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Social-Ecological Sustainability in Alaskan Boreal Forests: The Challenges of Global Change

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Abstract

Human activities are altering many factors that determine the fundamental properties of ecological and social systems. Is sustainability a feasible goal in a world in which these controls are changing with a directional trend over time? This is global problem, but Alaska is particularly appropriate place to address this question because of rapid climate warming. This has profoundly affected factors that influence landscape processes (climate regulation and disturbance spread) and natural hazards; the goods that people harvest from ecosystems such as food, water, and wood; and many of the cultural benefits that people derive from ecosystems. Four broad policy strategies emerge for sustaining social-ecological systems at times of rapid change: (a) reducing vulnerability by sustaining basic ecological processes and reducing those hazards and stress that cause changes; (b) increasing adaptability by maintaining a diversity of options and experimenting with potentially innovative solutions; (c) fostering resilience by learning to cope with surprises and strengthening feedbacks that stabilize the current state of the system; and (d) facilitating transformation to new, potentially more beneficial states by taking advantage of opportunities created by crisis. Each strategy provides societal benefits, and all of them can be pursued simultaneously.

Introduction

The world is undergoing unprecedented changes in many of the factors that determine both its fundamental properties and their influence on society. Throughout human history, people have interacted with and shaped ecosystems for social and economic development (Turner et al. 1990, Redman 1999, Diamond 2005). In the last 50 years, however, human activities have changed ecosystems more rapidly and extensively than at any comparable period of human history, with even more rapid and extensive changes projected for the next half century and beyond (Steffen et al. 2004, Foley et al. 2005, MEA 2005). As human population expands, the increased demand for food and natural resources has led to an expansion of agriculture, forestry, and other human activities, causing large-scale, land-cover change and loss of habitats and biological diversity. Increased human mobility is spreading plants, animals, diseases, industrial products, and cultural perspectives more rapidly than ever before.

This globalization of economy, culture, and ecology is important because it modifies the life support system of the planet (Odum 1989), i.e., the capacity of the planet to meet the needs of all organisms, including people. The dramatic increase in the extinction rate of species (100- to 1000-fold in the last two centuries) indicates that global changes have been catastrophic for some species, although a few have benefited and expanded their ranges. Human society has both benefited and suffered from global changes, with increased food production, increased income and living standards (in parts of the world), improved treatment of many diseases, and longer life-expectancy being offset by deterioration in ecosystem services, the benefits that society receives from ecosystems. More than half of the ecosystem services on which society depends for survival and a good life have been degraded – not deliberately, but inadvertently as people seek to meet their material needs (MEA 2005). Change creates both challenges and opportunities. People have amply demonstrated their capacity to alter the life support system of the planet.

Given the importance and difficulty of fostering sustainability in a world with an uncertain future, many approaches are being explored (Gunderson and Holling 2002, Berkes et al. 2003, Clark and Dickson 2003, Turner et al. 2003). In this paper I integrate several of these approaches and apply this framework to the impacts of climate warming on Alaska's boreal forest (Chapin et al. 2006c). I then describe a suite of policy strategies that could contribute to sustainability. Alaska is a particularly appropriate place to apply this framework, because ecosystem services, which are key processes that mediate climate effects on society, are critical to the sustainability of traditional subsistence livelihoods and culture. Most of ideas presented here have been published previously (Chapin et al. 2006b, Chapin et al. 2006d) and are the basis of a textbook on natural resource stewardship now in preparation (Chapin et al. In preparation).

Integrating Conceptual Frameworks

Global-Local Linkages

Ecological and social systems affect one another so strongly that they are best viewed as a *social-ecological system* (i.e., a coupled human-environment system) (Berkes et al. 2003, Clark and Dickson 2003) (Fig. 1). Although the relative importance of social and ecological processes may vary from forests to farms to cities, the functioning of each of these systems, and of the larger regional system in which they are embedded, is strongly influenced by physical, ecological, economic, and cultural factors. They are, therefore, best viewed, not as ecological *or* social systems, but as social-ecological systems that reflect the interactions of physical, ecological, and social processes.

