## Fire-Mediated Changes in the Arctic System: Interactions of Changing Climate and Human Activities

### Introduction

Perhaps the most urgent challenge facing humanity is to understand the factors determining the limits to resilience of regional systems that are changing directionally in biophysical (Vitousek et al. 1997) and social drivers (Berkes and Folke 1998). The arctic and adjacent boreal forest form an excellent study region to explore these changes for several reasons. (1) Its natural ecosystems and cultures are relatively intact, making it easier to understand the natural coupling of physical, biological, and social components of the regional system. (2) The biophysical and social drivers of regional processes are changing as rapidly as anywhere on Earth (Serreze et al. 2000, Krupnik and Jolly 2002, Hinzman et al. Submitted), so changes in the functioning of the system have already begun and are likely to continue. (3) Arctic System Science has taken a leadership role in developing the methodology to integrate biological and physical sciences to study the Arctic System (Weller et al. 1995, McGuire et al. In press-b), as has the BOREAS program in the Canadian boreal forest (Sellers et al. 1997), so the methodology, data sets, and experience are in place for regional studies. (4) The Arctic-Boreal region combined is the largest biome on Earth and plays a major role in the functioning of the global system, so changes in this regional system are globally important.

We argue that a basic understanding of changes in high-latitude regional systems will benefit from studies that integrate mosaics of forested and non-forested lands. The arctic differs from the boreal forest primarily in the absence of trees. The distribution of most other arctic plants and animals extend well into the boreal forest (Chernov 1995, Walker 1995, Callaghan et al. In press), and some important animal populations, such as the Porcupine caribou herd, migrate annually between boreal forest and tundra. Many northern cultures, such as the Inupiaq and Athabascan, occupy both forested and non-forested lands. More importantly, most large-scale regional processes affect both arctic and boreal landscapes, so coupled changes in these processes in either landscape affect the entire region. Arctic nations develop policies that affect both arctic and boreal lands. The boreal region mediates the interaction between arctic and temperate air masses during most of the year. Boreal landscapes account for most of the watershed area and freshwater inputs to the Arctic Ocean. Permafrost, the arctic soil property that most strongly influences ecosystem processes extends well into the boreal forest (Kane et al. 1992), and fire, the dominant boreal disturbance, extends well into the Arctic (Wein 1976). Finally, the changes that will likely have greatest impact on high-latitude regional systems (e.g., loss of permafrost, expansion of treeline, changes in fire regime) will likely exhibit their most non-linear responses in the mosaic of forested and non-forested landscapes that constitute the forest limit.

Although arctic and boreal studies have provided international leadership in studying regional systems, they have not adequately incorporated human activities into this perspective (ARCUS 1997, Huntington et al. Submitted). Most efforts to study the role of humans in the Arctic System have focused on the effects of arctic change on people (Krupnik and Jolly 2002). Does the sparse human population at high latitudes mean that human activities in northern lands have only a minor effect on the functioning of the Arctic System?

The role of arctic people as an *interactive component* of the Arctic System has been studied primarily with respect to trophic dynamics, in which people both affect, and are affected by, marine and terrestrial food resources, such as marine mammals, fish, and reindeer (ARCUS 1997, Huntington et al. Submitted). In addition, human activities in the Arctic could potentially affect the climate system of the Arctic through changes in land-surface properties that affect the interactions between the land and atmosphere. The primary mechanisms of land-atmosphere interaction are trace gas fluxes, water and energy exchange, and river-runoff effects on thermohaline circulation (Chapin et al. 2000b, McGuire et al. 2002, Sturm et al. In press). Impacts on these climate feedbacks are likely to be important only if they are (1) large per unit area and (2) large in aerial extent. The two mechanisms by which human activities are most likely to have large impacts on the coupled interaction between the land surface and atmosphere are (1) global warming, which is influenced primarily by human activities outside the Arctic and (2) extensive alteration of land cover within the Arctic, which is most likely to occur as a result of changes in climate (a consequence of non-arctic activities) and fire. The latter is sensitive to both climate warming and to human activities at high latitudes.

The effects of human activities *outside* the Arctic on the climate and ecosystem structure/function of the Arctic have been intensively studied and synthesized (IPCC, ACIA). Recent arctic terrestrial research has focused on the consequences of these changes on feedbacks to the climate system through trace gas fluxes (Oechel et al. 1993, Christensen et al. 1995, Zimov et al. 1996, McGuire et al. 2000, Oechel et al. 2000, McGuire et al. 2002), water and energy exchange (McFadden et al. 1998, Chapin et al. 2000a, Rouse 2000, Beringer et al. Submitted), and river runoff/thermohaline circulation (Peterson et al. 2002). Similar studies have documented climate feedbacks in boreal Alaska (Randerson et al. 1999, Lynch and Wu 2000, McGuire et al. 2002, Chambers and Chapin In press, O'Neill et al. In press). There is therefore considerable information available on climate-ecosystem interactions.

Fire is the dominant form of disturbance in the boreal forest (Kasischke and Stocks 2000) (Viereck 1973) and in transition zones between forest and tundra, such as the Seward Peninsula (Lloyd et al. In press). Fire frequency often declines in tundra due to low fuel loads, high soil moisture, and high relative humidity (Wein 1976), but is just as common in some arctic regions (e.g., the Seward Peninsula) as in boreal forest (McGuire et al. 2002) and is likely to become increasingly important in tundra if climate continues to warm. Fire affects land-atmosphere interactions directly through emissions of trace gases and particulates (Kasischke et al. 1995, Zimov et al. 1999, O'Neill et al. In press) and indirectly through effects on microclimate and vegetation (McGuire et al. 2002, Chambers and Chapin In press). Fire-induced changes in vegetation are one of the few large negative feedbacks to high-latitude warming (Chapin et al. 2000b), as described below. Fire management therefore provides one of the few tools available at the regional scale to mitigate high-latitude warming. The utility of this mitigation strategy depends, however, on the net effects of fire on climate and on human welfare. These interactive effects have never been studied.

Fire has been associated with human activities since the Neolithic (Pyne 1982, 2001), in part because people light fires to promote ecosystem changes that enhance their own well being, including improved habitat for game animals, food plants, and human travel. This relationship with fire changed radically at the beginning of the Industrial Revolution, when people became less immediately dependent on large land areas for food and built more permanent communities and other infrastructure that were threatened by fire (Pyne 1982, 2001). Increasing fire suppression effort has therefore changed human-fire interactions from being a positive feedback to a negative one, in which people attempt to reduce fire frequency. This change in fire-human interactions has implications for the climate system at high latitudes, because it could reduce the strength of fire-induced negative feedback to climate warming. However, the magnitude of this effect has not been documented in the North.

