PACTS

Pan-Arctic Cycles, Transitions, and Sustainability

A Science Plan

Written by the LAII Science Steering Committee

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FOREWORD

This document presents a plan for a research program—*Pan-Arctic Cycles, Transitions, and Sustainability* (PACTS)—focused on transitions and changes in arctic biophysical, biogeochemical and social systems, a component of the National Science Foundation's Arctic System Science Program. The focus of the research is the interaction of physical and living systems (e.g., the hydrological cycle and the tundra ecosystem), rather than the individual systems themselves. The guiding principles behind the research are *vulnerability* and *sustainability*: How much will changes in climate and the pathways of change affect biotic-abiotic interactions and what will the consequences be for humans, plants and animals? How might these changes feed back to the climate? Because change is inherent in all systems, we ask the question: "How vulnerable will individual components of the Pan-Arctic System be to the expected changes?"

The plan builds on ideas and research accomplishments from the Land-Atmosphere-Ice Interactions (LAII) program, but it represents a departure from previous plans by having a more explicit emphasis on biotic and abiotic interactions. Its scale and scope are larger as well, with a regional viewpoint that seeks to understand the Pan-Arctic as a large complex system. The plan provides a bridge between past interdisciplinary, geographically organized research and a more thematic structure in which system change is addressed in a way that cuts across disciplinary, geographic, and temporal boundaries.

The LAII steering committee took the lead in developing this science plan, which was reviewed by a broad segment of the ARCSS science community. The major objectives of the plan are:

1) Using new knowledge generated during LAII and other ARCSS programs, identify important unanswered questions related to arctic biophysical and biogeochemical systems, and from these questions, define the critical areas of research that will

best advance our knowledge of the Arctic System as a whole,

2) Provide a strategy and approach that can guide how the new integrated research will address the critical questions, and

3) Create a mechanism for the implementation of PACTS.

This document is intended for the use of the National Science Foundation, investigators preparing proposals, and reviewers and panels evaluating those proposals.

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Pan-Arctic Cycles, Transitions, and Sustainability (PACTS):

Biophysical, Biogeochemical and Social Systems
as Engines of Change in the Arctic

Executive Summary

The Pan-Arctic Region plays a crucial role in global change though three major pathways: fluxes of trace gases (CO_2 and CH_4), energy and water exchange between the land surface and the atmosphere, and freshwater input to the Arctic Ocean. In each of these pathways, living organisms—plants, microbes, and animals (including humans)—play important, complex, and incompletely understood roles. PACTS focuses on biophysical feedbacks and biogeochemical cycling between the biotic and abiotic components of the Arctic System. Understanding these interactions is critical to successful characterization of change and assessment of its limits of predictability, and understanding its societal impact.

Two thematic questions motivate and guide PACTS:

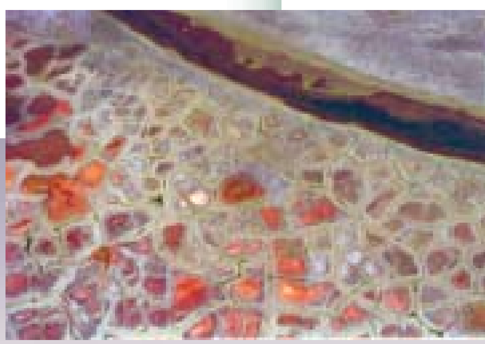
1) How vulnerable are current arctic ecosystems and food webs, and what will be required to sustain arctic societies in the face of environmental change?
2) How will changes in arctic biogeochemical cycles and biophysical feedback processes affect both arctic and global systems?

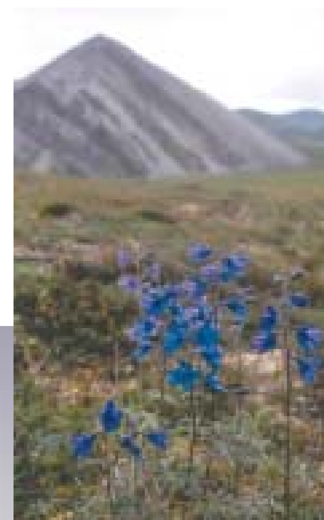
These questions evolved out of, and are consistent with, the research objectives of ARCSS, yet no other ARCSS program or initiative focuses specifically on living systems and their physical, chemical, and thermal environment.

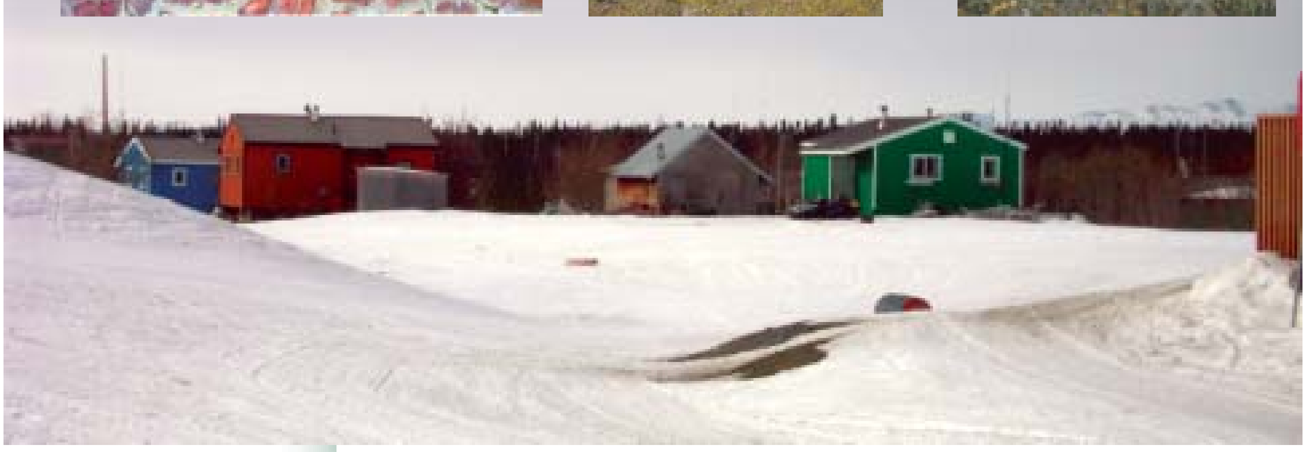
PACTS will employ the concepts of *vulnerability* and *sustainability* to link the research directly to issues with societal importance. Strong evidence suggests that some components of the Arctic System are highly vulnerable because a) the thermal state of the Arctic System is centered on the freezing point of water (0ºC), with changes in the balance of time the system spends above and below this threshold dramatically altering biotic function, b) much of the Arctic is underlain by permafrost, the thawing of which can have profound consequences, and c) there is a high dependence of many arctic peoples on critical

subsistence species like caribou, whale, and salmon. Research will be directed toward understanding what governs the vulnerability of natural and human communities and the food webs that link them, and determining to what degree human activities and natural perturbations might change the basic state or framework of the system.

In order to develop the ability to predict potential future states, PACTS research will also focus on biophysical interactions and biogeochemical cycles and transitions. These are inextricably linked at a myriad of scales, so by necessity, the Arctic will be treated as a regional complex system under PACTS with the goal of understanding the ensemble functioning of the whole system. This scale of understanding, while essential, is going to require greatly improved knowledge of the relationship between controls over short-term vs. long-term changes in ecosystems, landscapes, and regions, as well as controls on landscape-scale spatial variability. In particular, three challenges







will warrant specific attention: 1) developing the ability to separate *important* heterogeneity (that which will affect prediction) from that which is *unimportant*, 2) determining which feedback mechanisms will stabilize (vs. destabilize) the system when multiple mechanisms are operating, and 3) differentiating primary from secondary or tertiary system responses so as to ensure that response time scales are appropriate to the questions and predictions of interest.

PACTS research will be pursued using (though not limited to) the following approaches:

1. Process studies that permit the development of parameterizations for regional and global models linking biotic and abiotic systems.
2. Manipulations or comparison experiments conducted at spatial scales sufficient to incorporate landscape heterogeneity.
3. Observations that contribute to spatial and temporal scaling.
4. Modeling and observations that identify parameters to which the Arctic System is most sensitive, and which may prove the most useful in developing predictive scenarios.
5. Vulnerability assessment to determine consequences of the coupled interactions between the Arctic System and human activities.
6. Space-for-time and time series comparisons; integration of paleo-records with modern time series and process studies.
7. Integration studies related to biotic-abiotic interactions that bring together results from other NSF programs.

PACTS will also have a strong community outreach component, through education and mentoring in the scientific community, through outreach to the general public through the news media, museum displays, and most importantly, through researcher-to-arctic resident contacts.

1. INTRODUCTION

The Arctic System supports a wide range of plants and animals, as well as human inhabitants. The life and health of arctic peoples and living things are intimately coupled to the physical parts of the system, the atmosphere, water cycle, soil, and rocks, through a complex web of biophysical, biogeochemical and social pathways. Under a changing climate, it is possible that step-like changes, potentially larger than observed in historic times, could take place within a generation, and that these would affect arctic life in a profound way. In that sense, the Arctic is a vulnerable place. Pan-Arctic Cycles, Transitions, and Sustainability (PACTS) *seeks to further our understanding of the interconnections between arctic living systems and their physical environment, and more specifically, to assess the response of these systems to change.*

1.1 Global Change and the Pan-Arctic Region

The Pan-Arctic Region plays a crucial role in global change not only because it responds sensitively to changes in the Earth System, but also because those responses feed back to and affect the Earth System as a whole. There are three major pathways by which these feedbacks are known to occur:

1) *Fluxes of trace gases, such as CO_2 and CH_4.* These affect the radiative forcing of the atmosphere and therefore global climate. Large stores of carbon found throughout the Arctic (Michaelson et al., 1996; Ping et al., 1997; Dai et al., 2002), sources of methane and CO_2, have the potential to influence the global trace gas budget in important ways. Research, some of it done under the LAII program, has focused on quantifying the arctic CO_2 budget (Zimov et al., 1993, 1996; Oechel et al., 1993, 1997, 2000a; Welker et al., 2000; McGuire et al., 2002) and investigating the fate of

the stores of carbon in the active layer and permafrost, but many issues associated with arctic trace gas fluxes remain unresolved.

2) *Energy and water exchange between the land surface and the atmosphere.* Alterations in albedo and energy partitioning in the boundary layer will affect local and regional arctic climates (Geiger, 1957), which, in turn, will interact with, and affect, the global climate system. The sea ice albedo feedback mechanism (Dickinson et al., 1987; Ingram et al., 1989; Moritz et al., 1993) is one well-known example where changes in arctic surface conditions could have profound global climate ramifications. Similarly, changes in the extent and residence time of long-lasting areas of terrestrial snow cover (Kellogg, 1973; Brown and Ward, 1996), or changes in the distribution of shrubs (Sturm et al., 2001a) and trees (Rupp et al., 2001; Lloyd and Fastie, 2002), with concomitant changes in surface energy balance (Beringer et al., 2001), could also have a large impact on regional weather (Pielke and Vidale, 1995; Lynch et al., 2001) and therefore global climatic conditions. With much of the arctic land mass covered by vegetation, land surface conditions have the potential to change on relatively short time scales, and could feed back in non-linear and unexpected ways to the climate. Such changes involve tightly coupled biophysical and biogeochemical cycles about which we still have much to learn.

3) *Freshwater input from arctic rivers to the Arctic Ocean*. Freshwater input from arctic rivers to the Arctic Ocean influences the strength of the thermohaline circulation, which exerts a major control over Earth's climate system (Broecker, 1997; Carmack, 1990, 2000). Large changes in the state of the global climate system in the past (e.g., the Younger Dryas) have been attributed to disruptions in thermohaline circulation (Rühlemann et al., 1999). Ultimately, many processes affect the arctic hydrologic cycle, the discharge of fresh water into the Arctic Ocean, and the role of this water in global climate, making this a research area where fully integrated and multi-disciplinary research is essential. In arctic basins and watersheds, interactions between soil, soil moisture, microbes, plants and run-off are particularly complex because of the presence of permafrost and a seasonally frozen active layer and snow cover (Vörösmarty et al., 2001).