Ecological components of social-ecological systems respond to a spectrum of controls that operate

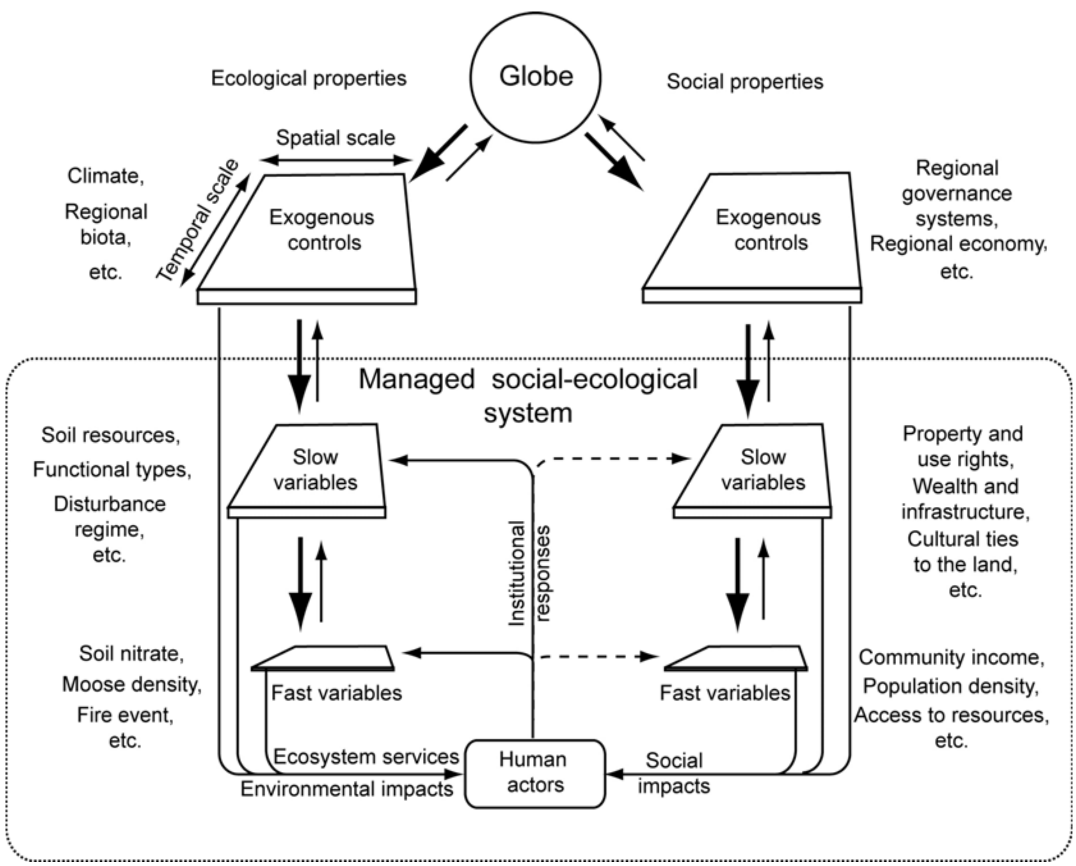

Figure 1. Diagram of a social-ecological system comprised of an ecological subsystem (left-hand side) and a social subsystem (right-hand side), each with a spectrum of controls that operate across a range of temporal and spatial scales. Environmental impacts, ecosystem services, and social impacts govern the well-being of human actors, who affect ecological and social systems through a variety of institutions. Modified from Chapin et al. (2006b).