We propose a research program that will document the changing role of fire, particularly as affected by human activities, on the Arctic-Boreal Climate System and its human residents. The research will focus on Alaska and Yukon Territories, a large regional system in which fire is important.

## Objectives and general approach

*Objectives*

1. Evaluate the changing role of human activities in the fire regime of the Alaska-Yukon region as this is determined by changes in the effects of people on fire (ignition and suppression) and the effects of fire on people, including economics (e.g., wages, property risk) and ecosystem services (e.g., game, berries, firewood, timber and other wood products, climate feedbacks).
2. Evaluate the consequences of climate- and human-induced changes in fire regime on land-surface properties that are important to climate.
3. Document the past and plausible future changes in climate feedbacks in the Alaska-Yukon region that result from climate warming and from climate- and human-induced changes in fire regime. We will compare the contribution to atmospheric heating that comes from (a) trace-gas fluxes vs. water/energy exchange and (b) arctic vs. boreal landscapes.

4. Explore the human and climatic consequences of policy scenarios that alter high-latitude fire regime.

*General approach*

We have selected Alaska and adjacent Yukon Territory of Canada as our study region for several reasons: (1) It is a large region that encompasses the major sources of variability in terrestrial-climate feedbacks and in plausible future changes in these feedbacks. (2) It is a region with rapid climatic and social change. (3) It has received intensive study as a regional system: the FLUX and ATLAS studies in Alaska, the Mackenzie Basin Impact Study in Canada, and the arctic and boreal LTER programs in Alaska, so much of the essential background data are available. We focus particularly on fire regime and its interaction with climate and human activities, because this is one of the most important ways in which human activities are likely to influence high-latitude land-surface change and therefore feedbacks to the climate system. The Alaska-Yukon region includes tundra, boreal forest, and mosaics that combine the two. Its climate ranges from arctic to boreal and from maritime to continental. These attributes enable us to consider a wide range of climate-vegetation-fire interactions. The region also includes two potential sources of variation in human-fire interactions. It spans two nations with distinct fire policies. Within each country it includes areas in which indigenous traditions are still strong and other areas along road networks that have a stronger western influence.

McGuire and Rupp have assembled gridded data sets for the entire region of current vegetation, historical climate (1900-2001), and fire regime (1950-2001) in the Western Arctic Linkage Experiment (WALE) project. They are using these data to drive a fire-climate-vegetation model (ALFRESCO) coupled to a biogeochemical model (TEM, the Terrestrial Ecosystem Model) to reconstruct a historical record of carbon storage and energy feedbacks to climate for the entire region. We will build on this research by modifying and testing ALFRESCO so it has the capability to consider human effects on the fire regime and by using these models to assess climate feedbacks associated with plausible scenarios of future climate and fire regime that we will develop.

To add an understanding of human effects on the fire regime to ALFRESCO, we will conduct a regional analysis of past and present human-fire interactions. Our approach to analyzing the history and current pattern of human-fire interactions is to stratify first by country (U.S. vs. Canada) and then by predominant cultural influence (indigenous communities along rivers vs. western communities along road systems). Across the region, we will then assess patterns of variation associated with climate and vegetation.

*Hypotheses*

Our research addresses the following hypotheses:

1. Human impact on fire regime is a function of population density. Culture influences the direction of this effect, whereas policy and climate determine the regional extent of this effect. Indigenous and frontier cultures enhance fire frequency because ignition exceeds suppression, whereas modern western society reduces fire frequency because effects of suppression exceed those of ignition. Future human impacts will depend largely on the future patterns of culture, settlement, and their interactions with climate and vegetation.
2. Fire enhances cultural sustainability of Native communities remote from roads by (a) enhancing ecosystem services that sustain subsistence and (b) providing sufficient wages from fire fighting to allow families to maintain a rural lifestyle.
3. Fire suppression will become increasingly ineffective in reducing fire risks to life and property in areas of active suppression due to (1) increase in the proportion of flammable vegetation on the landscape and (b) climatic warming that increases the probability of extreme fire weather and associated large fires that cannot be contained.
4. Fire acts as a short-term positive feedback to high-latitude warming by enhancing $CO_2$ emissions and a long-term negative feedback to warming by increasing regional albedo. The net climatic impact of fire is uncertain but is likely to be large relative to changes in climate

feedbacks within tundra because of the large aerial extent of fire-dominated landscapes in the region, a pattern that is typical of arctic nations.

## Proposed research

*Human-fire interactions*

### Background

Human effects on fire regime. In the continental U.S. and central Canada there is growing evidence that Native Americans actively used fire to manage most of the land, despite low population densities (Pyne 1982, Hunter 1996). There is anecdotal and oral-history evidence of indigenous burning in Alaska (Lutz 1959, Roessler 1997, Natcher In press), but the common scientific perception is that fire regime is largely a function of climate and vegetation with minimal past or current human impact (Viereck 1973, Kasischke et al. 2000, Kasischke et al. In press). Our study seeks to assemble a broad array of information types to assess the changing role of people in Alaska's fire regime.

Throughout the period of human occupancy in Alaska and the Yukon Territory (10,000 to 15,000 years), the use of fire has varied both spatially and temporally as population densities, settlement patterns, and cultural practices have changed. Rather than being passive recipients of nature, human beings have, to varying degrees, both influenced and been influenced by their environments. Indigenous peoples used fire at strategic times, in selected areas, and under optimal conditions to influence the relative abundance and distributions of natural resources and wildlife species (Lewis 1978, Natcher In press). These practices may have not only increased the frequency of fires, but may also have changed the intensity, location, and time of year that fires would occur (Bonnickson 2000). If, as some reports suggest (Boyd 1999, Stewart 2002), indigenous burning occurred in early spring, when natural ignitions are less common, such fires might have reduced the overall extent of fire by reducing fuel loads at times when vegetation would not normally burn. Non-Native explorers, missionaries, travelers, prospectors, and miners also used deliberately set fires. Fires were used to hunt, repel insect pests, clear land, facilitate mineral exploration by removing groundcover, and thaw ground along gold-bearing creeks (Roessler 1997). Together the above activities may have increased the frequency of landscape fires during the historic period (Fastie et al. In press). Although anecdotal evidence indicates that these human impacts occurred, their magnitudes and patterns of geographic variation have never been estimated in the Alaska-Yukon region.