These three pathways share a common trait: key physical processes (e.g., trace gas flux, run-off, energy exchange) are mediated in important ways by biota. In each of these three pathways, living organisms—plants, microbes, and animals (including humans)—play important, complex, and incompletely understood roles. The biota directly and indirectly affect trace gas fluxes, land surface conditions, run-off, and the hydrologic cycle. Through thermal impacts on permafrost, changes in surface roughness and albedo, modification of subsurface water storage, and in a myriad of other ways, living things cause changes in, and simultaneously respond directly to, the changing Arctic.

These living systems are inherently complex, and they are tightly coupled to the physical and chemical components of the Arctic System. This tight coupling has challenged our attempts to understand and predict future changes. Changes in one part of the system are certain to produce a cascade of effects in another part. For example, as the climate warms, Alaskan tundra may be in the process of being converted into shrub tundra (Chapin et al., 1995; Sturm et al., 2001b). The increased shrub canopy produces changes in shading and surface litter (Chapin et al., 1995) that impact the active layer. Soil moisture storage (Kane et al., 2001) and snow cover depth and duration (Sturm et al., 2001a) are also affected. These, in turn, can either increase or decrease trace gas fluxes, depending on the time scale (Oechel et al., 2000b). With increasing shrubs there is a change in herbivory (forage), which may eventually transform subsistence hunting. At a larger scale, a widespread increase in shrubs could have a large impact on surface energy exchange through alterations in albedo and roughness (Pielke et al., 2002).

In short, understanding and predicting the role of the Arctic in global change requires understanding the hydrologic, biophysical, and biogeochemical feedbacks that exist *between* biotic and abiotic components. Although a reductionist approach, wherein individual system parts are studied, is a useful component of achieving an understanding of the Arctic System, alone it is unlikely to be successful. In this plan, we take a complex, Pan-Arctic approach that centers on the interaction of biotic and abiotic systems, and in which focused studies are integrated into a whole-system scope. We believe this approach is a necessary step toward understanding the Arctic System as a component of the global Earth system in the context of global processes and change.

1.2 Why Study Global Change in the Arctic?

If our goal were solely to understand global change, we would still need to focus considerable attention on the Arctic. It has an outsized impact on the global climate system as discussed above, and for that reason alone it is essential that we understand how it functions. In addition, the Arctic is home to many people for whom local and regional changes will have important effects. We need to anticipate, and wherever possible, predict these changes, recognizing that in some cases it will be impossible to anticipate all the impacts of change. Where such limitations exist, we will strive to clarify the vulnerabilities and in the case of human society, suggest practical adaptations. A third reason to study the Arctic, however, is equally compelling: the Arctic is potentially one of the best places to develop an understanding of a complex system at a regional scale. This type and scale of understanding is needed, not just in the Arctic, but wherever we hope to anticipate and deal with environmental change. While all communities are unique in some ways, models for the development of policies that enhance the resilience of Arctic communities in the face of environmental change can be used to provide lessons for communities around the world.

Several conditions simplify the complex regional system problem for the Arctic and make achieving understanding more likely:

1) The Arctic System is more “closed” than most other regional systems, with fluxes into and out of the system often constrained to well-defined pathways. The unusual geography, a central ocean ringed by land with most rivers flowing into the Arctic Ocean, limits freshwater export from the Arctic to a few narrow and well-constrained locations (Fram Strait, Davis Strait, the Bering Sea) (Carmack, 2000), while equator-to-pole thermal gradients ensure a general northward movement of atmospheric heat and moisture.

2) Recent rapid changes in arctic climate, possibly the result of polar amplification of global climate change (Kattenberg et al., 1996), have caused distinct and readily

observed effects in the structure and functioning of Arctic ecosystems (e.g., Serreze et al., 2000). As a result, the Arctic can provide an opportunity to study a system in transition. In addition, well-developed paleoecological records (Ager, 1983; Anderson and Brubaker, 1993; Brubaker et al., 1995; Hu et al., 2002) tell a story of a region that has repeatedly undergone profound land surface changes in the past. These records can be used to place current observations and experimental results in context and inform us of the range of possible changes that might occur.

3) Low species diversity and reduced structural complexity of ecosystems make the Arctic System more feasible to study than those farther south where higher diversity can obscure trends and function. For comparison, the arctic regions have about 1200 species of vascular plants (Hultên, 1968) while the tropics support nearly 250,000 species (Campbell and Hammond, 1989).

4) The coupling of biological and physical systems is extremely close; arctic plants and plant communities cannot be understood without understanding the geophysics of the winter snow cover, soil conditions, and the nature and fate of fresh water. Microbial processes in soil are strongly constrained by soil conditions, including permafrost depth. Permafrost depends on the snow, on the summer air temperature, and the nature and albedo of the prevailing plant cover. The export of nutrients to the ocean depends on run-off, land cover, and stream processes, while arctic fishes and animals depend on all of the above.

5) Arctic biophysical and biogeochemical linkages between the atmosphere, and arctic biota, soils, and permafrost are often readily apparent and produce strong feedbacks that make them easier to trace and study.

6) Finally, in the Arctic the climate signal is less "contaminated" by local human impacts like encroaching urbanization, deforestation (or reforestation), and agricultural use, making it easier to relate changes in land surface and other biotic systems to global and regional climate signals. The impact of changing climate on arctic residents, who typically rely more heavily on subsistence activities

than residents of industrialized countries at lower latitudes, is also likely to be amplified. This provides a unique opportunity to study the effects of climate change on human activities.

Integrated system studies of the Arctic are crucial to understanding global change because of the potential for strong feedback between the Arctic and the globe. For the reasons outlined above, these studies could also provide the lead in learning how to deal with complex systems at a regional scale outside of the Arctic.

1.3 A Focus on Biophysical, Biogeochemical, and Social Cycles and Transitions

Three thematic questions will motivate and guide ARCSS in the next five years (ARCUS, in press):

1) *How do human activities interact with changes in the Arctic to affect the sustainability of ecosystems and societies?*

2) *What are the limits of Arctic System predictability?*

3) *How will changes in arctic cycles and feedbacks affect arctic and global systems?*

These questions cut across the three physical realms—land, sea and air—that have been the basis for the subdivisions in the ARCSS Program for the past decade. The questions emphasize cycles or processes that occur at the transition between realms, and in many cases they require knowledge coupling two or more realms. All three questions have a direct or implied human aspect, an important element because ARCSS research needs to inform and guide societal decisions and the development of wise policy related to environmental change. Inherent and fundamental to each of the questions is the role of biota, including humans, in the Arctic System. While on-going and planned ARCSS initiatives (see *Box 1*) address some interactions of biological and physical systems, none has a specific focus on this crucial area. Yet this is an area where it is essential that we achieve a solid understanding if we are to answer the three key ARCSS questions listed above. We therefore believe a research program (PACTS) focused on biophysical and biogeochemical interactions is essential to the ARCSS Program. PACTS addresses these interactions through two thematic questions examined more fully in Section 2:

1) *How vulnerable are current arctic ecosystems and food webs, and what will be required to sustain arctic societies in the face of environmental change?*

2) *How will changes in arctic biogeochemical cycles and biophysical feedback processes affect both arctic and global systems?*

1.4 Biophysical and Biogeochemical Research in ARCSS

Over the past decade, three LAII projects—the Flux Study, ATLAS and ITEX (*Box 2*)—have focused on terrestrial biotic systems, particularly plant systems, with an emphasis on trace gas, energy and water fluxes from these systems and their biophysical and biogeochemical controls. As a result of this research, substantial progress has been made in improving our understanding of the exchanges of energy and mass between the land surface and the atmosphere, as well as elucidating the controls on this exchange. In addition, the LAII results have shown the value, in fact the essential nature, of conducting integrated multi-disciplinary studies to achieve this understanding. At the same time, the work highlighted the practical, programmatic and human difficulties involved in developing this high level of integration. During the LAII program, researchers developed an open, collaborative attitude, sharing data and ideas, that led to better system science results. The ARCSS and LAII infrastructures were essential to fostering this collaborative spirit, and a group of researchers now exists who fully embrace this mode of work. A new generation of graduate students brought up under the system are now researchers in their own right, and are prepared to undertake the research highlighted in this document.

ATLAS
Arctic Transitions in the Land-Atmosphere System (part of LAII)

CHAMP
pan-Arctic Community-wide Hydrological Analysis and Monitoring Program

Flux
Study of energy, moisture and trace gas fluxes in the Arctic (part of LAII)

HARC
Human Dimensions of the Arctic System

ITEX
International Tundra Experiment (associated with LAII)

LAII
Land-Atmosphere-Ice Interactions

LSI
Land-Shelf Interactions

NATEX
North American Tundra Experiment (part of ITEX)

OAII
Ocean-Atmosphere-Ice Interactions

PARCS
Paleoenvironmental Arctic Sciences

RAISE
Russian-American Initiative on Shelf-Land Environments in the Arctic

SBI
Western Arctic Shelf-Basin Interactions

SHEBA
Surface Heat Budget of the Arctic Ocean

TEA
Teachers Experiencing Antarctica and the Arctic

Box 1: Acronyms of ARCSS programs and projects.

As a result of LAII research, we now have a reasonable understanding of the vertical coupling between the land surface and the atmosphere, particularly with respect to the exchange of energy, mass, and trace gases. Where landscape heterogeneity is not severe, or where the heterogeneity can be determined using remote sensing, processes can be interpolated between points with some confidence. Models have expanded from plot- to basin-scale and beyond. For some processes, pan-Arctic models have been developed. However, the past decade of research has also shown with great clarity that point processes cannot adequately describe complex biotic systems that are inherently coupled by lateral transport processes and the movement of energy and mass from one heterogeneous element of the landscape to another. LAII research and other work has also shown that the end points of spatial and temporal extrapolation curves are rarely connected in a linear fashion (Fig. 1), and that prediction of future states requires understanding real rather than idealized trajectories of change (Shaver et al., 2000). Moreover, there is an awareness that abrupt state transitions frequently occur, and that these can ramify through the system rapidly. The growing awareness of such phenomena has emerged recently, driving home the point that we have much to learn about the interactive functioning of arctic terrestrial biotic and abiotic systems.

Project	Start	End	Focus
Flux Study	1993	1998	*A multi-university effort to investigate the variables and processes controlling the fluxes of CO_2, CH_4, water, nutrients and energy between arctic terrestrial ecosystems and the atmosphere.*
NATEX	1995	2003	*An international network designed to monitor the performance of plant species, communities, and ecosystems on a circumpolar basis in undisturbed habitats with and without environmental manipulations in order to ascertain the response to climate warming.*
ATLAS	1998	2003	*A multi-project study to determine the geographical patterns and controls over climate–land surface exchange (mass and energy) and to develop reasonable scenarios of future change in the arctic system.*

Box 2: A chronology of LAII projects.

Multi-disciplinary research similar to that conducted under LAII has started in OAII. Project SHEBA, part of OAII, focused primarily on the ice albedo feedback mechanism and the exchange of energy over the ice pack. A modest companion program on marine biology was instituted under SHEBA, but a full synthesis and collaboration was not achieved. Now, however, the Western Arctic Shelf-Basin Interactions project (SBI) is underway and directed at elucidating the underlying physical and biological shelf and slope processes that influence the structure and functioning of the Arctic Ocean, with the goal of developing enhanced predictive capability for global change impacts in the Arctic. The expected results should provide knowledge of marine biotic-abiotic interactions analogous with LAII results linking terrestrial physical and biological processes. In a slightly different way, research in HARC has also always had a strong biotic component, but as a general rule, HARC research has relied upon findings from other programs to elucidate the connections between biotic and abiotic systems. It seems likely that many of the same core questions related to complexity and biotic-abiotic interactions that arose in LAII are likely to surface as SBI and HARC mature.

In short, the past decade of ARCSS research, while achieving good success, has produced a new set of issues and questions, more fascinating perhaps than the original questions, and probably more difficult to address. One set of issues concerns the spatial and temporal extrapolation of complex processes, while the other relates to identifying real trajectories of change. These are the types of issues that must be resolved in the next phase of research if we are to achieve our stated goal of understanding the Arctic System, and they are core issues of PACTS research.

