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REVIEW ARTICLE

Toward understanding the human dimensions of the rapidly changing arctic system: insights and approaches from five HARC projects

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Abstract Human dimensions research focuses on the interrelationships between humans and the environment. To date, human dimensions research in arctic regions has concentrated primarily on local events and contexts. As such, it complements analysis elsewhere of adaptation and sustainable development within broad institutional, social, and environmental contexts. This paper reviews five projects from the Human Dimensions of the Arctic System (HARC) initiative, established by the US National Science Foundation in 1997. Common themes and findings are highlighted: climatic variations or change affect societies through interactions with human activities; population dynamics provide key quantitative indicators of social impacts and well being; and specific impacts and responses are the result of complex, context-sensitive interactions. Congruent approaches to the challenges of interdisciplinary research are also identified: multivariate time plots aid the integration of data, retrospective and prospective studies are part of a continuum and reinforce one another, comparative studies are essential for understanding general principles of human dimensions, and arctic residents can play a vital role in research and action.

Keywords Arctic · Environmental change · Human dimensions · Social change

Introduction

Large-scale environmental changes have been underway for several decades in the Arctic, and could well accelerate in the future, with potentially major impacts to humans in and beyond the Arctic. Climatic variations on seasonal, annual, decadal and longer time scales tend to be greater here than elsewhere (IPCC 2001a). Modeling studies suggest that climatic change will be amplified and expressed most dra-

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matically in the Arctic (Manabe and Stouffer 1994; Holland 2003; Serreze and Francis 2006). Observational research has identified many changes that are in progress already (Morison et al. 2000; Serreze et al. 2000; Hinzman et al. 2005; Stroeve et al. 2007). Because human societies in the Arctic tend to have daily, intimate relationships with their environments, changes are felt strongly and immediately (e.g., Krupnik and Jolly 2002; Vörösmarty et al. 2001). Basic environmental conditions such as permafrost, snow cover, sea ice, river runoff or wave erosion affect nearly all aspects of life from housing and infrastructure to subsistence hunting and fishing. Climatic and other large-scale changes are thus crucial for Arctic communities, where relatively simple economies (depending heavily on resource extraction and subsidies) leave a narrower range of adaptive choices (e.g., Berkes et al. 2003). Indigenous cultures might also have different priorities than immigrants or outside researchers. The Arctic thus presents a critical region for examining the human dimensions of environmental change.

Human dimensions (HD) research in the Arctic, as elsewhere, examines the interrelationships between humans and their environment, particularly with respect to changes in the environment (e.g., Raynor and Malone 1998; Liverman et al. 1999; Huntington et al. 2003; Turner et al. 2003). In contrast to broad studies of governmental policies (e.g., Parry et al. 1998; Pielke 1998; IPCC 2001a) or institutional responses (e.g., Dietz et al. 2003; IPCC 2001a), arctic HD research has generally been regional or local in scope, focusing on specific contexts and conditions. In this respect, arctic HD research provides a useful complement to more aggregated or generalized HD research. The primary aim of this paper, therefore, is to provide, for the broader regional environmental change community, a review of five recently completed arctic HD research projects, examining in particular common threads in results and approaches.

In 1997, the US National Science Foundation issued a call for proposals specifically to address human dimensions of the arctic system (HARC; see ARCUS 1997; Huntington et al. 2003). To date, over a dozen studies have been carried out or begun under this program, on a variety of topics. The five studies (see Fig. 1) reviewed in this paper are as follows:

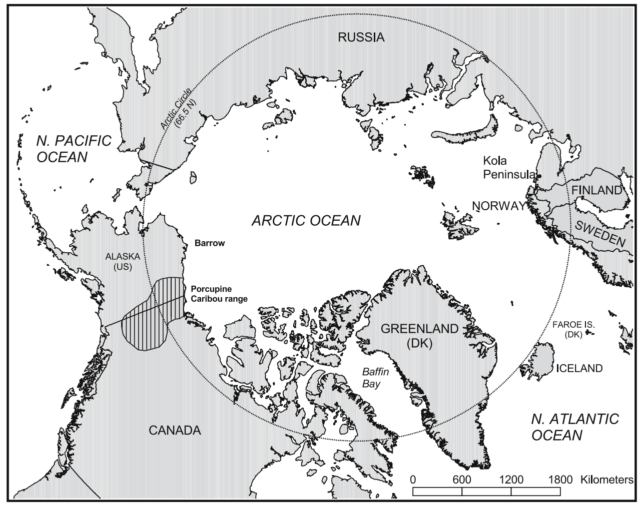


Fig. 1 The north circumpolar region, showing locations of HARC research described. (Map by Cliff Brown)