The federal policy of suppressing wildfire, initiated in 1910 (Pyne 2001), was first implemented in Alaska in 1939, when the Alaska Fire Control Service was assigned the task of suppressing wildfires (MacDonald 1940). Federal and state funding for fire suppression have gradually increased to protect the growing population (Gotholdt 1998). It has, however, never been feasible to suppress all wildfires throughout Alaska. An Alaskan fire-management policy, the Alaska Wildland Fire Management plan, established in 1991 formalized a pragmatic pattern of fire suppression practiced earlier, in which wildfires are suppressed primarily in areas close to human habitation. All of Alaska (149 million ha) is classified into one of four protection categories. About 17% of Alaska's land is under the Critical or Full management options, where all fires are immediately attacked, 60% under Limited management option, where fires are generally allowed to burn, and 16% under an intermediate Modified category that provides relatively high protection during critical burning periods, but less protection when fire risks are smaller. Since the top priority in suppressing wildfire is the protection of human life and property, the geographic pattern of these management options reflects human settlement patterns.

The Fairbanks region, which includes most of the road and road-associated towns of interior Alaska and the highest density of Critical and Full lands, had 8.4-fold more fires per unit area than rural areas, where human activities are centralized around Native villages along rivers (DeWilde and Chapin unpubl.). In the Fairbanks region 83% of fires were human-caused and 17% lightning caused, whereas in rural areas, 90% were lightning-caused and 10% human caused. Overall, the Fairbanks region has four-fold less annual area burned than rural areas (DeWilde and Chapin unpubl.). These data suggest a large geographic variation in human impact on fire regime. Although appropriate data are available at the Alaska Fire Service, we currently do not know the relative importance of geographic variation in climate, past land-use change, current vegetation, human ignitions, and fire suppression in explaining the current geographic pattern of fire regime of Alaska. For Alaska as a whole, human activities accounted for 62% of the fires from 1956-2000 but only 10% of the area burned (Gabriel and Tande 1983, Kasischke et al. In press) because most of these fires are lit in places where, or at times when, the landscape is not highly flammable. If these data were analyzed at a finer scale and stratified by community type (road vs. roadless), climate, and vegetation, they would provide insight into the interactions between cultural practices, vegetation, climate, and fire regime.

Fire effects on society. The greatest short-term societal impacts of fire are the risks to life, property, and health (smoke inhalation). We hypothesize that negative economic impacts exhibit a non-linear relationship to population density and differ substantially between road- and roadless areas. Fire also has short-term positive effects that accrue primarily to rural residents. Wages to seasonal firefighters account for up to 50% of the annual cash income in many rural villages. This income could be important in sustaining populations and subsistence traditions in Athabascan villages where there is 50-90% unemployment and few alternative income sources. Many Native groups are outspoken advocates for a policy of active fire suppression, presumably because of the substantial risks to life and property in remote areas and the economic benefits that accrue to villages from fire fighting.

The long-term effects of fire on society depend on the changes in ecosystem services that result from fire. Early successional vegetation supports production of mushrooms in the first 2-4 years after fire, berries in the first 2-20 years after fire, and moose and furbearers for the first 10-30 years after fire. Conversely, firewood, timber, and other wood products are reduced for the first 30-80 years after fire. The less flammable deciduous vegetation that develops after fire reduces fire risk to adjacent property owners for about 30-60 years in black-spruce-dominated lowlands and about 80-100 years in white-spruce-dominated uplands (Van Cleve et al. 1991), but this vegetation effect on fire probability declines in dry years, when fire is most extensive (Kasischke et al. 2000). Although suitable data are available, these fire effects on ecosystem services have been analyzed from this perspective only for moose (Maier et al., in preparation). The quantity of ecosystem services used by local residents has been quantified for road-based (Alaska Boreal Forest Council, unpubl.) and roadless communities (Caulfield 1983). Thus many of the necessary data are available to assess fire effects on ecosystem services used by communities.

Policy feedbacks to fire regime. Public opinion has the potential to affect the magnitude and distribution of fire suppression effort in Alaska at several scales: (1) the national policy of extinguishing all fires that threaten life and property (Pyne 2001), (2) the state fire policy that specifies geographic units of suppression priority, and (3) the implementation of fire policy by the Fire Management Officer (FMO) who decides the quantities of people and equipment (and therefore cost per fire) to be used on a specific fire. Analysis of the sensitivity of fire policy to public opinion at each scale could elucidate the nature and strength of human feedbacks to fire regime (Chapin et al. In press). A similar situation exists in Canada, where fire suppression efforts are the direct responsibility of individual provinces, territories, and national parks, and the Canadian Interagency Forest Fire Centre, which coordinates suppression efforts among agencies (McGuire et al. In press-a, Stocks et al. In press).

*Activities*

Activity 1.1. Human effects on fire regime (Prime responsibility: Natcher and Huntington)

We will assess human effects on fire regime in three periods--the Native period, a Gold Rush period, and a Statehood period, which differed in population size, settlement pattern, economic bases, and resource-exploitation strategies. During the Native period, our first goal is to determine whether there is evidence for a relationship between fire frequency and extent and human presence. Pre-contact population densities were about 80,000 (Levin 1991), which declined following the 1900 influenza outbreak. We will synthesize information on the geographic and temporal changes in human habitation based on patterns of archeological sites for comparison with patterns of charcoal (a surrogate of fire frequency) (Lynch et al. In press), pollen (a surrogate of vegetation composition) (Brubaker et al. 1983, Hu et al. 1993, Lynch et al. In press), and climate (based on GCM climate reconstructions) (Bartlein et al. 1998, Edwards et al. 2001) during the Holocene in the Alaska-Yukon region. This analysis provides a qualitative basis for testing our hypothesis that there is a positive relationship between indigenous presence and fire. We will also use interviews and surveys to assess the extent and traditional patterns of burning used by Native residents, including territorial range, location, geographical extent of burns, seasonality of ignition, and frequency of use. This will enable us to assess whether patterns of seasonal residencies or choice of hunting camps were influenced by (or influenced) fire history.

During the Gold Rush period, we will develop scenarios of human impacts on fire regime based on historical and oral history sources. This information should permit us to distinguish among three hypotheses: (1) Native and non-Native residents had a universally large influence on fire; (2) human impact on fire regime is spatially variable, depending on population density and/or cultural background; or (3) human activities had no detectable effect on fire regime, which can be adequately explained based on climate and vegetation. We will use the ALFRESCO model (described below) to examine the consequences for the geographic pattern of fire regime for each of these hypotheses based on (1) maps of the geographic patterns of Native and mining populations and (2) plausible impacts of each cultural group on fire probability. These will be compared with data on the distribution of stand age in rural areas (Yarie 1981, Yarie and Billings 2002) and near Fairbanks (Fastie et al. In press). This will be done collaboratively with Rupp and Mann, who are currently analyzing extensive field data on the distribution of stand ages throughout interior Alaska in a Joint Fire Science Program project.