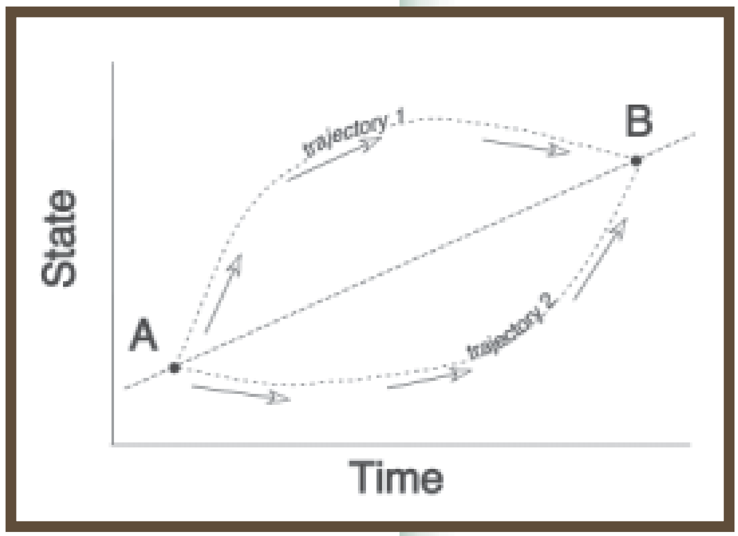


Figure 1: A schematic showing how a temporal change in state (from A to B) might be realized in two quite different ways (trajectories). Linear extrapolation between states (straight dashed line) would either under- or over-estimate state changes, depending on trajectory and the time span of interest. If we are attempting to predict the response over the time (B-A), then the linear extrapolation will be accurate, but if we are trying to predict the response over shorter periods, then large errors would result.

2. PACTS RESEARCH QUESTIONS

2.1 Core Questions

PACTS builds on the three ARCSS theme questions (*Box 3*) by focusing specifically on the critical biotic-abiotic interactions that underpin these themes. Two over-arching questions guide PACTS research (*Box 4*). Each has a number of important subsidiary questions:

1) *Sustainability and Vulnerability*: How vulnerable are current arctic ecosystems and food webs, and what will be required to sustain them in the face of environmental change?
   a) What governs the vulnerability of ecological and human communities and the food webs that link them?
   b) To what degree will human activities and natural perturbations change the basic state or framework of arctic ecosystems?

2) *Cycles and Transitions*: How will changes in arctic bio-geochemical cycles and biophysical feedback processes affect both arctic and global systems?
   a) How do spatial and temporal heterogeneity affect processes and our ability to predict the ensemble behavior of a complex system like the Pan-Arctic?

Box 3: Three ARCSS theme questions

- *How do human activities interact with changes in the Arctic to affect the sustainability of ecosystems and societies?*
- *What are the limits of Arctic System predictability?*
- *How will changes in arctic cycles and feedbacks affect arctic and global ecosystems?*

Box 4: The core questions of PACTS

- *Sustainability and Vulnerability*
- *Cycles and Transitions*

b) What is the nature of the complex interplay of competing and complementary feedback processes?
c) How does the existence of "hot spots," non-linear effects, or the potential for multiple temporal trajectories affect system behavior and therefore our ability to make meaningful local and pan-Arctic predictions?

The two core PACTS questions evolved out of the revised research objectives of ARCSS, as spelled out in *Box 3*, as well as the 1998 ARCSS science plan *Toward Prediction of the Arctic System* (ARCUS, 1998). In 1998 the chief scientific goals of the ARCSS Program were defined as 1) understanding the biophysical and social processes of the Arctic System that interact with the total Earth System and thus contribute to or are influenced by global change, and 2) advancing the scientific basis for assessing predictability of environmental change on a decade-to-centuries time scale, and for formulating policy options in response to the anticipated effects of global changes on human beings and societal support systems.

We find these goals just as germane and compelling today as they were four years ago, but we realize that in order to achieve the stated goals, the questions we ask need to be formulated in ways that ensure we focus our research on those areas most critical to understanding and most likely to produce useful results. PACTS fills a unique role in the ARCSS family with its focus on living things, and the interaction of these living systems with their physical, chemical and thermal environment. With this focus, we can use the concept of sustainability (*Box 5*) in PACTS to link the research directly to issues with societal importance. Sustainability provides a bridge between the natural science focus that has existed and dominated ARCSS since its inception, and the need to provide a sound scientific basis for sustainable management of the ecosystems with which human societies interact. It also provides a framework around which practical and achievable goals for prediction can be defined. We use the concept of vulnerability (*Box 5*) to address issues related to what level of forcing is required to initiate and sustain change.

2.2 Research Details

2.2.1 *Sustainability and Vulnerability*: How vulnerable are current arctic ecosystems and food webs, and what will be required to sustain arctic societies in the face of environmental change?

While we may be able to predict the *range* of possible future arctic states, it is unlikely that we will be able predict with precision the *exact* future state of the Arctic System. A more productive approach to the question of prediction, therefore, is to assess the vulnerability and sustainability of Arctic Systems: What is the range of perturbations to which system components can be subjected and still return to their original state (resiliency)? Which components are the most vulnerable, and if these do change, will they cause irreversible changes in the more stable components? Under a given set of observed or predicted changes, how well will the system continue to support humans and animals? How sustainable are subsistence hunting/gathering and resource extraction in the face of likely future changes in climate? Through vulnerability analysis, research attention in PACTS will be focused

Box 5: Glossary of terms related to vulnerability and sustainability

— *Arctic System*: A coupled system of atmosphere, oceans, land, and its residents. It includes the Arctic Ocean, circumarctic terrestrial ecosystems, and the lower-latitude oceans and lands that directly influence them.

— *Predictability*: Capacity to predict the future state of a system, usually not in a precise way, but rather as a scenario or within a range of states.

— *Regional biocomplexity*: Interactions in a regional system resulting from positive and negative feedbacks between biotic and abiotic systems, legacies of past events, and non-linear responses to change.

— *Resilience*: Speed of return to the original state after a perturbation.

— *Resistance*: Capacity to maintain the current state in the face of perturbation.

— *Stable:* Resistant to change; requiring strong forcing to initiate change.

— *Sustainability*: Ability to maintain important physical, biological, and social properties of a local or regional system.

— *Vulnerability*: Susceptibility to long-term or sudden change; opposite of resilience.

on those components of the Arctic System that are most vulnerable to change, thereby concentrating scarce scientific resources in priority areas for research. In addition, in order to achieve successful assessment of vulnerability, knowledge will need to be integrated across biotic and abiotic system boundaries, thereby producing multi-disciplinary synthesis and integration. The process of determining vulnerability will also have the added benefit of focusing research on those issues most relevant to the human residents of the Arctic System, forging a natural linkage between PACTS and programs like HARC.

Assessing vulnerability, or if we are dealing with human systems, sustainability, requires that the spectrum of environmental and human threats to a resource or system be evaluated and prioritized with respect to their likelihood of occurrence, the potential damage if they do occur, and the combination of adaptation or mitigation necessary to reduce the risk. Concepts of vulnerability and sustainability have been applied at local to regional scales (Downing et al., 2001; Kabat, in press). Interestingly, in the Arctic, vulnerability and sustainability, as defined in the previous paragraph and in *Box 5*, may often depend as much on changes in the timing of events or the frequency of extreme events as on changes in the mean state of environmental conditions. For example, a short sharp freeze after bud-burst can produce a more deleterious effect on tundra than a marked reduction in either the average winter or summer temperature. Similarly, rain-on-snow events are currently a rare phenomenon, but if they were to occur with greater regularity, caribou and other winter grazers that rely on digging away the snow could suffer serious adverse impact. Using the concept of vulnerability, we can move away from more simplistic measures of global and regional change (e.g., a 4° warming) and begin to focus on the true complexities inherent in all environmental change.

Evidence suggests that some components of the terrestrial Arctic System are highly vulnerable, or in the case of arctic communities, not easily sustained if conditions change (Vörösmarty et al., 2000). This high vulnerability appears to arise from at least three sources:

1) The Arctic System functions in a thermal state that is nearly centered on the critical threshold condition for the freezing point of water (0ºC). There are dramatic

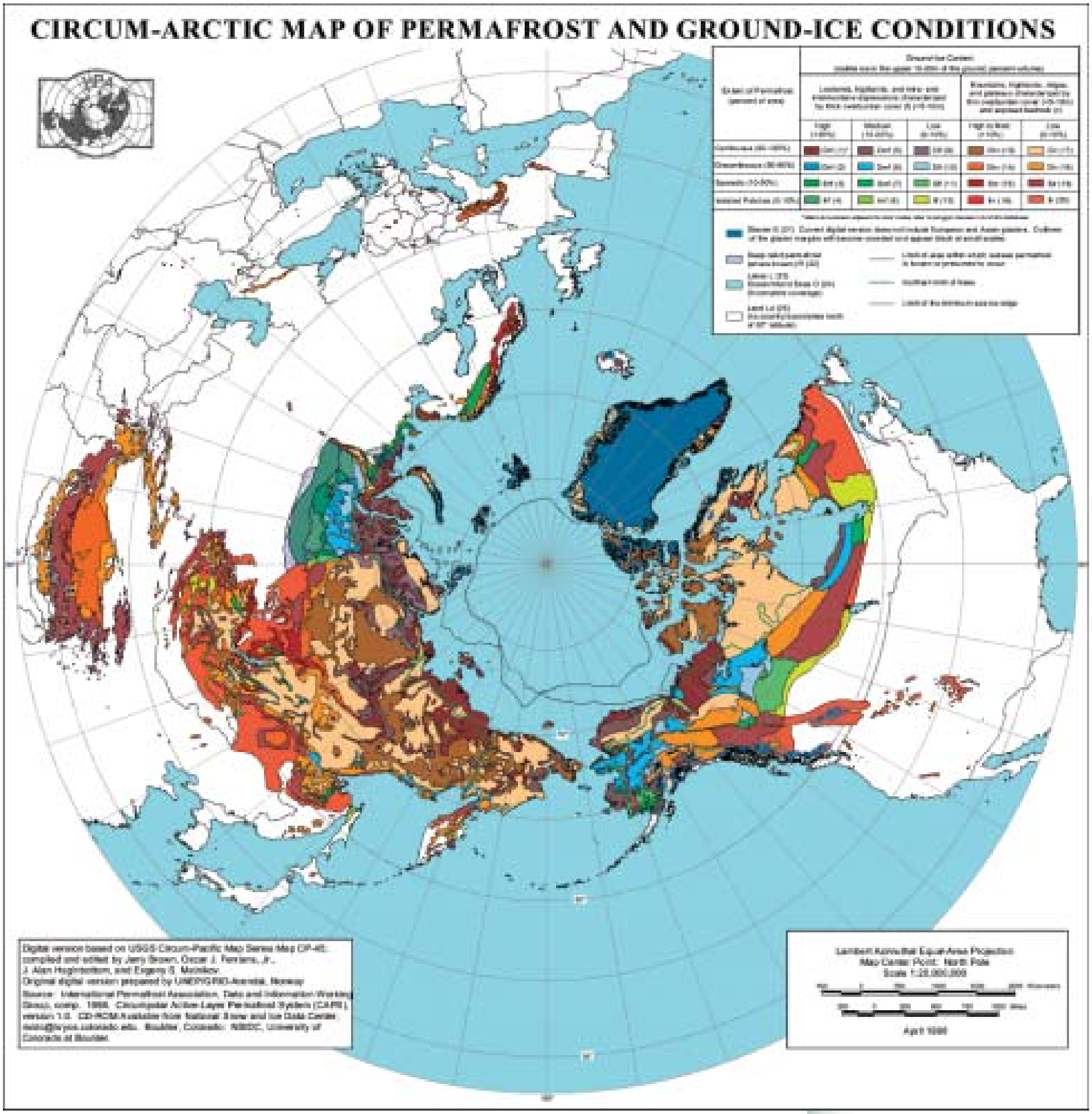


Figure 2a: Map of the distribution of permafrost in the Arctic (colors represent different classes of permafrost and varying levels of soil ice content) (Brown et al., 1998).

changes in all components of the system when this threshold is crossed. Changes in the balance of time that the system is above and below this threshold will dramatically alter its functioning.