- *Landscapes and seascapes of Iceland ("the Iceland study")*. The primary goal of this project was to elucidate and understand the dynamics of linkages between human populations and marine and terrestrial environments. There were three main research foci: (1) climatological and environmental questions related to the documentation of twentieth-century changes and the assessment of potential future changes relative to the recent past; (2) analyses of the impacts of these environmental factors on the society of Iceland in the context of other socio-economic pressures; and (3) actual and potential human adaptations to these impacts. Results included: a compilation of local knowledge integrated with current fisheries practice in the community of Heimaey off the south coast of Iceland (Allansson 2004; Ogilvie 2002a, b); insights into local knowledge of farming practices in the inland community of the Mývatn region in the north of Iceland (Ogilvie and McGovern 2004; Ogilvie et al. 2005); and also climatological analyses (Björnsson and Jónsson 2003; Ogilvie 2005).
- *Fisheries dependent societies of the North Atlantic Arc ("the North Atlantic study")*. This project examined the influence of environmental changes on modern fisheries-dependent societies across the northern rim of the Atlantic, from Newfoundland to Norway. These places share a common history of development around a few major fisheries, primarily cod or herring. After building up to unprecedented peak catches in the mid-twentieth century, their staple fisheries suffered declines, and in several cases collapse, brought on by overfishing, environmental changes, or both. Shifts in marine ecosystems thus could be driven by human activities, but then in turn forced changes among the human societies on land. Basic social indicators, including population and migration changes, reflect these fisheries effects. The North Atlantic project's findings have been described in several broad comparative papers (Hamilton and Otterstad 1998a; Hamilton and Haedrich 1999; Hamilton and Duncan 2000; Hamilton, in review). Other reports focus on case studies in Newfoundland (Haedrich and Hamilton 2000; Hamilton and Butler 2001; Hamilton et al. 2004a), Greenland

(Hamilton et al. 2000, 2003; Rasmussen and Hamilton 2001), the Faroe Islands (Hamilton et al. 2004b), Iceland (Hamilton et al. 2004c, 2006), and Norway (Hamilton and Otterstad 1998b; Hamilton et al. 2006).

- *Human and ecosystem dynamics of the Imandra Watershed, Kola Peninsula, Russia ("the Imandra study").* This project employed a participatory approach that incorporates input from local stakeholders in order to develop multi-scale qualitative and quantitative models and simulations. These are used to enhance understanding of pollutant behavior and the relationship between local humans and the environment. See Voinov et al. (2004) and Moiseenko et al. (2006) for further details.
- *Context and climate change in Barrow, Alaska ("the Barrow study").* This project sought to provide scientific analysis and insight to support the efforts of the community of Barrow, Alaska, to reduce its vulnerability in the face of the effects of climate change. The community placed particular emphasis on the impacts of storms, flooding and erosion, as well as ice retreat and permafrost thaw, since substantial problems were already evident. An overview of the project is provided in Lynch and Brunner (2007). Details on specific project results include climatological analysis of extreme wind and storm events (Lynch et al. 2003, 2004, 2007; Cassano et al. 2006; Drobot and Maslanik 2003); and the policy/societal implications these events and coastal erosion for Barrow (Brunner et al. 2004; Lestak et al. 2004).
- *The sustainability of arctic communities ("the Sustainability study").* The main objective of this study was to understand how four major driving forces (climate, government spending, oil development, and other economic growth) would affect community and regional sustainability during the next 3–4 decades. An overview of the project is given by Kruse et al. (2004), and findings from specific disciplines have been reported in White et al. (1999), Epstein et al. (2000), George et al. (2003), Johnstone et al. (2002), Kofinas et al. (2002), Berman et al. (2004), Russell et al. (2002), and Nicolson et al. (2002).

The purpose of this review is to describe a set of convergent ideas from these five studies as a first step towards a broader understanding of the nature of arctic human dimensions. As such, the paper is intended to stimulate further consideration of arctic HD work by the wider HD research community. Our intention through this paper is also to help the community of arctic HD researchers to consider the larger themes and principles that emerge from their work in addition to the specific results of their particular studies. In addition to addressing HD researchers, the paper may appeal to practitioners of other disciplines, particularly those in the natural sciences whose work has implications for human–environment interactions. Climatologists, oceanographers, and biologists, for example, may find ideas and/or approaches that resonate with their research and that encourage them to explore more rigorously the connections between the physical and ecological environment and society. We realize that one brief paper cannot address all topics of interest for a single audience, much less multiple audiences, but it may be able to stimulate further thought and collaboration among all those whose research involves some aspect of human dimensions.