For the Statehood period, we will assess human impacts on fire regime by statistically analyzing the large-firescar database of the Alaska Fire Service (Murphy et al. 2000, Kasischke et al. 2002). For each fire reported since 1970 (and for incomplete records since 1950), the presumed cause of the fire (lightning and several categories of human activities, including brush clearing, campfires, etc), initial and final fire size, fire location, cost of suppression, date that the fire started and was extinguished, etc. are recorded (Gotholdt 1998). From other databases, we can extract data on fire suppression classification, vegetation, fire weather, and topography. We can derive secondary databases on distance from rivers, roads, population centers, etc. We will analyze these data to determine whether the cause of fire ignition (lightning vs. human) has a significant effect on fire size and cost of suppression, when data are stratified by vegetation type, topography, and fire weather. When these data are summed over all fires, we can assess human and climatic effects on total area burned. If human impacts on fire regime are significant, we will develop proxies of these impacts such as population density (subdivided into populations along roads vs. populations in roadless areas) and distance from roads and rivers. These analyses will provide a geographically explicit database on human impacts on fire regime.

A deeper understanding of these human effects on fire regime requires assessment of their cultural basis. Some of this information comes from the large-firescar database. We will determine whether the type of human activity (brush clearing, campfires, etc.) influences fire size, when fires are stratified by vegetation and fire weather, and whether the relative frequency of these causes differs between road and roadless areas. We will also examine the parameters of human involvement in fires: the reasons for setting intentional forest fires (e.g., habitat manipulation by hunters, melting of permafrost and removal of organic overburden by gold miners); the size, timing, and spatial distribution of such fires; fire suppression methods and the circumstances in which fire suppression is or is not attempted; and how these parameters have changed over time. This information can be developed through interviews, archival research, and analysis of vegetation patterns in selected areas.

The research questions identified above will be explored through a multi-method, multi-phase approach, following methods used previously (Huntington 1998, Natcher 2001b). In communities, we will use semi-directive interviews, which confer two significant advantages: (1) they are closer to indigenous modes of conversation than is a more formal interview and thus create a more familiar social dynamic for the participant, and (2) they allow the participant to make associations and raise topics not anticipated by the interviewer. The use of community and project-wide workshops will draw on the lessons learned from previous experiences (Huntington et al. 2002). The essential components of collaborative research, particularly involving indigenous knowledge, are trust, flexibility, personal experience, and the time required to achieve them (Natcher 2001a). Because Natcher has worked previously in the region, the project can build on existing relationships (Natcher In press). Nonetheless, this research requires multiple visits to build knowledge and gain feedback, reporting and methodology appropriate to indigenous knowledge research, and a flexible, adaptive research framework that allows for appropriate adjustments in methodology to accommodate a collaborative approach with communities.

Site Selection. This research must be guided by a representative sampling of sites under realistic conditions of human/fire interaction. We begin by choosing a sample of communities regionally representative of socio-economic variation. Two types of communities will be chosen for intensive study: two roadless Native communities with strong subsistence utilization, and two road-accessible communities that are more economically dependent on commercial activities. Because no two communities are identical, this approach provides a continuum based on economy (i.e., subsistence and commercial reliance) and cultural backgrounds. Potential communities include the Yukon River communities of Fort Yukon [560 people], a predominantly Gwich'in community strongly reliant on subsistence resources and also a regional center for fire suppression logistics, and Steven's Village [140 people], a Gwich'in and Koyukon community tightly linked to subsistence use that has been affected by extensive fires in the recent past. Final selection of participant Native communities will be based on further discussions with community representatives and Native Regional Corporations (Tanana Chiefs Conference, Doyon, and the Council of Athabascan Tribal Governments [CATG]). Road accessible communities will include Tok [1200 people], which was sensitized to fire issues by a major wildfire that burned to within 200 m of the town in 1989 and Glennallen [500 people], which is surrounded by high fire-risk black spruce and has had no recent fires. Representing the Yukon Territory will be the communities of Dawson (Pop. 4,000) and Carmacks (pop. 461). These communities are accessible by road and river and are representative of mixed economies involving both subsistence resources and wage-earning opportunities, including fire fighting. With the signing of the Yukon Comprehensive Land Claims, the First Nations that reside within these communities - Tr'ondek Hwich'in in Dawson and Little Salmon Carmacks in Carmacks - are planning to use this collaborative research as a means to reintroduce controlled burns to Settlement Lands. This is being done in order to reduce fuel accumulation near seasonal residencies, to enhance wildlife habitat, and to transfer generational knowledge of the traditional uses of fire from First Nation elders to youth. In addition to intensive studies in these communities, we plan to survey 10-20 rural communities to further analyze the range of variability in socioeconomic processes. This study design provides comparisons with regard to climate, human role in fire regime, and cultural heritage. This survey will include communities in tundra, treeline, and boreal regions.

Activity 1.2. Fire effects on people (Prime responsibility: Naylor, Zavaleta, and Chapin)

Some of the effects of fire on people (described above) can be directly quantified; others are strongly modified by a cultural filter of human perceptions. Ultimately it is the human perceptions of fire effects that link the consequences of fire back to human impacts on fire regime. We hypothesize that both the effects of fire and the perceptions of these effects differ among fire managers, people living along roads (dominated by western influences), and people living remote from roads (largely Native people). We will quantify the effects of fire and assess the influence of these fire effects on the perceptions of three groups of people using data from agency records, interviews, and surveys.

The first step in the socioeconomic analysis is to assess the direct costs and benefits of fire to stakeholders. Costs to individuals of wildfire will be based on records of property loss. Costs to managers will be analyzed in terms of the cost of running organizations that monitor and suppress fires (the Alaska Fire Service and the Alaska Division of Forestry) and the additional costs of fighting fires (wages to fire crews, aircraft, retardants, etc.). We will document the partitioning of these costs among fire suppression agencies and state and federal landowners, who reimburse these agencies for fighting fires on their lands. We will also analyze these costs relative to the types of fires that are actively suppressed (large vs. small; road vs. roadless areas; severe vs. mild fire weather) to assess how managers assign resources to fires of different types. We will assess the direct economic benefits from fires in terms of the wages earned by fire suppression personnel according to their location of residence (urban, road communities, Native communities, non-Alaskan). We will place these economic inputs to communities into context be determining other income sources (other jobs, permanent fund dividends, etc.).