across a range of temporal and spatial scales. These can be roughly grouped as exogenous controls, slow variables, and fast variables (Fig. 1). *Exogenous controls* are factors such as regional climate or biota that strongly shape the properties of broad regions. They remain relatively constant over long (e.g., a century) time scales and are not strongly influenced by short-term, small-scale dynamics of a single forest stand or lake. At the scale of an ecosystem or watershed, there are a few *critical slow variables* (i.e., variables that strongly influence social-ecological systems but remain relatively constant over years-to-decades despite interannual variationin weather and other factors), because they are buffered by stabilizing (negative) feedbacks that prevent rapid change (Chapin et al. 1996, Carpenter and Turner 2000). Critical slow variables include presence of particular functional types of plants and animals (e.g., evergreen trees or herbivorous mammals); disturbance regime; and the capacity of soils or sediments to provide water and nutrients. Slow variables in ecosystems, in turn, govern *fast variables* at the same spatial scale (e.g., moose or aphid density, individual fire events) that respond sensitively to daily, seasonal, and interannual variation in weather and other factors. When aggregated to regional or global scales, changes that occur in ecosystems, for example those mediated by human activities, can modify the environment to such an extent that even regional controls such as climate and regional biota that were once considered constant parameters are now directionally changing at decade-to-century time scales (Foley et al. 2005). Regardless of the causes, persistent directional changes in broad regional controls, such as climate and biodiversity, must logically lead to directional changes in critical slow variables and therefore the structure and dynamics of ecosystems, including the fast variables. The exogenous and slow variables are particularly critical to long-term sustainability, but most management and public attention focuses on fast variables, whose dynamics are more visible.

Analogous to the ecological subsystem, the social subsystem can be viewed as composed of exogenous controls, critical slow variables, and fast variables (Straussfogel 1997). These consist of vertically nested relationships, ranging from global to local, and linked by cross-scale interactions (Ostrom 1999, Young 2002, Adger et al. 2005). At the sub-global scale a predominant history, culture, economy, and governance system often characterize broad regions or nation states (Chase-Dunn 2000). These exogenous social controls tend to be less sensitive to interannual variation in stock-market prices and technological change than are the internal dynamics of local social-ecological systems; these exogenous controls constrain local options. This asymmetry between regional and local controls occurs in part because of asymmetric power relationships between national and local entities and in part because changes in a small locality must be very strong to substantially modify the dynamics of large regions. Regional controls sometimes persist for a long time and change primarily in response to changes that are global in extent (e.g., globalization of markets and finance institutions), but at other times change can occur quickly, as with the collapse of the Soviet Union in the 1990s or the globalization of markets and information (Young et al. 2006). As in the biophysical system, a few slow variables (e.g., wealth and infrastructure; property-and-use rights; and cultural ties to the land) are constrained by regional controls and interact with one another to shape fast variables like community income or population density. Both slow and fast social variables can have major effects on ecological processes (Costanza and Folke 1996, Holling and Sanderson 1996).

Human-Environment Interactions

Important advances in understanding the effects of climate change on social-ecological systems have occurred by focusing on processes that link ecological and social subsystems through their effects on human actors (Fig. 1) (Young 2002). These linkages include direct environmental impacts (Turner et al. 2003, McCarthy et al. 2005) and ecosystem services (i.e., the benefits that society derives from ecosystems; Daily 1997, MEA 2005). I use the categories of ecosystem services developed by the Millennium Ecosystem Assessment (MEA 2005). The ecosystem services most readily incorporated into a socioeconomic framework are the goods (*provisioning services*) that are directly harvested and used by society (e.g., food, water, and fuel wood). In addition, there are *supporting services* (basic ecological processes that shape the structure and dynamics of ecosystems); *regulating services* such as climate and disturbance regulation that extend the spatial scale of social-ecological interactions from individual stands to landscapes; and *cultural services* that provide a sense of place and identity, aesthetic or spiritual benefits, and opportunities for recreation and tourism. The societal importance of ecosystem goods is well recognized, because they are valued and traded in the market place. Other ecosystem services, especially supporting and cultural services that do not enter the marketplace, are often taken for granted by society and are particularly vulnerable to unintended degradation, despite their societal value (Costanza et al. 1997, Daily et al. 2000).