2) Much of the Arctic is underlain by permafrost (Fig. 2a) (Brown et al., 1998; Hinkel and Nelson, in press). The existence of permafrost requires maintenance of a thermal state that is affected by abiotic (temperature, radiation,

snow cover, hydrology), biotic (moss, shrub canopy, soil microbes), and mixed (interaction of shrubs and snow) factors (see Fig. 2b). Not only can the mean state of these factors influence the permafrost and active layer conditions, but the phenology of these factors will have a marked impact on active layer and permafrost as well. Changes in permafrost produce a cascade of changes in biotic and abiotic components of the soil (McGuire et al., 2002) (Fig. 3), with changes in soil moisture one of the most important ramifications. A graphic example: the thaw lake cycle on the Arctic Coastal Plain of Alaska, where changes in permafrost can convert tussock tundra into a lake (Black and Barksdale, 1949).

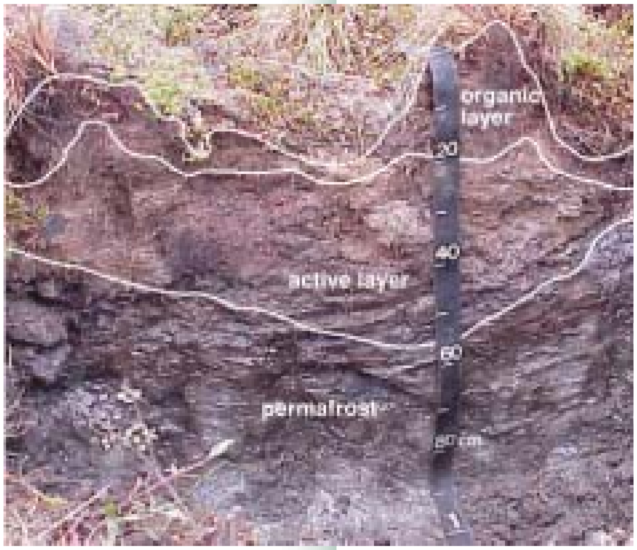


Figure 2b: A soil pit in tussock tundra showing the organic layer, active layer and the permafrost underlying them.

3) There is a high dependence of many arctic people on subsistence species like caribou, fish, and whale that are more vulnerable to changing environmental conditions than species from lower trophic levels.

Two questions emerge as important foci for research related to sustainability and vulnerability:

1) *What governs vulnerability of natural and human communities and the food webs that link them?*

The vulnerability of ecological communities depends on present-day interactions between biota and the physical environment, and on potential future changes in biota, environment and interactions (e.g., migration or extinction of species or loss of permafrost). Vulnerability is thus a dynamic property of an ecosystem, and can be expected to change over time as the structure and function of ecosystems change. Under changing climatic conditions, ecosystems are constantly trying to adapt to new conditions, but due to response times that can vary widely, they are unlikely to be in steady-state or in balance with external conditions. One emphasis of PACTS will be to investigate

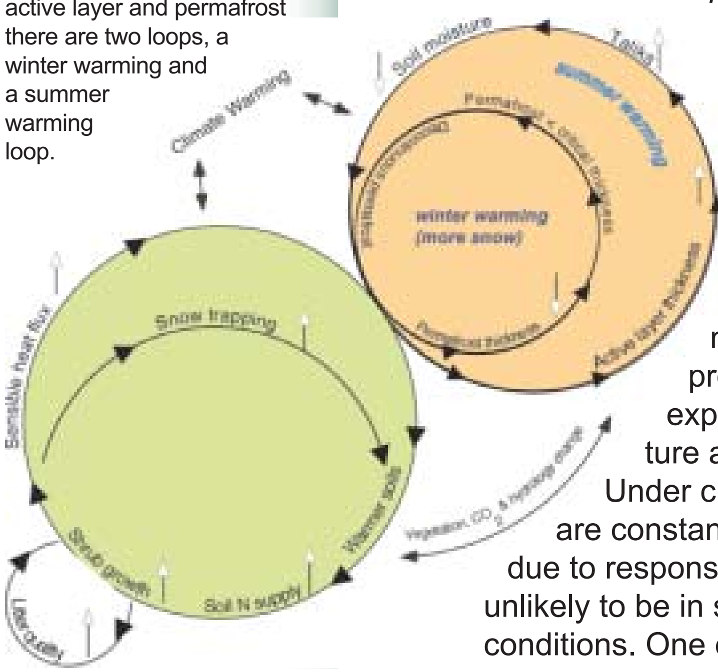


Figure 3: The complex linkages between permafrost, active layer, snow depth, plant community make-up, soil microbes, and soil nutrients. Open arrows indicate the direction of change. Solid black arrows indicate feedback loop cause-and-effects. Note that for the active layer and permafrost there are two loops, a winter warming and a summer warming loop.

the controls over vulnerability at a wide range of scales. Particular attention will be paid to two-way effects: the effects of environmental conditions on the ecosystem, and the effects of the ecosystem on the local to regional climate and environment.

Research will be expanded beyond the assessment of vulnerability by examining food webs (Fig. 4). Organisms (including humans) and communities are linked together through these webs. By analyzing the webs, we can identify the linkages through which community interactions take place. For example, humans participate in both marine and terrestrial food webs through subsistence hunting and gathering. Socioeconomic conditions can result in a change in community dependence on subsistence. This will impact both terrestrial and marine food webs, and the perturbations the changes cause in the webs can illuminate how these systems are linked and how they function. Unlike vulnerability assessment, which tends to focus on those system components most susceptible to change, the examination of food webs tends to focus on the interconnections between components.

Figure 4: Food webs link together life in the Arctic, as exemplified by these grazing caribou.

2) *To what degree will human activities and natural perturbations change the basic state or framework of arctic ecosystems?*

Perturbations include both distant effects related to global changes in climate, and local effects resulting from human social and economic activities within the Arctic. Studies of the effects of global change pervade all aspects of Arctic System Science and will be an important part of PACTS, but in addition, human effects on the ecosystem will also be investigated, an activity that is not currently in other ARCSS programs. Two human activities within the Arctic of particular importance are the cumulative impacts of industrial development, and the effects of human use of biological resources (including forestry, wildlife, and fisheries). Natural perturbations, such as long-term changes in P-E (precipitation minus evaporation), are also likely to be important.

2.2.2 *Cycles and Transitions:* How will changes in arctic biogeochemical cycles and biophysical feedback processes affect both arctic and global systems?

Our understanding of biophysical interactions and biogeochemical cycles and transitions, the time scales on which they operate, and the way they vary across the arctic landscape, feed directly into our ability to make meaningful predictions of future states. Although the goal of precise prediction is probably unattainable, policy and management decisions rely on science to provide some description of the range or limits of future states. The second research area of PACTS, therefore, focuses on determining the range of future conditions that might be experienced in the Arctic. It requires not only a sound understanding of the basic processes at work in biophysical interactions and biogeochemical cycles, but also how they interact and how their function and interaction might change in the future. This approach complements the sustainability/vulnerability assessment described previously, which tends to highlight sensitivity to change, by focusing on the processes and mechanisms that control and moderate change.

The task of developing reasonable scenarios of future change can only be accomplished by approaching the Arctic as a regional complex system. Virtually all the biogeochemical cycles are linked at myriad scales and are heavily moderated by biophysical interactions throughout. Through these cycles and interactions, biotic community composition and structure can change, altering the climate near the ground, the food webs, and the strength and nature of the biogeochemical cycling. Both positive and negative feedback effects can be generated. Through the active mixing they produce, stream and river water systems—and the hydrologic cycle in general—ensure that complex linkages exist across a wide range of scales. Terrestrial biotic-abiotic interactions are linked to marine interactions through the export of freshwater and nutrients, and through impacts on climate.

Approaching biotic-abiotic complexity at a regional scale is new, and, given the limited state of our current understanding of complex biotic-abiotic systems, a real challenge. This scale of understanding, while essential, is going to require greatly improved knowledge of the relationship between controls over short-term vs. long-term changes in ecosystems, landscapes, and regions. Improving our knowledge and understanding of "hot spots" (locations where processes and fluxes are enhanced), non-linear effects, and the potential for multiple temporal trajectories (Fig. 1) will be of particular importance because these may be dominant features at the regional scale. Our ability to make meaningful Pan-Arctic predictions will probably hinge on successfully distinguishing those aspects of the Arctic System that cannot be predicted with simple models from those that can, while developing the ability to separate intermediate from final responses to the changing conditions.

In particular, three challenges related to biophysical interactions and biogeochemical cycles have emerged from prior research efforts that will warrant specific attention in PACTS research. First, like all systems, the Arctic is heterogeneous, and that heterogeneity in time and space confounds our current ability to extrapolate and predict change based on the limited understanding of processes we currently hold. We lack, at this point, the ability to separate *important* heterogeneity (that which will affect prediction) from *unimportant* heterogeneity (that which can be safely ignored). Second, the strong feedbacks between biotic and abiotic systems can act to either stabilize or destabilize the system, leading to a wide range of possible trajectories of future change, which vary in both magnitude and direction of change. Taken one at a time, we can usually distinguish damping from amplifying interactions, but when all feedback mechanisms are operating at once, complex, non-linear interactions make even the sign of the effect difficult to ascertain. Third, trajectories and rates of system change vary across temporal scales that range from seasons to millennia, and from one landscape to another. Primary responses may actually be opposite in sign to secondary or tertiary responses (Fig. 1). Our "understanding" of a particular response may be appropriate over the time scale on which the understanding was based (perhaps a decade), but we may be asked for predictions over much longer (century) intervals, where our information is no longer valid.

Landscape heterogeneity and connectivity: Our ability to produce accurate spatial extrapolations, particularly those that will allow Pan-Arctic prediction and regional assessment, requires that we identify the relevant spatial scales over which key biophysical and biogeochemical processes occur, and that we identify the regions and time scales at which our current models are most likely to fail. Effective spatial extrapolation is an iterative process based on observations and experiments, incorporation of the resulting understanding into models, validation of model prediction at new sites with new observations, etc. Because we cannot measure everything everywhere all the time, we suggest three criteria for initial studies aimed at improving spatial extrapolation.

1) We must develop the initial studies with *sufficient spatial replication* to identify those system properties that can be generalized.

2) Studies must be *mechanistic* enough to identify and analyze critical processes and interactions.

3) Validation sites should be selected that represent *strong tests* of our ability to extrapolate. A strong basis for spatial extrapolation, for example, requires study of new sites that differ in important ecological, atmospheric, and hydrologic properties from sites where models were originally developed.

In addition, we need to encourage and facilitate the development of data bases covering large regions of the Arctic or the full Pan-Arctic system (Fig. 5). These data bases can be used as a basis for extrapolation or as test beds against which model products can be compared.

In the LAII program, considerable progress was made in understanding the complex dynamics that occur in Arctic Systems and in relating short-term measurements at one spatial scale to measurements made at other scales. There are, however, several remaining challenges. First, there are still processes, particularly some of those that occur below ground and in winter, that we do not understand sufficiently to model with

Figure 5: The Circum-Arctic Vegetation Map (CAVM) (Walker et al., 2002) is an excellent example of the type of regional data base, produced as part of LAII, that will be needed for PACTS research.

