegetation component. He has 31 years experience in Arctic Alaska vegetation, soils, remote sensing, and geographic information systems. He is on a 50% FTE and is requesting 3 mo salary support per year. Dr. Marilyn Walker ‘s salary is covered by the US Forest Service. Her contribution to the project is covered through support of Jamie Hollingsworth (3 mo/yr) who will assist with the vegetation analyses, focusing on the biocomplexity and path analysis aspects. The other senior personnel from UAF include: Dr Vladimir Romanovsky (1 mo/ yr) will be in charge of the field operations to monitor climate, permafrost and frost heave. Dr. Chien-Lu Ping (1 mo/yr) is in charge of the of soil and biogeochemstry component. Rorik Peterson (6 mo/yr) is on a post doc and will develop the DFH model.

Other technical staff at UAF include Julie Knudson (6 mo/yr) who will coordinate the field operations and be in charge data management and development of the web page. Gary Michaelson (1 mo/yr) will be responsible for much of the soil analysis. Hilmar Meier (2 mo/yr) is the GIS technical expert and system manager and will assist with many of the GIS and mapping aspects of the project. Martha Raynolds (6 mo/yr) is a geobotanist who will assist in all aspects of the vegetation analysis and mapping.

F.1.3 Permanent equipment

Funds are requested for one snow fence (estimated at $15,000) and three weather-proof field computers based on estimated costs of $4,000 each.

F.1.4 Travel

Fieldwork in Alaska – Support for travel is requested for two round trip airfares for four from Fairbanks to Prudhoe (estimated at $500 for a total of $4,000 annually). registration) for field work at the Alaska fields sites along the Dalton Highway.

National and LAII meetings- Support for travel to annual meetings is requested for two round trips for six including per diem (estimated at $150/day for 5 days) and registration (based of $1800 each) for years 1-5.

International Travel-Funds are requested for round trip airfares for three to Yellowknife (estimated at $6,000) in the first year for reconnaissance and ten round trip airfares in remaining years for field work (estimated at $20,000).

F.1.5 Participant support costs

Round-trip airfares per diem and lodging are requested for 10 participants in an Arctic Biocomplexity Workshop, which will be held in conjunction with the 2003 Permafrost Conference in Switzerland.

A synthesis workshop will be held at the International Arctic Research Center in Fairbanks in year 5. Funds are requested for air fare, per diem, and lodging for 20 participants.

F.1.6 Other direct costs

Supplies/Instrumentation:

Funds are requested in year one include the following to instrument the climate and permafrost monitoring sites at Happy Valley, and the three Canadian sites:

Temperature sensor	4	$ 340	$ 1,360
Anemometer	4	$ 855	$ 3,420
Sonic snow measuring devices (SR50 Campbell)	7	$ 855	$ 5,985
Soil moisture probes (Vitel Inc.)	9	$ 280	$ 2,520
Temperature logger (MRC, multiple depths)	12	$ 750	$ 9,000
Soil heat flux plates (HFT3) Campbell)	18	$ 315	$ 5,670
Data logger (Campbell CR10X)	4	$ 1,190	$ 4,760
Multiplexer (Campbell AM416)	4	$ 575	$ 2,300
Weather tower (Campbell CMR/CM10)	4	$ 325	$ 1,300
Solar panel (HD 10 watt)	4	$ 200	$ 800
12-volt batteries	8	$ 100	$ 800
Heavometers	12	$ 200	$ 2,400
Campbell instrument shelters	4	$ 250	$ 500
Expendable supplies		$ 1,000	$ 1,000

Funding for additional years include $500 in year two for four Campbell instrument shelters and $1,000 for expendable supplies. In years 3-5 we also request funds or expendable supplies based on estimated costs of $1,000.

Services

We estimate that about 50% of the NEAML lab effort will be devoted to this project. Annual computer services including maintenance contracts, software licenses, system management, repair and replace ment are estimated to $10,000. Phone services and communication services are estimated at $800 in the first year with a 3.5% increase included for the following years.

Aerial photographs and satellite images will be needed for the vegetation mapping, and we have budgeted $3000 per year in years 1 and 2 for these costs.

Soils analysis will be performed in the Palmer Lab and $23,000 per year are budgeted for these costs.

We have estimated annual tuition cost for the grad students at $6,048 each for the first (out-of state tuition). In the subsequent years tuition is budget at $3,096 for each student.