Human actors (both individuals and groups) respond to social, environmental, and ecological impacts that they perceive through a complex web of institutions (i.e., the rules of the game that give rise to enduring regularities of human action; Young 2002, Ostrom 2005) (Fig. 1). Human actions, mediated by institutions, then affect slow and fast variables of both ecological and social systems. Institutions are a useful focus for analyzing societal responses to directional environmental changes because they affect politics by organizing and directing social behaviors (Putnam 1993). In addition, institutions are shaped by and structure history (Putnam 1993) by offering particular organizational opportunities, perpetuating values, and cultivating a set of actors within the political system (Brosius 1999, Lovecraft 2004).

Social-Ecological Response to Warming in Interior Alaska

Climate warming has triggered pronounced ecological and social change in Interior Alaska. Since 1950, air temperature has increased by 0.4°C $decade^{-1}$, the growing season has lengthened by 2.6 days $decade^{-1}$, and permafrost (permanently frozen ground) has warmed by 0.5°C $decade^{-1}$, with projections that air temperature will increase more rapidly during the 21^{st} century (0.4-0.7°C $decade^{-1}$) (Hinzman et al. 2005, Chapin et al. 2006c).

Warming has affected ecosystem and population processes (i.e., supporting services), primarily through changes in the hydrologic cycle that alter two categories of slow variables – soil resources and the disturbance regime. As climate warms, increased evapotranspiration, combined with modest increase in precipitation, has lowered regional water tables, causing soil drying (Hinzman et al. 2005), reductions in tree growth (Barber et al. 2000), increases in severity and extent of wildland fire (Kasischke and Turetsky 2006), and bark beetle outbreaks, in part because warming reduced the length of the beetle's life cycle from two years to one, causing a threshold shift in the balance between the tree and the insect (Berg et al. 2006). Warming and disturbance foster other disturbances. Insect outbreaks increase the probability of fire and salvage logging. Permafrost thaw occurs more rapidly after fire because loss by combustion of the insulative organic mat makes permafrost temperature more responsive to warming air temperature. In lowlands, permafrost thaw creates ponds and wetlands, and in uplands it amplifies soil drying through improved vertical draining. The large predicted increases in permafrost thaw (Hinzman et al. 2005) would profoundly alter the hydrologic controls over ecosystem processes and challenge ecological resilience.

Climate warming affects social slow variables through both direct environmental impacts and changes in ecosystem services. In Interior Alaska, buildings and oil pipelines are generally built with a sufficient safety margin that permafrost thaw has had modest impacts on infrastructure, whereas in Siberia, where safety margins are smaller, permafrost thaw has contributed to catastrophic failure of roads and pipelines, causing oil spills and erosion that have substantially impacted the ecosystem services on which local reindeer herders and fishers depend (Forbes et al. 2004). This illustrates the importance of regional variation in exogenous social controls and institutional responses when assessing societal impacts of climate warming. Climate warming directly reduces access and use of lands surrounding villages in Interior Alaska by reducing summer river levels and slowing the rate at which river ice freezes to a thickness that supports winter travel by snow machine. Thin ice reduces the safety of over-ice travel. Warming also reduces access because the more extensive fires destroy trapping cabins and topple trees, making overland travel more hazardous and difficult (Huntington et al. 2006). Cues that were traditionally used to predict weather and assess the safety of over-ice travel are now less predictive, eroding cultural ties to the land (Berkes 2002).

The impacts of climate warming on Alaska depend on a hierarchy of interactions among processes occurring at different scales (Peterson 2000, Adger et al. 2005). Warming is largely the product of global-scale processes, including anthropogenic emissions of greenhouse gases, but is amplified at high latitudes as reflective sea ice, glaciers, and snow cover are replaced by heat-absorbing water, land, and forests (McGuire et al. 2006). The impacts of warming on fire regime depend on legacies of human activities, such as the active burning of forests by early 20th-century gold miners, which increased the proportion of less flammable early successional deciduous forests, in contrast to current fire suppression, which increases the continuity of late-successional flammable fuels (DeWilde and Chapin 2006). In summary, understanding the warming effects on a societally important property like fire risk depends on processes occurring at many temporal and spatial scales.