Our second step is to quantify the effects of fire on ecosystem services through analysis of agency records, ecological surveys, and interviews with residents. We will stratify these fire effects by upland forest, lowland forest, tundra, and wetland. These vegetation types, which can be mapped using remote sensing signatures and digital elevation maps, differ in their sensitivity to fire and ecosystem services provided. Within each of these four vegetation classes, we will assess how ecosystem services change with time after fire. In some cases (e.g., moose density) quantitative data are available (Alaska Dept. of Fish and Game). In other cases, we will use abundance classes (uncommon, some, abundant) that can be assessed from interviews and rapid field surveys. The ecosystem services we will assess include firewood, timber and other wood products, berries, mushrooms, other plant foods, moose, furbearers, and caribou.

The third step in our analysis is to assess how stakeholders in boreal and adjacent arctic communities view fire and fire management in terms of the combined ecological, economic, and health-safety impacts. The goal of this analysis is to determine the perceived values of ecosystem services, employment, personal property, and human health and safety within a dynamic ecological context. In the first year, we will participate in the community-based interviews and workshops described above to identify perceived values for different sets of stakeholders. For example, Native communities without large crews of fire fighters may perceive greater ecosystem-related benefits of fires through associations with improved subsistence hunting and gathering. Communities with fire crews may strongly value fire-fighting employment and income and hence more intensive fire control policies. Similarly, residents living in forested areas but employed elsewhere in the economy may strongly value their personal property and safety, and hence prefer active fire management. Results from our workshops will be compared with patterns observed 25 years ago (Caulfield 1983). The analysis will thus incorporate both cross-section and time-series evaluations of human values.

Information from these workshops will provide the basis for our assessment of conservation and management objectives for the future. We will use a scenario planning approach (Peterson et al. 2003) to involve stakeholders in the different communities in the process of defining relative costs and benefits of fire, as well as the probable impacts from different fire management strategies given the ecological and climatic uncertainty of the system. Under conditions of irreducible uncertainty (e.g., climate change and its influence on fire extent, location, and severity), a framework of optimal decision-making cannot be used to evaluate alternative ecological decisions (Ludwig 2002), particularly when human behavior (e.g. fire management, ignition) is involved. In essence, a scenario approach examines alternative models of how the system might behave under various sets of assumptions, and it seeks to develop policies that are robust to the underlying uncertainty. Scenarios thus depict future conditions that *could* be rather than future conditions that *will* be (Van der Heijden 1996, Raskin et al. 1998, Chapin et al. In press). They are constructed to provide insight into determinants of change, reveal the implications of current trends for society and ecosystems, and illuminate options for action (Peterson et al. 2003).

The construction of plausible scenarios for this project will result directly from community meetings and workshops in the first year. The optimal number of scenarios is greater than two (variation is required to detect drivers of change and trajectories), but no more than four (too many "futures" becomes confusing to everyone involved). Although we cannot define the scenarios precisely prior to receiving community input, they could hypothetically consist of the following: 1) "Globalization of the boreal/arctic" as defined by increased urbanization of the region's population, increased oil sales, and a rise in the Alaska permanent fund allocation per capita; 2) "Ruralization of the boreal/arctic" as defined by increased settlement in rural areas, particularly along road corridors, and more people staying in rural communities where fire fighting jobs provide essential income; and 3) business as usual. For each scenario quantitative and qualitative trajectories of change will be evaluated. The quantitative assessments will come directly from the ecological and climate models, and the qualitative assessments will come from community workshops and discussions with stakeholders. For each scenario, different policy and management options will be tested to illuminate how the future might look. A realistic look at the future is often the best medicine for immediate reform in human behavior and policy.

The fourth step of socioeconomic research will be based on a broader, statistically based survey (e.g., with respondents from about 20 different communities) that relates perceptions of economic and ecological effects of fire to opinions about fire policy for each stakeholder group. In this phase of research, we will use ANOVA and regression techniques to evaluate the relationship between economic/ecological value preferences and a set of socioeconomic variables (e.g., demographics, migration, income sources, culture, location of residence) within and across communities. The survey will be used to obtain quantitative values of boreal forest and adjacent arctic ecosystem goods and services for each stakeholder group, an input needed for the ecological mapping of ecosystem services. Quantitative estimates of ecosystem values will be based on revealed preference and hedonic approaches of valuation (Goulder and Kennedy 1997). The analysis will also provide quantitative estimates of the economic importance of fire management (wages, personal property) by region, age, and cultural origin.

Activity 1.3. Policy feedbacks (Prime responsibility: Chapin, Rupp, Zavaleta, and Naylor)

We will analyze geographic and annual variation in maps of fire suppression categories used by fire management agencies as their basis for fire suppression policy. Geographic variation analyzed by landowner constitutes willingness to pay suppression costs and with respect to natural and human features on the landscape (e.g., inhabited structures, remote cabins, timber allotments, roads, scenic features, etc.) that provide potential proxies for predicting future fire suppression pattern. We will interview managers responsible for generating maps to assess the reasons for geographic and interannual variation in fire management option classification. We hypothesize that fire policy is relatively rigid, despite large interannual variation in public concern about fire impacts and expenditures for fire suppression.

Based on interviews with Fire Management Officers (FMOs), we will develop a set of fuzzy decision rules that relate resources requested for suppressing a particular fire to the properties of that fire (land classification for suppression, proximity to structures or communities, fire weather, vegetation, topography, etc.). We will compare these rules based on interviews with a multiple regression analysis of the large-firescar database, from which we can derive the same information. Finally, we will compare the increase in fire size (final size minus initial attack size) with these same variables to assess the effectiveness of fire suppression as a function of resources expended, fire size, fire weather, and vegetation.

*Human-fire-vegetation interactions*

Background.

Fire and vegetation form a negative feedback loop, whose strength depends on fire weather. In most years during the peak fire season early successional deciduous forests are less flammable than late successional conifer-moss forests (Viereck 1973, Van Cleve et al. 1991, Johnson 1992, Kasischke et al. 2000, Kasischke et al. In press). In severe fire years, deciduous forests have greater probability of burning, weakening the fire-vegetation feedback loop. If ignited by people, deciduous forests can also burn in early spring (prior to the lightning season), fueled by dry litter from the previous year and absence of moist live foliage. An increase in fire frequency reduces the extent and connectivity of late-successional flammable conifer vegetation (Turner et al. 1997, Rupp et al. 2000b, Turner et al. 2003), which reduces the probability of very large fires (Starfield and Chapin 1996, Chapin and Starfield 1997, Rupp et al. 2001). Regional variation in fire return time (e.g., 40-100 years for black spruce) (Yarie 1981, Dyrness et al. 1986, Kasischke et al. 1995) results from climatic and vegetation effects on fire probability. Black spruce, for example, resumes dominance within 25-40 years after fire (Zasada et al. 1992), unless aspen colonizes after fire (Mann and Plug 1999), which prolongs the deciduous phase to perhaps 100 years before returning to black spruce dominance. Landscape-scale interactions between vegetation and disturbance are particularly important at the forest-tundra ecotone (Noble 1993, Starfield and Chapin 1996, Chapin and Starfield 1997) where vegetation change could have large feedbacks to climate (Pielke and Vidale 1995, Beringer et al. Submitted).