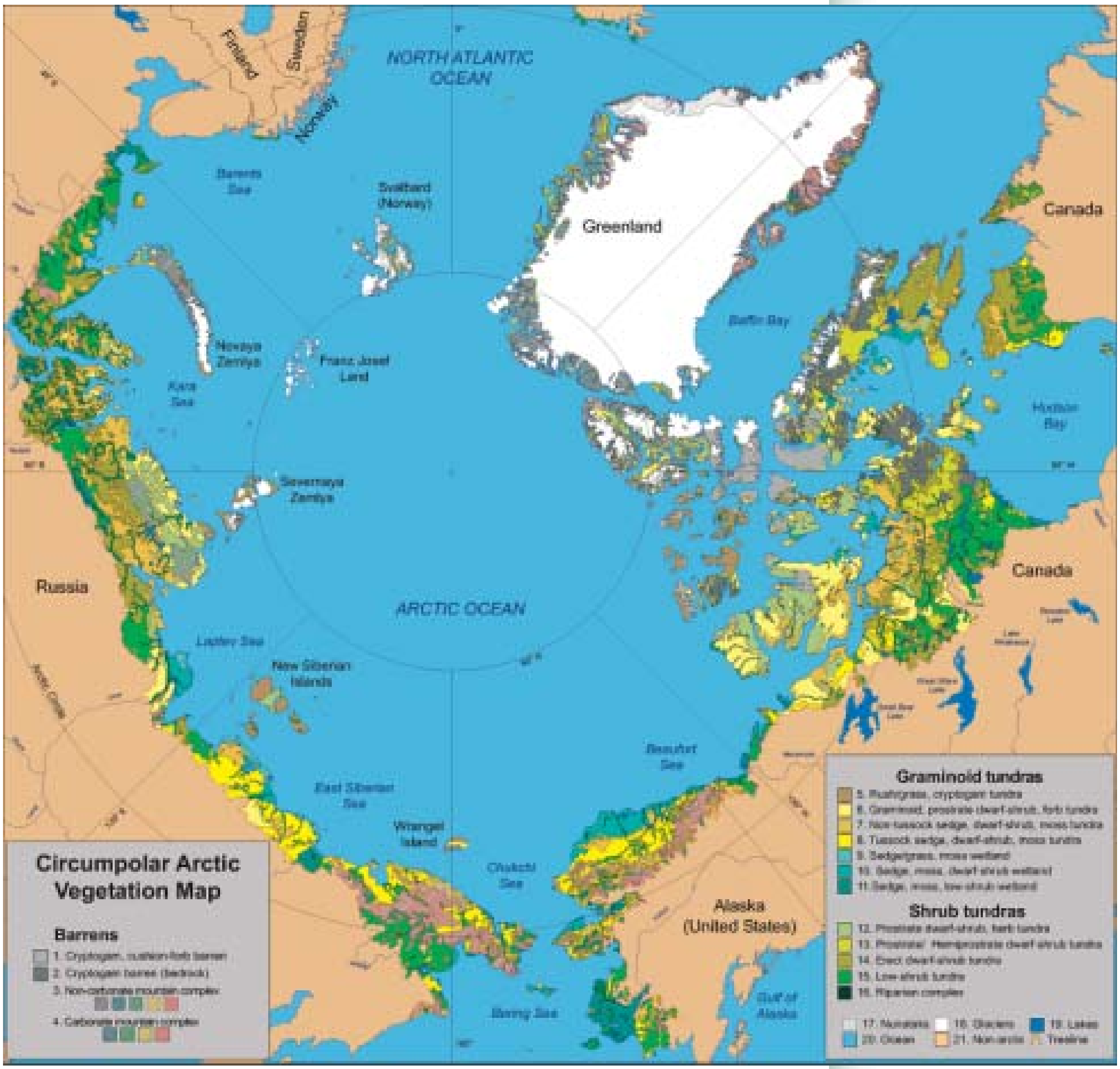


Figure 6: Much remains to be learned about many areas where biotic and abiotic systems interact. One area in particular is those processes occurring below ground and in winter. Here, a typical arctic Alaskan winter snow pack overlies tussock tundra and shrubs.

any confidence (Fig. 6). Second, we need to develop scaling strategies based on the underlying processes that allow predictions at large temporal and spatial scales. Spatial extrapolation requires an understanding of the spatial scale of important processes and the errors associated with aggregation. For example, the development of mesoscale circulation models requires patches that are about 10 km in width, and hydrologic modeling requires inclusion of all upstream components within a catchment or drainage basin, e.g., the boreal portions of major Eurasian rivers that drain into the Arctic Ocean. Models developed for spatial extrapolation may need to evaluate scaling issues related to spatial patterns (e.g., slope and aspect or degree of continentality) and horizontal interactions (e.g., land-water linkages). Research on spatial scaling should take advantage of emerging technologies for measurement at different scales (e.g., chambers, towers, aircraft, regional atmospheric sampling networks, and remote sensing algorithms that are based on important system properties such as atmospheric moisture, soil moisture, and leaf area index). Third, research is needed on the methodology of combining scaling components. Scaling algorithms may have different forms and be applicable on different scales for different physical and biological systems. Understanding full system response over large areas requires that these algorithms be combined or amalgamated in some way, but we currently do not understand how this should be done or how the ensemble properties might vary in different ways for the individual scaling components. Some of the greatest scaling challenges require improved understanding of ways that human societies modify the scaling algorithms based on physical, biogeochemical, and biological processes. To what extent are the projections of change and vulnerabilities in one region mediated by social and cultural variables, and how do these socio-economic controls vary geographically and with time?

Feedbacks: Strong positive and negative feedbacks exist among key components of the Arctic System. We have some understanding of these individually (e.g., plant-soil, snow-permafrost, vegetation-atmosphere), but have not yet achieved an understanding of how they interact in ensemble, and thus of how simultaneous changes in multiple feedback systems will affect the Arctic System. Warming-induced changes in vegetation that enhance heat transfer to the atmosphere (e.g., shrub or tree encroachment) cause a positive feedback to regional warming; fire-related vegetation changes, however, may reduce heat transfer to the atmosphere, leading to regional cooling. Warming-induced acceleration in decomposition may act as a positive feedback over short time scales (net CO_2 release), but result in a negative feedback over longer time scales due to enhanced plant production. The strength and specific dynamics of these positive and negative feedbacks undoubtedly vary among arctic ecosystems. Feedbacks between the biota and other system components may act to increase the stability of the Arctic System and thus increase system predictability and decrease vulnerability. Feedbacks may also destabilize the system, making the system less readily predictable with linear models, and certainly more vulnerable. One example of this would be the melting of permafrost. Prediction of the dynamics of the system as a whole, therefore, requires that we know how these feedbacks interact, and how their resilience varies over time and throughout the Arctic. We must also be able to identify thresholds beyond which change occurs rapidly, but below which the system is buffered.

Prediction and Trajectories of Change: Predictions of system dynamics can, at best, define the envelope of possible future states of the system, e.g., the range of likely distributions of vegetation types that the Arctic System may exhibit in 50 years. Even with imperfect knowledge of system behavior, however, assessments of predictability can provide important insight into how the system functions and what controls its temporal dynamics. In this regard, two aspects of Arctic System dynamics are particularly important to investigate. First, changes in the global system (external perturbations) can cause state changes, such as shifts in vegetation composition and associated changes in fluxes of water, energy, and trace gases. Second, different kinds of perturbations may initiate different trajectories or temporal sequences of change among ecosystem types (e.g., different pathways of transition from tussock to shrub tundra). A comprehensive assessment of predictability in the Arctic System needs to focus on the nature of possible state changes (e.g., plausible transitions among vegetation types), the plausible trajectories of change between states (i.e., differentiating transient from final states), and time lags and thresholds for change.

Temporal scaling requires that we know whether the response of a system to change at one time scale is causally linked to responses at other time scales. The Arctic System is likely to be more predictable on some time scales than on others, and predictability is also likely to vary among system components. Stable systems, which we define as those with higher resistance and lower vulnerability (*Box 5: Glossary*), are likely to be inherently more predictable than unstable systems, but the latter may be more important. Unfortunately, we know little about the range of climatic and biotic conditions within which various arctic ecosystems are stable (i.e., resistant and resilient to environmental changes). Understanding the structure and dynamics of feedback loops provides a context for predicting stability, as negative feedbacks tend to stabilize a system, whereas positive feedbacks tend to move it to a new state (Chapin et al., 1996). This research challenge thus overlaps in important ways with that of improving our understanding of the interactions among feedback loops.

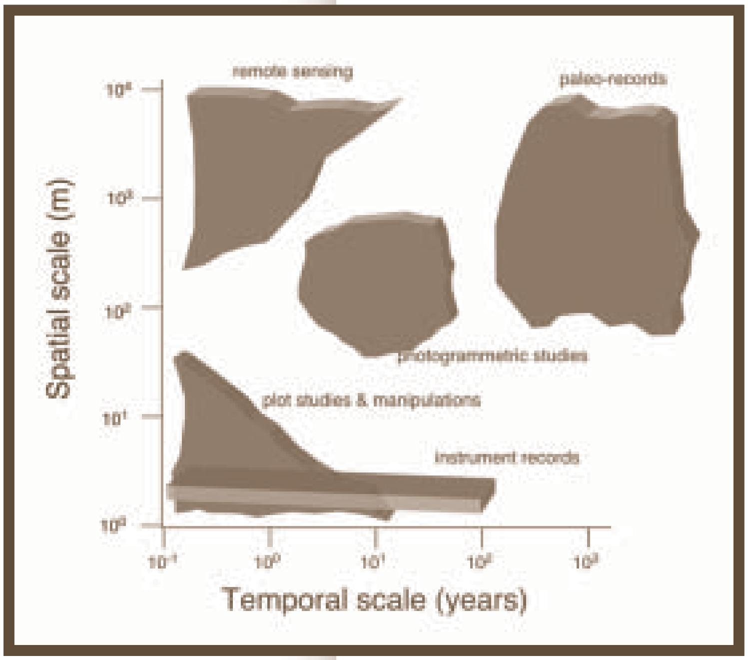


Figure 7: The approximate domain of various types of biophysical and biogeochemical measurements and observations. Large gaps in coverage exist, including for large scales of both time and space.

Our understanding of the time scales on which ecosystems change, and the relevant scales of temporal variation in the drivers of change, also remains incomplete (Fig. 7). Biotic and abiotic systems in the Arctic have time constants that govern the rapidity with which they can change and vary. Assessing the predictability of patterns of variation and change over time scales of decades to centuries is challenging because most of our underlying observations are made on short time scales where we cannot be certain that we aren't observing a transient state. Large-scale (e.g., watershed, landscape, regional) processes, for example, often have long time constants of change (e.g., decades, centuries, millennia), but it is generally impractical or impossible to conduct observational or experimental studies at that temporal scale.

We have been able to use small-scale experiments and spatially extensive observations to identify the initial vector of change and we have been able to use space-for-time studies to identify endpoints of change. Our ability to predict the mid-term trajectories of change in system states, however, remains weak. In a number of cases, for example, the initial vector of change points in a different direction than the vector connecting the beginning and end points (Fig. 1). In some cases, the systems are non-linear, with short-term trajectories of change dependent upon the initial state of the system. One good example of how short and long-term trajectories can differ is the response of tundra to soil warming. Initially this decreases soil organic matter (SOM) in alpine systems, but from gradient analysis we know that warmer systems will ultimately contain more SOM (Shaw and Harte, 2001).

We do not yet know how to assess the degree to which temporal scale mismatching leads to misleading information about the relative importance of causes of change. Paleoecological techniques and space-for-time substitutions provide a window into processes of change at long time scales and large spatial scales, but linking data obtained from these type of studies with short-term experimental data is not straightforward. For plants, detection of change, and determining the cause of the change, is easier at smaller spatial and temporal scales where experimental manipulations can be done, but we do not yet understand how small-scale processes interact to produce the landscape patterns (i.e., species persistence and dominance) that are critical at the regional scale.

Two tasks must be accomplished in order to achieve better integration of small-scale experimental/observational studies and large-scale studies that employ paleoecological methods or space-for-time substitutions. First, we must determine the limitations of substituting space for time when attempting to identify the "end products" of long temporal processes. Second, we must also improve our ability to link modern process studies with paleoecological data. Determination of paleo-vegetation distributions with concurrent information on the environmental conditions that prevailed at the time the vegetation existed can provide the validation needed for future landscape projections under a changed climate and for testing the output from dynamic vegetation models. This integration can be achieved in a number of ways, including co-locating paleoecological and experimental studies, selection of response variables that can be studied on both short and long time scales (e.g., species abundance), and the development of models that directly predict paleo-observations (delta O-18, pollen, etc.), thereby limiting our reliance on problematic transfer functions that may not be representative of the full range of processes affecting the record.