Identifying Policy Strategies

The previous section shows that climate warming has had pervasive effects on social-ecological processes in Interior Alaska. No cohesive policy response, however, has yet developed. Recent advances in the emerging science of sustainability (NRC 1999, Gunderson and Holling 2002, Clark and Dickson 2003, MEA 2005) now provide a suite of at least four policy strategies that could be integrated to address the consequences of large directional changes: (1) reduced vulnerability, (2) enhanced adaptive capacity, (3) increased resilience, and (4) enhanced transformability. Each of these approaches emphasizes a different set of processes by which sustainability is fostered (Table 1, Fig. 2). Vulnerability addresses the nature of stresses that cause change, the sensitivity of the system to these changes, and the adaptive capacity to adjust to change. Adaptive capacity addresses the capacity of actors or groups of actors to adjust so as to minimize the negative impacts of changes. Resilience incorporates adaptive capacity, but also entails additional system-level attributes of social-ecological systems that enhance flexibility to adjust to change. Transformability addresses active steps that might be taken to change the system to a different, potentially more desirable state. Although anthropologists, ecologists, and geographers developed these approaches somewhat independently (Janssen et al. 2006), they are becoming increasingly integrated (Berkes et al. 2003, Turner et al. 2003, Young et al. 2006). This integration of ideas provides policy makers and managers with an increasingly sophisticated and flexible tool kit to address the challenges of sustainability in a directionally changing world.

Reduce vulnerability

Vulnerability is the degree to which a system is likely to experience harm

Table 1. Principal sustainability approaches and mechanisms (Levin 1999, Folke et al. 2003, Turner et al. 2003, Chapin et al. 2006b, Walker et al. 2006).

- Vulnerability
  - Reduce exposure to hazards or stresses
  - Reduce sensitivity to stresses
    - Sustain natural capital
    - Maintain components of well-being
    - Pay particular attention to vulnerability of the disadvantaged
  - Enhance adaptive capacity and resilience (see below)
- Adaptive capacity
  - Foster biological, economic, and cultural diversity
  - Foster social learning
  - Experiment and innovate to test understanding
  - Select, communicate, and implement appropriate solutions.
- Resilience
  - Enhance adaptive capacity (see above)
  - Sustain legacies that provide seeds for recovery
  - Foster resilience learning
  - Foster a balance between stabilizing feedbacks and disturbance
  - Adapt governance to changing conditions
- Transformability
  - Enhance diversity and adaptation
  - Enhance capacity to learn from crisis