Subcontracts

A subcontract to the International Institute of Tropical Forestry in Puerto Rico is for the services of Dr. William Gould, who will be a Co-PI and in charge of the Education component. His Ph.D. thesis was conducted along the Hood River, NWT, where he did a complete phytosociological, mapping and remote sensing study. He has conducted many arctic field ecology expeditions including the 1999 Canadian expedition for the Circumpolar Arctic Vegetation Map. He is budgeted for a $50,000/yr subcontract.

A subcontract to the University of Virginia is for the participation of Dr. Howard Epstein, who will also be a Co-PI, and in charge of the ArcVeg Model component. His Ph.D. thesis examined the ecological responses of grasses along climatic gradients in the Great Plains. He has extensive experience modeling the relationship between climate, soils, vegetation and NDVI in Alaska, Great Plains and South America. He is budgeted for a $50,000/yr subcontract.

A subcontract to the University of Cincinatti is for the participation of Dr. William Krantz, who is a senior member of the research team. Dr. Krantz developed the DFH model in conjunction with Rorik Peterson and will participate in the modeling effort.

F.1.7 Indirect costs

An agreed **modified total direct cost (F&A)** rate is set at 51.3% by the University of Alaska Fairbanks. All professional and technician salaries are increased 3% annually. All materials and service costs are estimates based on current information available at the time of the writing.

F.1.8 Logistic costs not in this budget to be covered by the LAII logistics budget.

An attached letter from Veco Polar Resources outlines the estimated costs to support this project. Their preliminary estimate is $406,363 for the five years of the project.

G CURRENT AND PENDING SUPPORT

	Source	**Title**	**Amount**	**Period**	**Commitment**	**Location**
D.A. Walker	NSF	Arctic climate change, substrate, and vegetation	$375,000	1998-1999	4 mo	University of Colorado
	Ecosystem Center	GIS support for Arctic LTER project	$15,000/y	1999-2005	0.5 mo	University of Colorado
	NSF	Supplement: Canadian Tundra transect	$66,275	1999-2000	0	University of Colorado

H FACILITIES EQUIPMENT AND OTHER RESOURCES

H.1 NORTHERN ECOSYSTEM ANALYSIS AND MAPPING LABORATORY, INSTITUTE OF ARCTIC BIOLOGY, UNIVERSITY OF ALASKA FAIRBANKS

The mission of the Northern Ecosystem Analysis and Mapping Laboratory (NEAML) is to explore and understand global tundra ecosystems and to foster responsible land use and conservation of these systems. We share a commitment to excellence in field research and teaching and making our teaching and research relevant to societal issues and concerns. NEAML's lab facilities include equipment to support vegetation and soil field research and computer equipment to support GIS and remote sensing work. NEAML's current computer configuration includes 3 SUN workstations, and 10 Macintosh computer systems. The lab maintains a full complement of peripheral devices to support our GIS and remote sensing environment. The major software packages currently used at NEAML include IMAGEZ graphic software from ONYX Graphics Corporation, ARC/Info from Environmental Research Systems, Inc. for GIS and the ENVI remote sensing software from Research Systems, Inc. For supporting plant research, NEAML is equipped with a plant-canopy analyzer, an LAI meter, a line-quantum sensor, and spectrometers. NEAML also maintains a plant sorting lab complete with dryers and freezers. To support field research in Alaska and other remote locations, NEAML is equipped with camping gear, field gear, and a 4WD truck and trailer. NEAML is located in the Institute of Arctic Biology (IAB) at the University of Alaska Fairbanks. The facilities of the Institute include a well-staffed administrative office, and a library specializing in northern topics.

H.2 UNIVERSITY OF ALASKA, PALMER RESEARCH CENTER

The Palmer Research Center of UAF has a state of the art laboratory capable of handling most of the wet chemistry procedures including SOM extraction, fractionation, and soil characterization and analysis. The laboratory is equipped with instruments funded by previous NSF project and will be available for the proposed work including O-I Oceanography Carbon analyzer, automated temperature-control incubator (MicroOxyMax Respirometer, Columbus Instruments), Buchi Rotovapor vacuum evaporator, GC. The laboratory has standard analytical equipment including HPLC, Perkin Elmer ICP Optima 3000, LECO CHS analyzer, and ion chromatograph.