These observed landscape-scale fire patterns have been incorporated into ALFRESCO, a spatially explicit model that simulates the broad-scale effects of climate and vegetation on landscape patterns of fire and succession (Rupp et al. 2000a, Rupp et al. 2000b, Rupp et al. 2001, Rupp et al. 2002). Simulations span hundreds of years with an annual time-step on landscapes of 1000's of square kilometers with a 1-km resolution. ALFRESCO has been calibrated and used to simulate landscapes in the forest tundra and boreal regions of Alaska (Rupp et al. 2000a, Rupp et al. 2000b, Rupp et al. 2001, Rupp et al. 2002) and western Canada (McGuire and Rupp unpubl.). Model inputs are derived from remote sensing and climate analyses. ALFRESCO simulates four general ecosystem types – tundra, black spruce forest, white spruce forest, and broadleaf deciduous shrubs. The model uses a cellular automaton approach to simulate the spatial processes of fire spread and seed dispersal. Landscape flammability is a function of climate, vegetation type and fuel build-up (e.g., canopy cover, time since last fire, and connectivity) (Rupp et al. 2000a, Rupp et al. 2000b, Rupp et al. 2001). Climatic effects on fire are implemented through a drought index (Thornthwaite and Mather 1957, Trigg 1971, Starfield and Chapin 1996).

Activity 2.1 Human-fire-vegetation interactions (Prime responsibility: Rupp)

We are modifying ALFRESCO to explicitly simulate the impacts of humans on the fire regime through their effects on both ignitions and suppression (Chapin et al. In press) (Rupp and Henkelman in preparation). Currently the model simulates ignitions by lightning stochastically. We will modify the fire ignition subroutine based on observed patterns of human-caused fires near settlements and along roads. We will modify the fire-spread subroutine to incorporate the fire management plan as a spatial layer of suppression options that is updated annually as management option boundaries change. In this manner we can explicitly model the impacts of fire suppression on vegetation distribution and, vice versa, the impact of vegetation distribution on future fire suppression requirements. By knowing fire effects on ecosystem goods and services (activity 1.2), the ALFRESCO simulations provide estimates of short- and long-term impacts on important ecosystem goods and services. Changes in the stocks of ecosystem goods and services will be estimated through complete enumeration of gridded cells in ALFRESCO, based on vegetation type, stand age, and distance from settlements and transportation.

Once these modifications have been completed, we will use ALFRESCO to run various scenarios of climate and human impacts on fire regime. These scenarios will allow a qualitative/quantitative assessment of the impacts on important ecosystem goods and services, direct economic effects, and possible policy implications. The specific scenarios implemented will reflect our findings on human fire effects (activity 1.1), human responses (activity 1.2), and fire policy (activity 1.3). These will be carefully chosen to represent predicted future climate regimes (activity 3.1) and demographic projections for both urban and rural populations (activity 1.1). Feedbacks between landscape dynamics and policy-driven fire management will emerge from comparisons of simulations based on different scenarios.

Comparison of human impacts among the three historical periods enables us to assess the consequences for fire and vegetation of the changes in human impacts on fire regime. This will enable us to identify potential thresholds of human impact above which we might expect a different response by the system. These historical reconstructions will provide "benchmarks" for the parameterization and calibration of the model (Cissel et al. 1999). In addition, we will conduct sensitivity analyses (Beres and Hawkins 2001) to identify those parameters (and thresholds) in the fire-vegetation-climate complex that are particularly sensitive to human impacts on fire ignitions and suppression. We are particularly interested in short- versus long-term landscape response and the role of reactive versus preventative fire management strategies.

*Fire-vegetation feedbacks to climate*

Background

Northern ecosystems (arctic and boreal forest) play a critical role in the changing Earth System (Melillo et al. 1996). Their large carbon stores are sensitive to drought and temperature (Van Cleve et al. 1986, McGuire et al. 1995, Barber et al. 2000, Ping et al. 2002). They could be part of the "missing sink" of $CO_2$, if they are accumulating carbon (Ciais et al. 1995, Randerson et al. 1999, Myneni et al. 2001, Schimel et al. 2001) or a carbon source if warming increases fire frequency or decomposition more than plant production (Kasischke et al. 1995, Kurz and Apps 1995, Zimov et al. 1999). Fire-induced changes in carbon storage (Kasischke et al. 1995, Kasischke and Stocks 2000) would have immediate policy and economic implications, if tradable permits for carbon are institutionalized. Finally, land-surface change at high latitudes could significantly affect regional albedo and the rate of regional warming (Bonan et al. 1992, Foley et al. 1994, Chapin et al. 2000a).

Our understanding of the nature of these climate feedbacks is improving. Remote sensing (Myneni et al. 1997, Silapaswan et al. 2001, Zhou et al. 2001), field observations (Sturm et al. 2001, Thorpe et al. 2002), and experiments (Chapin et al. 1995, Shevtsova et al. 1997, Hobbie and Chapin 1998) show that warming within tundra increases the abundance of leaf area, particularly of shrubs. This in turn increase the energy absorbed (lower albedo) and transmitted to the atmosphere (particularly as sensible heat, which directly warms the air), leading to a large positive feedback to summer warming (McFadden et al. 1998, Chapin et al. 2000a, Beringer et al. Submitted). Forest advance into tundra (Lloyd et al. In press) acts as an even larger (but slower) positive feedback to warming by replacing the reflective snow cover with a dark forest canopy (Bonan et al. 1992, Thomas and Rowntree 1992, Foley et al. 1994, Bonan et al. 1995) and by increasing sensible heat flux in summer (Beringer et al. Submitted). Alternatively, disturbances like fire that kill mature trees (and their seeds) may reduce the rate at which forest successfully establishes in tundra leading to a negative feedback (Lloyd et al. In press). In contrast to tundra, a warming-induced increase in fire frequency of boreal forest could lead to negative feedback to warming if fire increases the proportion of deciduous stands on the landscape. Post-fire stands that are dominated by herbs, shrubs, and deciduous trees have a higher albedo in both summer and winter than do conifer stands which they replace and therefore transfer less energy to the atmosphere (Chambers and Chapin In press). The net effect of these changes in energy budget depends on their magnitude per unit area and aerial extent, which have not been carefully analyzed.