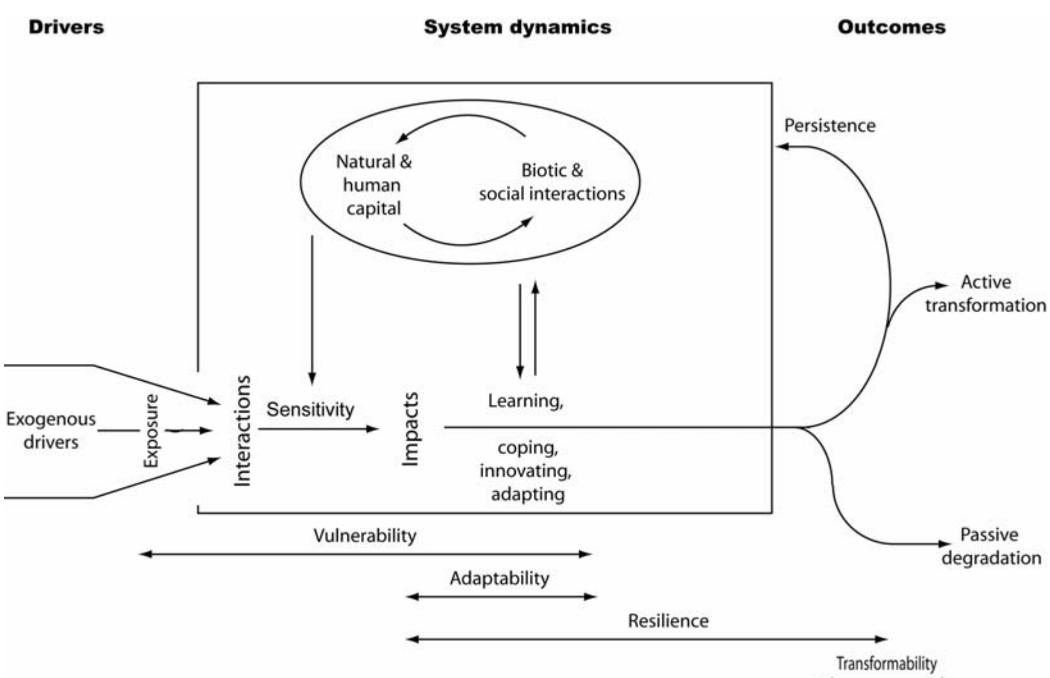

Figure 2. Conceptual framework linking human adaptability, vulnerability, resilience and transformability. Modified from Chapin et al. (2006b).

due to exposure to a specified hazard or stress (Turner et al. 2003, Adger 2006). Vulnerability theory is rooted in socioeconomic studies of impacts of events (e.g., floods or wars) or stresses (e.g., chronic food shortage) on social systems but has been broadened to address responses of entire social-ecological systems. Vulnerability theory deliberately addresses human values such as equity and is oriented toward providing practical outcomes. Vulnerability to a particular stress can be reduced by: (1) reducing exposure to the stress (mitigation); (2) reducing sensitivity of the system to stress by sustaining natural capital and the components of well-being, particularly for the disadvantaged; and/or (3) increasing adaptive capacity and resilience (see below) to cope with stress (Table 1) (Turner et al. 2003). The incorporation of adaptive capacity and resilience as integral components of the vulnerability framework (Turner et al. 2003, Ford and Smit 2004) illustrates the integration of different approaches to sustainability science.

Exposure to a stress can be reduced by minimizing its intensity, frequency, duration, or extent. Prevention of pollution or banning of toxic pesticides, for example, reduces the vulnerability of people who would otherwise be exposed to these hazards. Mitigation (reduced exposure) is challenging, however, when the stress is the cumulative effect of processes occurring at scales that are larger than the system being managed. Reducing the anthropogenic contribution to climate warming is the key to mitigating climate-change-related vulnerability in Interior Alaska. This is challenging because anthropogenic forcing of climate change is primarily the result of greenhouse-gas emissions at lower latitudes, where human demographic and technological change and political power are concentrated. Because the anthropogenic source of change is dispersed globally, it cannot be reversed by actions taken solely at high latitudes, where climate change and its ecological and societal impacts are most pronounced (McCarthy et al. 2005). If vulnerability to climate change is to be reduced, strong actions must be initiated promptly, given the long time-lag between changes in carbon emissions and reductions in atmospheric concentrations (Schimel 1995). The most logical approaches to mitigating climate change are to strengthen international institutions such as treaties (e.g., Kyoto Protocol) and market mechanisms (e.g., carbon credits) that address causes and consequences at the same scale and to foster cross-scale linkages among institutions, for example between locally based arctic indigenous groups and the Arctic Council, as described earlier. The United States accounts for 25% of anthropogenic CO_2 emissions (and arctic nations as a group account for 40% of these emissions), so increased responsiveness of arctic nations to arctic warming could substantially reduce climate forcing from emissions of greenhouse gases.

Sensitivity to a stress can be reduced in at least three ways: (1) sustaining the slow ecological variables that determine natural capital; (2) maintaining key components of well-being; and (3) paying particular attention to the needs of the disadvantaged segments of society, who are generally most vulnerable. The poor or disadvantaged, for example, are particularly vulnerable to food shortages or economic downturns, and people living in floodplains or the wildland-urban interface are particularly vulnerable to flooding or wildfire, respectively. An understanding of the causes of differential vulnerability can lead to strategies for targeted interventions to reduce overall vulnerability of the social-ecological system.