Modeling will play an essential role in developing the understanding we need to answer PACTS and ARCSS questions. Models will, of necessity, range from small-scale, physically based process models (e.g., frost heave in the active layer (Peterson et al., in press)), to parameterized regional ecosystem and climate models. Models will be used to detect where process understanding is poor, where data is sparse, and where uncertainty exists. A fully integrated model-measurement program such as that envisioned and described in the CHAMP document (Vörösmarty et al., 2001) will be needed in order to begin to understand the arctic regional complex system.

2.2.3 *Observations: A Crucial Underpinning:* The need for consistent, continuous, long-term data sets underpins PACTS research as well as virtually every other research initiative related to the detection, explanation, and prediction of change in the Arctic. These data need to be collected in a fixed location long enough to detect change against a background of what is often a "noisy" climate signal. In addition to the standard hydrologic and meteorological data we have come to expect as the basis for detecting changes in climate, these long-term data sets need to include less customary time series such as biomass, snow drift volume, and surface energy fluxes, that will allow us to detect changes in ecosystems. In some cases, these less customary data series (Fig. 8) can actually be used to detect change better than standard data. As we address pressing questions related to vulnerability and sustainability, and are forced to use ever more complex models to provide answers, these long-term observations are going to take on increased importance as the basis of ensuring we are not producing unreliable sce-

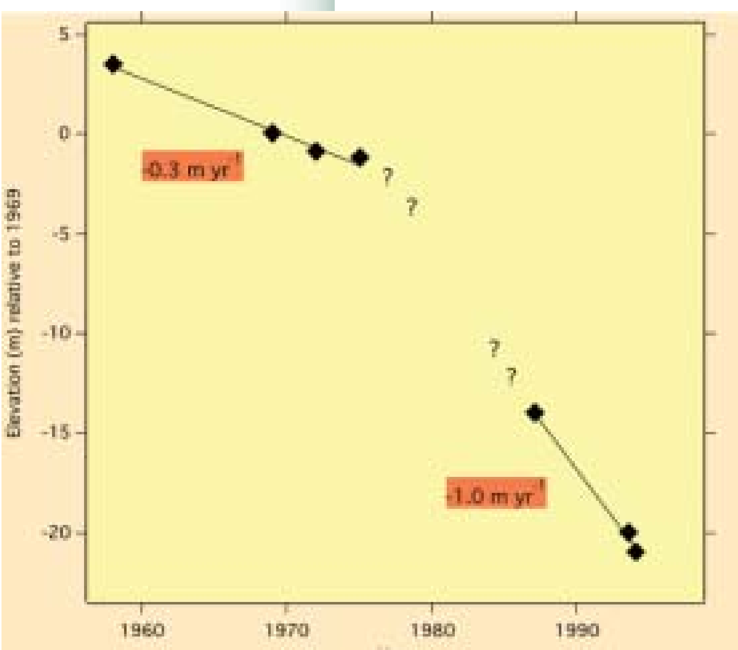


Figure 8. The rate of thinning of McCall Glacier (Brooks Range, Alaska) tripled sometime between 1975 and 1985. This rate provides an integrated measure of both temperature and snowfall, with the increase indicating both warmer and drier conditions. Although the sudden increase in the thinning rate is consistent with other evidence affirming increased warming since the 1970s, the obvious data gap makes it difficult to know when the climate signal changed, or to relate this change in detail to other time series records. (after Rabus et al., 1995)

narios and predictions. As Figure 8 illustrates, gaps in these records can greatly hinder our efforts to understand the changes.

3. RESEARCH APPROACH

Over the first decade of the ARCSS Program, research was done using a variety of approaches including:

1) Observations of changes in the Arctic System.

2) Studies of Arctic System processes that feed back to the global system.

3) Field manipulations of microclimate over decadal time periods.

4) Development of models based on processes that simulate components of the Arctic System.

5) Compilation of paleoenvironmental and paleoecological records documenting past changes in the Arctic System.

6) Model studies that extrapolated processes or tested system sensitivity.

7) Synthesis and integration of results from multiple studies and projects.

PACTS will employ similar approaches to those listed above, but will also include targeted approaches that include (but are not limited to) the following:

1) *Process studies that permit the development of parameterizations for regional and global models linking biotic and abiotic systems*

   Some processes that are important at small scales lose their predictive value at larger scales (e.g., the distinction between photosynthesis and primary productivity). A wide range of biogeochemical processes and cycles have already been studied in ARCSS. Under PACTS, we need to sort through these processes, identify those about which we need to know more and then carefully separate the remaining processes into those that are important at large scales, and those that are not. For the former set, PACTS studies will need to have an explicit focus that leads to understanding the processes and mastering the scaling issues related to them. One goal of this exercise is to develop parameterizations that allow simplification in modeling but which will retain the essential process features. PACTS field studies will need to be well integrated with modeling in order to provide critical mechanisms and parameters for the models that will be used at larger scales of space and time.

2) *Manipulations or comparison experiments conducted at spatial scales sufficient to incorporate landscape heterogeneity*

Figure 9: Experimental manipulation of tundra through warming and fertilizing. Greenhouse covering has been removed for photograph. Note taller and more abundant shrubs within the greenhouse.

Experimental manipulations of environmental conditions, plants, microorganisms, or other biota can play a key role in improving our understanding of the Arctic System or assessing its vulnerability (Fig. 9). It is an approach that can be particularly useful in isolating the effects of one process or interaction when a number of linked processes with different time responses are taking place simultaneously. To date, these manipulations have generally been at the plot scale, but large-scale manipulations can allow unique insights into the spatial interactions among heterogeneous patches over the landscape. Similarly, the importance of lateral movement of water and materials at the landscape scale, and the controls over propagation of disturbances, can be revealed most clearly when the movement is disrupted or changed by manipulation.

Because of practical and bureaucratic limits to the duration, size, and extent over which manipulations can be done, they will need to be paired with observational and paleoecological studies that facilitate extrapolation to larger scales. Paired observations, for example, are critical because they can allow greater replication than is possible with landscape-scale manipulations, and the paired observations can encompass a greater degree of spatial heterogeneity. These observations can also help bridge the problem of the limited time over which manipulations can be maintained. For example, experimental manipulations that measure controls over primary production could be paired with studies that reconstruct long-term variation in watershed-scale productivity from proxy variables in lake sediments.

3) *Observations that contribute to spatial and temporal scaling (geographic comparisons)*

In order to achieve an understanding of the Arctic System as a complex whole, it is essential that we develop concepts and methods of scaling observations from plot to landscape, and to regional scales. This will require an assessment of the "transferability" of process-level observations from one location to another, and the extrapolation of these processes and observations to larger domains than those in which they were developed. For example, the horizontal transfer of water vapor and the linkage of terrestrial with aquatic habitats may be controlled by quite different processes at different scales. Scaling also requires identification and measurement of parameters that integrate across time and/or space, and comparison of these large time or space domain measurements with small-scale measurements. To facilitate this type of scaling, methods of modeling and measuring at the aggregate scale must be developed and tested. Integrative measurements such as atmospheric moisture convergence and stream run-off and chemistry may be particularly useful in testing our capacity to scale. Paleoenvironmental proxy records are an excellent means toward this end.

4) *Modeling and observations that identify parameters to which the Arctic System is most sensitive*

Assessing the vulnerability of components of the Arctic System to change requires the development of "impact models" of specific components of the Arctic System and of the entire Arctic System. In this approach the parameters and input variables to these models are perturbed to represent all reasonable scenarios of possible future conditions. This allows identification of those parameters and variables to which the Arctic System or its components are most sensitive. Values can then be assigned to the ecosystem and societal significance of these sensitivities, as a step toward developing scenarios of adaptation or mitigation.

5) *Vulnerability assessment to determine consequences of the coupled interactions between the Arctic System and human activities*

   The vulnerability of the Arctic System and its components is critical both to understanding the potential impacts of human activities and to identifying the possible societal consequences of environmental change. Assessing that vulnerability requires identifying key environmental and societal parameters, significant drivers and thresholds of change, and the ways in which they may affect and be affected by global change. It also requires understanding the relationships between temporal and spatial scales of change in the Arctic System because the significance of the drivers and the consequences of change may be most apparent at vastly different scales. An example of a study that might contribute knowledge in this area would be to make a careful series of measurements of the response of the ecosystem at a site where drastic change has occurred.

6) *Space-for-time and time series comparisons; integration of paleo-records with modern time series and process studies*

   Because our observational base has a limited time length, we must continue to develop ways of projecting change over longer periods, extending records back into the past, and testing future predictions. Existing tools (like space-for-time studies) must be tested and their limitations determined quantitatively. Similarly, active efforts must be made to integrate paleo-records, which are being developed at increasingly high temporal resolution, with the results of modern process studies to determine the extent to which our understanding of causal processes (developed largely from modern process studies) are robust and sufficient explanations of dynamics observed on longer time scales.

7) *Synthesis and integration of results from multiple studies and projects.*

The scope of the science questions underpinning PACTS is so extensive that utilizing results from other studies, including past results from LAII, OAII, RAISE and PARCS and future results from CHAMP, SEARCH and Biocomplexity in the Environment, is going to be essential if substantial progress is to be made. To this end, PACTS will continue the ARCSS tradition of maintaining a strong commitment to comprehensive data archiving, not just after the program is finished, but during the course of the program as well. PACTS will need also to provide formal opportunities for synthesis and integration both within PACTS, and between PACTS and other ARCSS elements.

Box 6: Research challenges and approaches from the above list (numbered) that are likely to be effective in addressing those challenges.

Research Challenge	Relevant Approach
Landscape heterogeneity	1. Process studies that permit the development of parameterizations for regional and global models linking biotic and abiotic systems 2. Manipulations or comparison experiments conducted at spatial scales sufficient to incorporate landscape heterogeneity 3. Observations that contribute to spatial and temporal scaling (geographic comparisons)
Feedbacks	2. Manipulations or comparison experiments conducted at spatial scales sufficient to incorporate landscape heterogeneity 4. Modeling and observations that identify parameters to which the Arctic System is most sensitive 5. Vulnerability assessment to determine consequences of the coupled interactions between the Arctic System and human activities
Prediction and trajectories of change	1. Process studies that permit the development of parameterizations for regional and global models linking biotic and abiotic systems 2. Manipulations or comparison experiments conducted at spatial scales sufficient to incorporate landscape heterogeneity 3. Observations that contribute to spatial and temporal scaling (geographic comparisons) 6. Space-for-time and time series comparisons; integration of paleorecords with modern time series and process studies

4. IMPLEMENTATION OF PACTS

PACTS is described above in general, conceptual terms. Specific research initiatives will need to be developed through *Announcements of Opportunity*, scoping meetings, and through the creation of implementation plans. The guiding principle behind the implementation should be that of ensuring full integration and seamless cooperation across disciplines and between modelers and experimentalists. Integrated research is the key to regional assessment of global change in the Arctic. It requires effective communication and coordination. The complexity and novelty of PACTS research requires a system for coordination and communication that goes beyond the normal exchanges among investigators, institutions, and agency program managers. We anticipate that this will be provided in large part through a PACTS Science Steering Committee, but from the very initiation of the program, it is imperative that PACTS draw researchers from a range of communities so that integration happens both *within* and *among* projects. Several practical guidelines will help achieve this goal:

1) Field measurement projects need to be co-located in order to facilitate integration. Modeling efforts should be over domains that include these field locations, and should be matched as precisely as possible to the field measurements.

2) Model and measurement efforts should be planned together from their inception, with models used to suggest where and what type of field measurements might be appropriate, and measurements used to develop and test models.

3) Synthesis “retreats” should be used not only toward the end of the project, but also at the beginning to facilitate integration of initiative components.

4) Scientific expertise in planning, synthesizing and research should be drawn from outside the Arctic research community in order to ensure that the most viable methods are used in developing and implementing PACTS.