Warming also influences feedbacks to climate through changes in trace gas flux to the atmosphere. In tundra both theory (Shaver et al. 1992, Shaver et al. 2000) and observations (Oechel et al. 1993, Oechel et al. 2000) suggest that warming initially increases decomposition, leading to net carbon loss to the atmosphere (a positive feedback to warming), followed by nitrogen release and increased productivity, which enhance carbon gain. These effects are captured by biogeochemical models that simulate net ecosystem carbon balance in response to climatic change (McKane et al. 1997, Clein et al. 2000). Similar transient dynamics at treeline are expected to be larger in magnitude but to occur more slowly because of larger carbon sequestration in forests than in tundra (Smith and Shugart 1993). In the boreal forest this lag between responses of decomposition and production may be swamped out by changes in fire regime, which initially release large amounts of carbon to the atmosphere in the fire and subsequent decomposition (Kasischke et al. 1995) and subsequently regain carbon during succession (Harden et al. 2000). During the 1970s and 1980s, the fire frequency in northwest Canada increased substantially (Kurz and Apps 1999, Stocks et al. 2000, Podur et al. 2002), probably releasing substantial amounts of carbon to the atmosphere (Kurz and Apps 1999, Chen et al. 2000, Amiro et al. 2001). Climate projections suggest that fire frequency will continue to increase (Flannigan et al. 2001).

Although the processes responsible for climate feedbacks are now reasonably well understood in tundra and boreal forest, there net effect is uncertain. For example, the increased carbon sequestration due to forest planting or reduced fire frequency (a negative feedback to warming) may be largely offset by the reduced albedo and greater heat transfer to the atmosphere (a positive feedback to climate) (Betts 2000). The net effect of changes in high-latitude warming on changes in land cover and carbon storage of Alaska and the adjacent Yukon during the past century are currently being simulated through a coupling between TEM and a version of ALFRESCO without human effects (McGuire and Rupp, unpubl.; see WALE Project at http://picea.sel.uaf.edu). TEM is a highly aggregated ecosystem model that uses spatial data on climate, elevation, soils, and land cover change to make monthly estimates of important carbon and nitrogen fluxes and pool sizes at large spatial scales (McGuire et al. 2000, McGuire et al. 2001). The model has been used to evaluate how historical C storage in Alaska and Canada has been influenced by fire disturbance, climate changes, and changes in atmospheric carbon dioxide between 1950 and 1995

(McGuire et al. In press-a). In the WALE Project, TEM is currently being applied to unique trajectories of land cover change over the WALE domain from 1900 through 2001. An extension of the simulations of the WALE project into the future, using the new version of ALFRESCO, will provide us a continuous picture of how possible changes and land cover and carbon storage in the Western Arctic from 1900 to 2100 influence radiative forcing, and will allow us to examine how the relative roles of tundra and boreal forest and of humans and other factors (climate-induced fire, tree line change, change in shrub biomass of tundra) on climate change through the past and into the projected future.

Activity 3.1. Climate feedbacks (Prime responsibility: McGuire)

To evaluate historical and projected changes in the radiative forcing of climate associated with changes in land cover and carbon storage in the Western Arctic we will (1) conduct a coupled simulation between TEM and the new version of ALFRESCO (see activity 2.1) for the historical period (1900 – 2001) over the WALE domain; (2) develop data sets of projected changes in climate and other factors and extend the simulations of TEM-ALFRESCO to 2100 over the WALE domain; (3) calculate changes in radiative forcing associated with simulated changes in land cover and carbon storage; and (4) partition the changes in radiative forcing between tundra and boreal forest and between humans and other factors.

Because we are developing a new version of ALFRESCO in this study, our first task in Activity 3.1 will be conduct a simulation of TEM coupled with this new version over the WALE domain for the historical period (1900 – 2001) and evaluate its performance. Land cover change simulated by the coupled model will be compared to historical land cover change for the region over the period 1950 to 2001. Also, we will evaluate how the partitioning of the ALFRESCO simulations of changes in land cover to human vs. other factors by comparing the simulations with the diagnostic results of the statistical model developed in Activity 1.1. The estimates of changes in carbon storage by TEM-ALFRESCO for the historical period will also be compared to simulations of TEM driven by historical changes in land cover and climate that are currently being conducted as part of the WALE project. These comparisons will provide some confidence in the use of the coupled model for simulating future changes in land cover.

To extend the TEM-ALFRESCO simulations into the future requires the development of scenarios for climate and other factors that may change within the WALE domain from present to the end of the projected period in 2100. Our projections of climate will be based on the scenarios organized by ACIA. We will choose two scenarios that represent a range in temperature and precipitation changes over the region. Because these climate change scenarios are not well matched to contemporary climate at the regional scale, we will reprocess the scenarios so they represent smooth changes from a baseline current climate; we will use a methodology similar to that used earlier (McGuire et al. 2000). The procedure will allow us to drive TEM-ALFRESCO with a climate data set that smoothly crosses from the historical into the projected period and avoids artificial transient jumps of land cover change and carbon storage at that boundary.

We will apply the methodology of Betts (Betts 2000) to the results of the TEM-ALFRESCO simulations for calculating changes in radiative forcing associated with ecosystem change. This methodology allows us to calculate how regional changes in either land cover or carbon storage translates to forcing in watts meter$^{-2}$. While this methodology does not allow us to directly calculate the effects of these changes on regional climate, a calculation that would require a global application of coupled climate-biosphere model, it does allow us to compare changes in radiative forcing in a common currency at a variety of spatial and temporal scales. The changes in radiative forcing associated with land cover change and carbon storage will be calculated at a variety of spatial resolutions from subregional (tundra vs. boreal forest), to regional (for the WALE domain), to global (contribution of the region to global changes in radiative forcing. Because growing season changes will be represented in our simulations (Zhuang et al. In press), we will also calculate the subregional and regional changes in radiative forcing at monthly resolution as well as at annual resolution, while the contribution of the region to global changes in radiative forcing will be calculated at an annual resolution. For each of the simulations we will determine how changes and land cover and carbon storage are partitioned between human effects on fire and other factors (climate effects on fire, tree line changes, changes in shrubs biomass of tundra).

## Project Integration, Management, and Feasibility

We will work as an interactive team in which all participants contribute actively in all components of the project through quarterly meetings of Alaskan personnel and annual meetings of all personnel. Nonetheless, we have subdivided primary responsibilities to ensure that the tasks associated with each activity are actively planned and managed. The responsibilities are as follows: Overall project coordination and project linkages (Chapin), human interactions with fire regime (Natcher and Huntington), fire effects on ecosystem services (Zavaleta), economics of fire and of ecosystem services (Naylor), modeling of fire-vegetation-human interactions (Rupp and Starfield), and climate feedbacks (McGuire). The timetable for the research is as follows:

Year 1: Collect basic information on traditional fire-human interactions in rural communities, fire policy, fire-related economics, and climate scenarios that are specific for Alaska-Yukon. Develop statistical model of the effects of humans vs. other factors on the fire regime. Develop the human impacts module of ALFRESCO. Develop data sets of future climate scenarios for driving TEM-ALFRESCO. Initiate community interviews.