Making the system less sensitive to stressors can also reduce vulnerability (Turner et al. 2003). Actions can be taken to reduce the sensitivity of specific processes to climate warming—for example, the use of passive heat pumps to protect pipeline integrity from permafrost warming or mechanical fuel reduction programs to reduce wildland-fire risk to communities. Some ecological responses to warming reduce system sensitivity to warming (e.g., the increased proportion of less flammable early successional forests as climate-driven fires become more extensive). Other climate warming effects augment sensitivity to warming – for example, the increased likelihood of winter travel fatalities as river and lake ice becomes thinner and fails to support snow machines. In general, the options to reduce vulnerability to climate warming in Interior Alaska by reducing climate sensitivity appear relatively limited, except through human adaptation, for example by relocating villages threatened by coastal erosion.

Enhance adaptive capacity

Adaptive capacity is the capacity of actors, both individuals and groups, to respond to, create, and shape variability and change in the state of the system (Folke et al. 2003, Walker et al. 2004, Adger et al. 2005). Although the actors in social-ecological systems include all organisms, I focus almost entirely on people in addressing the role of adaptive capacity in social-ecological change, because human actors base their actions not only on their past experience but also on their capacity to *plan for the future* (reflexive action). This contrasts with evolution, which shapes the properties of organisms based entirely on their genetic responses to *past* events. Evolution has no forward-looking component. Adaptive capacity depends on: (1) biological, economic, and cultural diversity that provides the building blocks for adjusting to change; (2) the capacity of individuals and groups to learn how their system works and how and why it is changing; (3) experimentation and innovation to test that understanding; and (4) capacity to govern effectively by selecting, communicating and implementing appropriate solutions (Table 1).

Many types of learning could enhance adaptive capacity in Interior Alaska. For example, enhanced educational and training opportunities, especially for disadvantaged segments of society, increases social capital and therefore society's capacity to adapt (Turner et al. 2003). Alaska's relatively well-developed cyberinfrastructure for distance delivery and history of knowledge sharing between western scientists and traditional knowledge holders provide opportunities for different stakeholder groups to learn, in culturally appropriate ways, how climate warming will likely affect them. At a more technical level, the integration of science and technology with local understanding could provide novel solutions (e.g., heat pumps that prevent permafrost thaw or introduction of community gardens to regions that were previously too cold for gardening), often involving substitutions among financial, natural, physical, and human capital through time (Clark and Dickson 2003, Arrow et al. 2004). Development of plausible scenarios of future trajectories of entire suites of ecosystem services and environmental impacts is feasible and could interconnect some of the stove-piped institutions to allow more informed and comprehensive planning. Active experimentation in management and governance (i.e., adaptive management and adaptive governance, respectively) provide opportunities for social learning to foster adjustments to change (Walters 1986, Dietz et al. 2003, Carpenter and Folke 2006), for example managing a gradually evolving arctic fishery that will likely develop as the Arctic Ocean becomes increasingly ice-free and fish-rich (Chapin et al. 2006a). Active participation and interaction of multiple stakeholder groups is critical to effective learning, coping, innovating, and adapting and must be nested across organizational scales through development of flexible systems of adaptive governance (Dietz et al. 2003, Folke et al. 2005). Adaptation will be most successful if it is compatible with and supported by changes occurring at other scales (Adger et al. 2005, Berkes et al. 2005). Changes in management of commercial and subsistence salmon fisheries in Alaska, for example, are most likely to be successful if planned with the expectation that farmed salmon produced in other countries will continue to provide a cheap alternative to Alaskan salmon (NRC 2004).

Enhance Resilience

Resilience is the capacity of a social-ecological system to absorb a spectrum of shocks or perturbations to sustain its fundamental function, structure, identity, and feedbacks through either recovery or reorganization in a new context (Holling 1973, Gunderson and Holling 2002, Walker et al. 2004, Folke 2006). The unique contribution of resilience theory is the identification of system properties that foster regeneration and reorganization after perturbations (Holling 1973). Resilience depends on: (1) adaptive capacity (see above); (2) biophysical and social legacies that contribute to diversity and provide proven pathways for rebuilding; (3) the capacity of people to plan for the long term within the context of uncertainty and change; (4) a balance between stabilizing feedbacks that buffer the system against stresses and disturbance and innovation that creates opportunities for change; and (5) the capacity to adjust governance structures to meet changing needs (Holling and Gunderson 2002, Folke et al. 2003, Walker et al. 2006) (Table 1).