5. RELATIONSHIP OF PACTS TO OTHER ARCTIC PROGRAMS

PACTS complements and interacts with other ARCSS programs, and it builds on a long history of research related to biotic-abiotic interactions in the Arctic. It will draw upon the data and knowledge generated in these programs, using wherever possible infrastructures and monitoring efforts that were begun under these other programs. As early as 1947, terrestrial and marine ecosystem studies were begun at the Naval Arctic Research Laboratory in Barrow (Norton, 2001). Over the following four decades, these studies evolved into a number of research programs whose results directly inform and motivate the research outlined in this document. Notable among these programs were the International Geophysical Year, the U.S. Tundra Biome Project (Brown et al., 1980), the RATE program (Research on Arctic Tundra Environments) supported by the National Science Foundation, the R4D program run by the Department of Energy, and most recently, the development of NSF-funded Long Term Ecological Research stations at Toolik Lake (http://ecosystems.mbl.edu/arc/arc_gen.html) and Bonanza Creek.

Within the ARCSS Program, PACTS, with its focus on the interaction of biotic and abiotic systems, is complementary to two other programs (PARCS and HARC) and two ongoing ARCSS initiatives (CHAMP and SBI). It is consistent with the goals of SEARCH, and at the time of this writing, could be considered a component of the wider SEARCH initiative. Specific ties and connections to these ARCSS programs are listed below.

PARCS

Paleoenvironmental Arctic Sciences (PARCS) addresses the nature of past climate change and the response of natural systems to that change. PARCS and PACTS share the common goal of understanding the complex set of responses and feedbacks that constitute the climate system of the Arctic. In addition, both share a focus on biota, either as a component of a changing Arctic System, or as indicator of that change. The two differ in the time-scales of data collected, though both use modeling to test hypotheses about mechanisms controlling features of the arctic climate system. PACTS will be hampered by short temporal records, but will produce relatively precise spatial and temporal data and model results. PARCS has long temporal records, but often limited details related to biophysical feedbacks and biogeochemical cycling. The two programs will clearly benefit from close interaction. The coordination of paleoecological data and data from modern process studies is most effective, however, when data sets from each approach are developed in tandem, with a common research objective. Thus, we would envision close interaction of the two programs from the onset of PACTS.

HARC

There is substantial overlap between HARC (Human Dimensions of the Arctic System) and PACTS that is beneficial for both programs. The focus of HARC is humans, while the focus of PACTS is, broadly, all living systems. HARC seeks to answer specific societal questions; PACTS will address the general issue of sustainability. Much synergy between these initiatives is to be expected. Topics of joint interest include sustainability of arctic communities, impact of caribou populations on reindeer herding practices, and the impact of climatic change on coastal erosion. PACTS research will serve as a critical foundation on which HARC studies are based and will continue to have important implications for both arctic residents and the global community. As well, it is from such a foundation that valuable interdisciplinary research with policy relevance can be achieved. This research can provide data and modeling to develop integrated assessments and assess societal vulnerability to changes in the Arctic System.

CHAMP

CHAMP (*Community-wide Hydrological Analysis and Monitoring Program)*, which focuses on the hydrologic cycle, and PACTS share many common features, which is not surprising since many of the same researchers were involved in the development of both projects. The two programs can be viewed as two inter-meshed gears. Because the water cycle is so essential to life, virtually all of PACTS research could be viewed as related to the water cycle. The water cycle, in turn, is strongly controlled by plants and other biota. It is likely that CHAMP will place much of its research emphasis on the physical nature of the water cycle and linkages between the land, atmosphere, and ocean, with the role of humans and biota given lower priority. Since PACTS addresses these important elements, it is a natural counterpart to CHAMP.

SBI

An excellent opportunity exists to link PACTS closely to SBI. This could take the form of extending SBI toward land and making certain that PACTS includes near-shore marine biotic-abiotic interactions. The combined results of both programs would thereby encompass both the marine and terrestrial Arctic.

In addition, PACTS dovetails with three other on-going research programs in ways that are both close and complementary:

LTER

There are two NSF-sponsored Long Term Ecological Research (LTER) projects in northern Alaska. The Arctic LTER is located at the headwaters of the Kuparuk River Basin, and the other is located in the boreal forest near Fairbanks at Bonanza Creek. Both sites began observations in 1987 and expect to continue them for decades, providing a long-term perspective that will be essential to PACTS. Long-term and large scale manipulation experiments (e.g., fertilization, soil heating, food web changes) and an emphasis on research at a single location will provide a type of data and understanding that will be needed in PACTS, but which cannot be part of the PACTS program explicitly because the program lifespan is likely to be too short.

BIOCOMPLEXITY OF THE ENVIRONMENT

The Biocomplexity Initiative cuts across all research divisions of NSF. Three arctic projects are currently funded under this initiative. These have in common a focus on the interaction of arctic biota and physical factors imposed by the environment, though they are widely separated geographically (two in Alaska, one in Greenland). While the research from these projects should prove valuable, they are not integrated into a larger study or program.

ARM

The Atmospheric Radiation Monitoring Project of the Department of Energy includes a major site in Barrow (http://www.arm.gov/docs/sites/nsa/nsaaao.html). The focus of this research is on the effect of arctic clouds on the surface energy balance. ARM collaborated closely on the NSF-sponsored SHEBA project, and is poised to collaborate with a program like PACTS.

6. COMMUNITY OUTREACH

With its focus on living terrestrial and freshwater systems and assessment of sustainability, PACTS is inherently *human-oriented*. It is no surprise, then, that community outreach is viewed as an integral component of PACTS research. One key component of PACTS will be to encourage the development of structures that make the outreach easier. These might take the form of supplemental grants targeted specifically for outreach, much like those already in place in formal programs like the NSF-GK12 (Graduate Teaching Fellows in K-12 Education) and TEA (Teachers Experiencing Antarctica and the Arctic) programs. Short proposals with specific outreach objectives would be encouraged and aided by the PACTS steering committee. Other mechanisms for outreach are discussed below.

1) *The scientific community*

A major challenge facing researchers in Arctic System Science is conveying interdisciplinary results to a strongly disciplinary scientific community. There are few journals or other forums for presenting the results of integrated system science research. In addition to publishing in disciplinary peer-reviewed professional journals, researchers need to proactively pursue opportunities for cross-disciplinary and interdisciplinary transfer of information. For example, atmospheric scientists should target ecological journals to convey information on climatological research that is ecologically relevant. Conversely, terrestrial ecologists should write for atmospheric, hydrological, and anthropological audiences in addition to their normal disciplinary publications. The success of cross- and interdisciplinary research is ultimately dependent on the establishment of collaborative interactions among those in a diverse community. Outreach activities help to cultivate that process. Under PACTS, innovative ways to convey multi-disciplinary results will be sought out, including the following strategies:

a. Special issues of journals for component disciplines,
b. Targeted synthesis papers in a range of disciplinary journals, and
c. Special sessions in national meetings, with invited talks from other disciplines.

2) *Training the next generation of arctic scientists*

Coordinated, multi-investigator projects like the Flux Study, ATLAS, and ITEX represent unusually high-quality opportunities for undergraduates, graduate students, and postdoctoral researchers. Through their participation in these projects, young scientists not only learn the techniques and approaches used by a single discipline, they also learn the importance and advantages of integrated research involving multiple approaches and multiple methods. Conceptual synthesis through modeling and cooperation in carrying out an integrated research plan are important skills that are learned in such projects. This broad training is further strengthened by the diverse professional contacts made by students that often turn out to be useful in their later careers. The ITEX project, for example, has provided frequent opportunities for international collaboration among all the arctic countries that are not normally available to students. The ATLAS project involves significant exchanges with Russian scientists and students.

PACTS projects will specifically include educational components targeted at introducing new researchers and students to multi-disciplinary work, and in providing opportunity for talented young scientists to incorporate arctic research as part of their long-term research careers. We see this as an important contribution to training and developing the next generation of arctic ecologists and environmental scientists. Many of the REU students, graduate students, and postdoctoral researchers who have been trained in the ARCSS-LAII projects have continued to work in the Arctic, with several returning as principal investigators on their own grants. PACTS will continue this tradition.

3) *The general public*

Research in Arctic System Science is of tremendous relevance and importance to the general public because of the role of the Arctic in understanding the changing Earth System. PACTS will therefore make a concerted effort to convey relevant findings to the general public through several venues, including development of museum displays (stationary and traveling), real-time web-based dissemination of weather data, and scientific journals with a broad audience (Scientific American, American Scientist, Ambio). Integrated research programs will be urged to engage the press by discussing results and inviting them to field sites to observe issues of general public interest. Public venues that attract general audiences should be added to the academic gatherings where research results are presented. Other opportunities to convey information include existing web-based resource sites (e.g., the University of Connecticut's "Arctic Circle") and the production of videos about research programs and findings.

4) *Arctic residents*

Many investigators that are likely to be involved in PACTS have already undertaken efforts to introduce their research to residents of their study areas. These efforts have included visits to K-12 classrooms under the NSF GK-12 Pisces Program, public lectures in local villages, meetings with Tribal Councils, web-based outreach initiatives, and hiring of local high-school students to work as research assistants. Although these efforts have, individually, met with much success, future outreach to arctic residents can have much greater impact if done as a coordinated effort. Two types of outreach activities are particularly appropriate: (1) personal visits to villages and schools by project personnel, and (2) development of curriculum and other outreach materials based on PACTS research. Both of these approaches require two-way communication: researchers to local residents and local residents to researchers. PACTS programmatic structures will encourage this type of interaction.

Providing information to, and learning from, arctic residents is best achieved through face-to-face contact and long-term contact of individual researchers with residents. The contribution of community members to research includes guidance in appropriate research practices, participation in research to establish long- and short-term observations, and explanations of local- and-regional scale processes with a perspective not readily available to researchers. The establishment of research working groups with community partners can serve as an important investment of resource for a project team, especially where travel in village homelands by researchers or the implications of research on community life may have a perceived effect. Informal public talks and discussions, which should be arranged in advance with local Tribal Councils, can be effective when conceived of as conversations rather than as lectures. Where possible, outreach efforts will be coordinated among projects so that multiple visits can be arranged to interested villages, allowing residents and researchers to discuss the research process as it proceeds. Today many villages have access to the Internet, providing opportunities for additional exchanges. Enhanced community-research communications can also occur through web pages that describe research and local knowledge in an informative and accessible way.

Researchers under PACTS will be encouraged to look for funding and other opportunities to contribute to development of arctic curricula. Many aspects of PACTS research are of interest to K-12 and higher education teachers and are particularly effective when combined with local knowledge. Efforts to procure funding (and expertise) for development of a place-based curriculum in Arctic System Science, for example, should be encouraged. The holistic view that system science takes is very compatible with the local and traditional knowledge base of Native communities. The integrated approach described in the PACTS plan is well suited for development of a place-based earth-science/ecology curriculum that could be implemented effectively in Native villages.

7. REFERENCES

Ager, T.A., Holocene vegetational history of Alaska, in *Late-Quaternary Environments of the United States*, edited by J.H.E. Wright, pp. 128–141, University of Minnesota Press, Minneapolis, 1983.

Anderson, P.M., and L.B. Brubaker, Holocene vegetation and climate histories of Alaska, in *Global Climates since the Last Glacial Maximum*, edited by J.H.E. Wright, J.E. Kutzbach, T. Webb III, W.F. Ruddiman, F.A. Street-Perrott, and P.J. Bartlein, pp. 386–400, University of Minnesota Press, Minneapolis, 1993.

ARCUS, *Toward Prediction of the Arctic System*, 54 pp., Arctic Research Consortium of the United States, Fairbanks, Alaska, 1998.

ARCUS, Report on the ARCSS All-Hands Meeting, February 2002, Seattle, Washington, Arctic Research Consortium of the United States, Fairbanks, Alaska, In Press.

Beringer, J., F.S. Chapin III, I. McHugh, N.J. Tapper, A.H. Lynch, M.C. Serreze, and A.G. Slater, Impact of arctic treeline on synoptic climate, *Geophysical Research Letters*, *28*, 4247–4250, 2001.