Year 2: Intensive work in communities on human-fire interactions and ecosystem services based on community interviews. Develop policy scenarios, based on historical analysis of fire policy and interviews with agency personnel. Apply TEM-ALFRESCO for the historical period and compare with results of the statistical model and with TEM, driven by data sets of historical land-cover change. Apply TEM-ALFRESCO for future climate and policy scenarios.

Year 3: Evaluate policy x climate interactions for energy-budget and trace-gas feedbacks to climate. Partition changes in radiative forcing among human effects on the fire regime, climate-induced effects, tree line changes, and changes in shrub biomass. Conduct extensive surveys of numerous communities to assess generality of results on human-fire interactions.

We are confident we can accomplish the research we have proposed, because, as individuals, each person has already done the types of activities for which s(he) is responsible. For this reason, we know how to do the research and know we can complete the activities in the time allotted. More importantly, we have considerable experience working together as a team in research (see prior research) and in other teaching and research planning activities, so we know how one another think about this research and are confident we can work well together. As evident from CVs and reference lists, we all have interdisciplinary research experience and have worked with multiple aspects of the problems addressed in the proposed research.

## Prior NSF-funded Research

The proposed research would be impossible without the considerable previous research that others and we have done to develop databases and understanding of the arctic-boreal system. We describe how several of our prior research programs contribute to the proposed research. Selected publications emerging from these programs are indicated (*) in the references.

The FLUX study (DPP-9214906) and Arctic Transitions in the Land-Atmosphere System (ATLAS OPP-9732126) (Chapin, McGuire, Rupp) measured the climate feedbacks (carbon, water, and energy exchange) of major arctic and boreal ecosystem types and integrated this information into models of trace-gas flux and regional climate. The project also measured the impact of fire on climate feedbacks in tundra and modeled the effects of fire-climate interactions on treeline dynamics.

WALE (McGuire, Rupp) is determining the relative effects of climate and land-cover change in carbon and water budgets of the Yukon River Basin in the Western Arctic from 1980 to 2001.

The treeline-modeling project (OPP-9630913; Starfield, Rupp, Chapin) developed a point model of fire-climate-vegetation interactions at the latitudinal treeline. This model was made spatially explicit and adapted to tundra and boreal environments (ALFRESCO) for use in the proposed research.

FROSTFIRE (DEB-9728963; Chapin, McGuire) measured the climate feedbacks (carbon, water, and energy exchange) of major boreal ecosystem types in interior Alaska and integrated this information into models of trace-gas flux and regional climate.

Bonanza Creek LTER (DEB-9810217; (Chapin, McGuire, Rupp) studies have focused on succession, including the processes underlying ecosystem change after fire, factors governing fire probability and spread, and the consequences for ecosystem carbon balance. These studies provide the process-based understanding that underlie the ALFRESCO and TEM modeling efforts.

The IGERT graduate educational program in Regional Resilience and Adaptation (DEB-0114423; Chapin, McGuire, Naylor, Rupp, Starfield) integrates ecological, economic and cultural bases of regional sustainability. The courses developed in this program provide a theoretical framework for the proposed research. Two IGERT students have expressed an interest in participating in the proposed research.

A series of projects by Huntington (including traditional knowledge of beluga whales, OPP-9817923) documents traditional ecological knowledge held by Alaska Natives. These projects have demonstrated effective methods for documentation and application of traditional knowledge in research and management (Huntington 1998, 2000, Huntington et al. 2002), the degree of ecological detail that can be obtained from such study (Huntington and Communities of Buckland 1999), and the ways in which local people can be involved in studies of this type (Huntington 1998, Huntington et al. 2002).

## Education and Outreach

Education and training objectives will be approached in part through the involvement of a postdoctoral fellow, graduate students, and undergraduates as members of our research team. This provides several unique training opportunities, including (1) integration of natural and social sciences and (2) cross-cultural communication (between natural and social sciences, between academics and managers, between western and indigenous communities). We will engage IGERT graduate students from the program in Regional Resilience and Adaptation (see prior research) to provide research experience to students interested in integrating natural and social sciences.

In addition, we will involve community members as fully engaged members of our research team. True collaborations between academics and local residents have long been hampered by academic resistance to qualitative ethnographic research generated at the local level and its integration with experimental research. However, this linkage between western and indigenous knowledge systems can advance our understanding of regional systems by revealing insightful ways in which humans interact with the environment over centuries. This direct local involvement in research implementation will serve both to educate university researchers about traditional ecological knowledge as it relates to fire and to enhance local understanding of ecosystem processes. This collaborative approach (1) draws on local knowledge, observation and understanding of fire in a socio-natural context; (2) brings together indigenous and 'scientific' knowledge; (3) enhances community ownership in the research process; (4) provides voice to communities with respect to other stakeholders; (5) strengthens community research capacity; and (6) identifies knowledge gaps, misunderstandings, and future research opportunities. The direct involvement of community members will ensure that research findings are both relevant and accessible to community partners. We will return our findings to the communities through public presentations at the regional and community levels and through a series of interactive school presentations.

## Broader Impacts

The proposed research has impacts that extend well beyond the immediate research results. This is the first project to consider the overall consequences of human activities on climate feedbacks at high latitudes, including both global warming and local land-cover change induced by changes in fire regime. This will enable us to compare the magnitude of climate feedbacks between arctic and boreal regions and between trace-gas fluxes and water/energy exchange. If, as we hypothesize, enhancing boreal fire is the only large negative feedback to high-latitude warming, our research represents the first step in determining whether fire manipulation would be a plausible mechanism to reduce the magnitude of high-latitude warming. Given the reticence of industrial nations to reduce greenhouse-gas emissions, radical steps such as this may be the only mechanism of reducing the rate of high-latitude change. Our research on fire-human interactions will assess the societal impacts of potential changes in fire policy and fire regime. We will determine the long-term consequences for vegetation and fire regime of a wide range of fire policies potentially available to fire managers. Our analysis of the fire records will provide the first evaluation of the environmental factors governing the effectiveness and economic efficiency of current fire suppression efforts. Our work with communities provides several potential benefits, including (1) an analysis of fire effects on wages, ecosystem services, and subsistence opportunities and (2) direct involvement of community members in our research team.

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