Subsistence hunting and fishing are major components of the economy and diet of rural Alaskan communities (Magdanz et al. 2002). Subsistence depends on harvest of fish and game that are public goods rather than owned by private individuals or government. Extensive inter-comparisons of systems that manage these common-pool resources suggest that a well-developed system of institutional negative feedbacks increases the likelihood of sustaining these resources (Dietz et al. 2003, Ostrom 2005). These institutional analyses suggest that stabilizing feedbacks in Alaska could be strengthened through greater involvement of local users in the management, monitoring, and enforcement of subsistence-resource use. Game management to meet alternative social goals (e.g., equal access by local subsistence users and non-local sport hunters) requires a different set of socially imposed negative feedbacks to prevent over-harvest.

Institutions that foster biological, cultural, institutional, and economic diversity increase the likelihood that important functional components of the current social-ecological system will persist (Elmqvist et al. 2003). Although Interior Alaska has a low species diversity, which is typical of high latitudes, it has a high landscape diversity maintained by wildfire (Chapin and Danell 2001). By retaining wildfire as an important landscape process, Alaska has the opportunity to retain this source of landscape diversity in ways that are no longer feasible in more urbanized regions. In contrast to its ecology, Alaska's economy has low diversity and is dominated by extraction of one non-renewable resource (oil). Diversification of the economy could enhance Alaska's resilience to economic surprises such as pipeline corrosion that shuts down oilfields (Chapin et al. 2006a).

Enhance Transformability

Transformability is the capacity to create a fundamentally new system with different characteristics (Walker et al. 2004). There will always be a creative tension between resilience (fixing the current system) and transformability (seeking a new, more desirable state) because actors in the system will likely differ in their opinions about when to fix things and when to cut losses and move to a new alternative structure (Walker et al. 2004). In addition, the dividing line between resilience of a given system and transformation to a new state is often fuzzy. Even though total collapse seldom occurs (Turner and McCandless 2004, Diamond 2005), active transformations of important components of a system are frequent (e.g., from an extractive to a tourist-based economy). In general, diversity and adaptive capacity, which are key components of resilience, also enhance transformability because they provide the seeds for a new beginning and the adaptive capacity to take advantage of these seeds. Transformations (including socially beneficial transitions) are often triggered by crisis, so the capacity to recognize opportunities associated with crisis contributes to transformability (Gunderson and Holling 2002, Berkes et al. 2003). For example, the global increase in oil prices threatens the viability of many rural communities in Interior Alaska, which depend on diesel fuel for power and heat. This increases the economic feasibility of switching to biomass fuels, which could simultaneously provide wage income within the community and reduce warming-induced wildfire risk to communities (Fresco 2006).

Conclusions

Despite the substantial challenge of sustaining the beneficial attributes of complex social-ecological systems in the face of multiple large-scale directional changes, the dynamics of these systems suggest at least four general policy strategies that could meet this challenge. The greatest opportunities appear to include: (a) reducing vulnerability by reducing the anthropogenic contribution to climate warming (through reduced emissions of greenhouse gases) or reducing the sensitivity of vulnerable populations; (b) fostering human adaptive capacity through enhanced diversity and through learning and innovation within the context of changes occurring at other scales; (c) enhancing resilience by strengthening negative feedbacks that enhance the capacity to deal with change and surprise; and (d) facilitating transformation under circumstances where components of the current system are no longer desirable. Implementation of these strategies in a concurrent and complementary fashion could be most effective. Although strong directional changes in climate generate challenges and opportunities that are specific to Alaska, the general policy strategies described here should be broadly applicable.

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