Black, R.F., and W.L. Barksdale, Oriented lakes of northern Alaska, *Journal of Geology*, *51*, 105–118, 1949.

Broecker, W.C., Thermohaline circulation, the Achilles Heel of our climate system: Will man-made CO_2 upset the current balance?, *Science*, *278*, 1582–1588, 1997.

Brown, I., and R. Ward, The influence of topography on snowpatch distribution in southern Iceland: A new hypothesis for glacier formation?, *Geografiska Annaler*, *78A* (4), 197–207, 1996.

Brown, J., P.C. Miller, L.L. Tieszen, and F.L. Bunnell, *An Arctic Ecosystem. The Coastal Tundra at Barrow, Alaska.* US/IBP Synthesis Series 12. 571 pp., Dowden, Hutchinson and Ross, Inc., Stroudsburg, Pennsylvania, 1980.

Brown, J., O.J. Ferrians Jr., J.A. Heginbottom, and E.S. Melnikov, *Circum-Polar Active Layer Permafrost System (CAPS), Version 1.0*, CD-ROM Available from NSIDC (nsidc@kryos.colorado.edu), University of Colorado, Boulder, 1998.

Brubaker, L.B., P.M. Anderson, and F.S. Hu, Arctic tundra biodiversity: A temporal perspective from Late Quaternary pollen records, in *Arctic and Alpine Biodiversity: Patterns, Causes, and Ecosystem Consequences*, edited by F.S.

Chapin and C. Körner, pp. 112–125, Springer–Verlag, Berlin, 1995.
Campbell, D.G., and H.D. Hammond, Editors, *Floristic Inventory of Tropical Countries*, New York Botanical Garden, 1989.
Carmack, E.C., Large scale physical oceanography of the polar seas, in *Polar Oceanography*, edited by W.O. Smith, pp. 177–222, Academic Press, New York, 1990.
Carmack, E.C., The Arctic Ocean's Freshwater Budget: Sources, storage and export, in *The Freshwater Budget of the Arctic Ocean: Proceedings of the NATO Advanced Research Workshop, Tallinn, Estonia, 27 April–1 May*, edited by E.L. Lewis, E.P. Jones, P. Lemke, T.D. Prowse and P. Wadhams, pp. 91–126, Kluwer, Dordrecht, 2000.
Chapin, F.S. III, G.R. Shaver, A.E. Giblin, K.J. Nadelhoffer, and J.A. Laundre, Responses of arctic tundra to experimental and observed changes in climate, *Ecology*, *73*(3), 694–711, 1995.
Chapin, F.S. III, M.S. Torn, and M. Tateno, Principles of ecosystem sustainability, *American Naturalist*, *148*, 1016–1037, 1996.
Dai, X.Y., D. White, and C.L. Ping, Evaluation of soil organic matter composition and bioavailability by pyrolysis-gas chromatography/mass spectrometry, *Journal of Analytical and Applied Pyrolysis*, *62*, 249–258, 2002.
Dickinson, R.E., G.A. Meehl, and W.M. Washington, Ice-albedo feedback in a CO_2 doubling climate simulation, *Climate Change*, *10*, 241–248, 1987.
Downing, T.E., R. Butterfield, S. Cohen, S. Huq, R. Moss, A. Rahman, Y. Sokona, and L. Stephen, *Climate Change Vulnerability: Linking Impacts and Adaptation*, University of Oxford, Oxford, 2001.
Geiger, R., *The Climate Near the Ground*, 494 pp., Harvard University Press, Cambridge, Massachusetts, 1957.
Hinkel, K., and F.E. Nelson, Spatial and temporal patterns of active layer depth at CALM sites in Northern Alaska, 1995–2000, *Journal of Geophysical Research*, In press.
Hu, F.S., B.Y. Lee, D.S. Kaufman, S. Yoneji, D.M. Nelson, and P.D. Henne. Response of tundra ecosystem in southwestern Alaska to Younger-Dryas climatic oscillation. *Global Change Biology, 8*, 1156–1163, 2002.
Hultên, E., *Flora of Alaska and Neighboring Territories,* 1008 pp., Stanford University Press, Stanford, California, 1968.
Ingram, W.J., C.A. Wilson, and J.F.B. Mitchell, Modeling climate change: An assessment of sea ice and surface albedo feedbacks, *Journal of Geophysical Research*, *94*, 8609–

8622, 1989.
Kabat, P., Vegetation, water, humans and the climate: A new perspective on an interactive system. A Synthesis of the IGBP Core Project, *Biospheric Aspects of the Hydrological Cycle*, In press.
Kane, D., L.C. Bowling, R.E. Gieck, L.D. Hinzman, and D.P. Lettenmaier, The role of surface storage in a low-gradient arctic watershed, *Proceedings, Northern Research Basins, 13th International Symposium and Workshop*, 2001.
Kattenberg, A., F. Giorgi, H. Grassl, G.A. Meehl, J.F.B. Mitchell, R.J. Stouffer, T. Tokioka, A.J. Weaver, and T.M.L. Wigley, Climate models—projections of future climate, in *Climate Change 1995: The Science of Climate Change*, edited by J.T. Houghton et al., pp. 285–357, Cambridge University Press, Cambridge, UK, 1996.
Kellogg, W.W., Climatic feedback mechanisms involving the polar regions, in *Climate of the Arctic: Twenty-Fourth Alaska Science Conference*, edited by G. Weller and S.A. Bowling, pp. 111–116, Geophysical Institute, University of Alaska Fairbanks, Fairbanks, Alaska, 1973.
Lloyd, A.H., and C.L. Fastie, Spatial and temporal variability in tree growth and climate response of treelines in Alaska, *Climatic Change*, *52*, 481–509, 2002.
Lynch, A.H., A.G. Slater, and M.C. Serreze, The Alaskan Arctic frontal zone: forcing by orography, coastal contrast and the boreal forest, *Journal of Climate*, *14*, 4351–4362, 2001.
McGuire, A.D., et al., Environmental variation, vegetation distribution, carbon dynamics, and water/energy exchange in high latitudes, *Journal of Vegetation Science, 13,* 303–314, 2002.
Michaelson, G.J., C.L. Ping, and J.M. Kimble, Carbon storage and distribution in tundra soils of arctic Alaska, U.S.A., *Arctic and Alpine Research*, *28*, 414–424, 1996.
Moritz, R.E., J.A. Curry, N. Untersteiner, and A.S. Thorndike, *SHEBA: Surface Heat Budget of the Arctic Ocean—Prospectus*, ARCSS-OAII Report #3, 34 pp., 1993.
Norton, D. (Editor), *Fifty More Years Below Zero: Tributes and Meditations for the Naval Arctic Research Laboratory's First Half Century at Barrow, Alaska,* 576 pp., University of Alaska Press, 2001.
Oechel, W.C., S.J. Hasting, G. Vourlitis, M. Jenkins, G. Riechers, and N. Grulke, Recent change of arctic tundra ecosystems from a net carbon dioxide sink to a source, *Nature*, *361*, 520–523, 1993.
Oechel, W.C., G.L. Vourlitis, and S.J. Hastings, Cold-season

CO_2 emission from arctic soils, *Global Biogeochemical Cycles*, *11*, 163–172, 1997.

Oechel, W.C., G.L. Vourlitis, S.J. Hastings, R.C. Zulueta, L. Hinzman, and D. Kane, Acclimation of ecosystem CO_2 exchange in the Alaskan Arctic in response to decadal climate warming, *Nature*, *406*, 978–981, 2000a.

Oechel, W.C., G.L. Vourlitis, J. Verfaillie, T. Crawford, S. Brooks, E. Dumas, A. Hope, D. Stow, B. Boynton, V. Nosov, and R. Zulueta, A scaling approach for quantifying the net CO_2 flux of the Kuparuk River Basin, Alaska, *Global Change Biology*, *6* (Supplement 1), 160–173, 2000b.

Peterson, R., and W. Krantz, A mechanism for differential frost heave, *Journal of Glaciology*, In press.

Pielke, R.A., and P.L. Vidale, The boreal forest and the polar front, *Journal of Geophysical Research*, *100*, 25755–25758, 1995.

Pielke, R.A., G. Marland, R.A. Bettis, T.N. Chase, J.L. Eastman, J.O. Niles, D. Niyogi, and S.W. Running, The influence of land-use change and landscape dynamics on the climate system: relevance to climate-change policy beyond radiative effect of greenhouse gases, *Philosophical Transactions of the Royal Society of London, Series A*, *360*, 1705–1719, 2002.

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

Rabus, B., K. Echelmeyer, D. Trabant, and C. Benson, Recent Changes of McCall Glacier, Alaska, *Annals of Glaciology*, *21*, 231–239, 1995.

Rühlemann, C., S. Mulitza, P.J. Müller, G. Wefer, and R. Zahn, Warming of the tropical ocean and slowdown of thermohaline circulation during the last deglaciation, *Nature*, *402*, 511–514, 1999.

Rupp, T.S., F.S. Chapin, and A.M. Starfield, Modeling the influence of topographic barriers on treeline advance of the forest-tundra ecotone in northwestern Alaska, *Climatic Change*, *48*, 399–416, 2001.

Serreze, M.C., J.E. Walsh, F.S. Chapin III, T. Osterkamp, M. Dyurgerov, V. Romanovsky, W.C. Oechel, J. Morison, T. Zhang, and R.G. Barry, Observational evidence of recent climate change in the northern high-latitude environment, *Climatic Change*, *46*, 159–207, 2000.

Shaver, G.R., J. Canadell, F.S. Chapin III, J. Gurevitch, J. Harte, G. Henry, P. Ineson, S. Jonasson, J. Melillo, L. Pitelka, and L. Rustad, Global warming and terrestrial ecosystems: a conceptual framework for analysis, *BioScience*, *50*, 871–882, 2000.

Shaw, M., and J. Harte, Control of litter decomposition under simulated climate change in a subalpine meadow: the role of plant species and microclimate, *Ecological Applications*, *11(4)*, 1206–1223, 2001.

Sturm, M., J.P. McFadden, G.E. Liston, F.S. Chapin, C.H. Racine, and J. Holmgren, Snow-shrub interactions in Arctic tundra: a hypothesis with climatic implications, *Journal of Climate*, *14*, 336–344, 2001a.

Sturm, M., C.R. Racine, and K. Tape, Increasing shrub abundance in the Arctic, *Nature*, *411*, 546–547, 2001b.

Vörösmarty, C., P. Green, J. Salisbury, and R. Lammers, Global water resources: vulnerability from climate change and population growth, *Science*, *289*, 284–288, 2000.

Vörösmarty, C.J., L.D. Hinzman, B.J. Peterson, D.H. Bromwich, L.C. Hamilton, J. Morison, V.E. Romanovsky, M. Sturm, and R.S. Webb, *The Hydrologic Cycle and its Role in Arctic and Global Environmental Change: A Rationale and Strategy for Synthesis Study*, 84 pp., Arctic Research Consortium of the United States, Fairbanks, Alaska, 2001.

Walker, D.A., W.A. Gould, M.K. Reynolds, and H.A. Maier, The Circumpolar Vegetation Map: environmental controls, AVHRR-derived base map and integrated mapping procedures. *International Journal of Remote Sensing, 23*, 2551–2570, 2002.

Welker, J.M., J.T. Fahnestock, and M.H. Jones, Annual CO_2 flux from dry and moist arctic tundra: responses to increases in summer temperatures and winter snow depth. *Climatic Change, 44*, 139–150, 2000.

Zimov, S.A., I.P. Semiletov, S.P. Davidov, I.V. Voropaev, S.F. Prosyannikov, C.S. Wong, and Y.H. Chan, Wintertime CO_2 emission from soils of northeastern Siberia, *Arctic*, *46*, 197–204, 1993.

Zimov, S.A., S.P. Davidov, Y.V. Voropaev, S.F. Prosiannikov, I.P. Semiletov, M.C. Chapin, and F.S. Chapin III, Siberian CO_2 efflux in winter as a CO_2 source and cause of seasonality in atmospheric CO_2, *Climate Change*, *33*, 111–120, 1996.

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