Common findings and themes across the HARC studies

Human activities can greatly amplify the effects of climatic variability and change on arctic societies

The HARC studies discussed here found numerous examples of such interactions. The Iceland study, for example, found an intricate and complex relationship between changes in climate and varying fish stocks. Evidence for human impacts on North Atlantic fisheries date back to Viking times. Although pre-twentieth century catches were small compared to those of the present and recent past (Ogilvie 1997; Ogilvie and Jónsdóttir 2000), it has been argued that this long-term influence on the cod stocks exacerbated the overfishing impacts which became observable in the mid-twentieth century (Amorosi et al. 1996). During the early-twentieth century warming around Iceland, many changes in fish distribution were observed, and by the late 1920s, cod were becoming far more abundant than before (Vilhjálmsson 1997). During the period 1926 to 1956 when conditions were generally warm, the spawning and consequently, the fishable stock, was very large, with the spawning stock fluctuating between about 1.0 and 1.7 million tonnes (Vilhjálmsson 1997).

Beginning in the late 1950s, however, there followed a rapid decline of recruitment and stock abundance. The mortality of the cod stock around this time could be attributed mainly to fisheries exploitation as deterioration in the climate did not occur until the period 1965 to 1971. Since then, in spite of greatly improved climatic conditions in recent years, there has been no corresponding increase in stocks as earlier. However, there is no doubt that the favorable impact of the climate on the fish fauna in the earlier part of the twentieth century did have a very strong socio-economic impact in Iceland and the revenue engendered greatly increased prosperity.

The North Atlantic study noted several similar cases in which climatic variations and fishery activities interacted to cause fisheries collapses off Newfoundland, Greenland, Iceland, the Faroe Islands, and Norway (references noted above). In several cases, fish populations experienced environmental (climate-related) stress while also under heavy fishing pressure, leading to decline or collapse more severe than environment or fishing might have caused alone. Although variability is to be expected in natural systems, the impacts of such variability can be magnified through interactions with human activities that also stress resources (see Huntington et al. (2007) for further discussion in an arctic context, or Leichenko and O'Brien (2002) in an African context). Similarly, the implications of environmental changes for human societies vary with the degree and nature of their dependence on their local environment (see below).

The Barrow study, focusing on coastal erosion and flooding rather than fisheries, reveals other kinds of interactions between environmental variation and human decisions. Flooding at Barrow is caused by a combination of storm surge and waves, which depend on a number of factors. Because central pressures in arctic storms are generally not very low, the effects of atmospheric pressure are usually small. At Barrow, the primary cause of storm surge is winds from the west or southwest, which push water onshore. A common feature of the most damaging storms is the presence of open water, which limits the possible damping of both waves and wind-driven storm surge by sea ice. Annual ice concentrations decreased by 3 to 9% in the Beaufort and Chukchi seas between 1978 and 1996 (Drobot and Maslanik 2003). These reductions have been associated with the persistence of open water offshore longer into the autumn season than was characteristic of the earlier record. Hence, the available open water to contribute to wave development has been greater in recent years, particularly during autumn. Barrow residents historically have feared autumn storms the most and have prepared for them in recent decades.

Concurrently with changes in the climate system, over a four-decade period the population of Barrow tripled from about 1,350 in the early 1960s to nearly 4,650 in 1998 (NSB 1999) and with it, new infrastructure became necessary to support the community. The centerpiece of infrastructure improvements in Barrow is the buried utility corridor, or utilidor, which began to provide potable water, sewage, and other services at an initial cost of $270 million in 1984. Since then a newer direct-bury technology has been used to extend the utilidor in Barrow, and to provide equivalent services for smaller North Slope communities. While the utilidor is a major improvement in public health and convenience, it leaves Barrow more vulnerable to coastal erosion and flooding. The system uses gravity to collect sewage at holding tanks at seven stations, which pump the sewage to a lagoon for disposal. But two of the pump stations are close enough to the shore to be exposed to major storms, risking flooding of the entire system (Lynch and Brunner 2007). With more people and more infrastructure, Barrow now is more vulnerable than it has been, even if the sea ice had not been decreasing. It has been a recurrent theme in the arctic that development has costs as well as benefits, although the costs are not always obvious when development is first proposed.

In all three cases, either environmental or human factors alone would have caused impacts on human societies, but their actual consequences have been made worse by the way that environmental and human factors interacted or combined. Such interactions are illustrated schematically in Fig. 2 as the double-tailed arrow connecting the physical and human components of the overall system to the biological component (or, in the Barrow case, to vulnerability to storms). While this type of interactive effect can happen in other directions, too, the significance of human amplification of effects has typically been underestimated, at least for the Arctic (Huntington et al. 2007).

An obvious corollary to this observation is that human decisions also can facilitate adaptation, for example through planning fisheries management or infrastructure in light of possible climate change. Of course, adaptation is not the same as preventing the change, but the capability of humans to positively affect the impacts of environmental change, or to compensate for these changes (at least, on the scales recently observed) should not be underestimated—especially bearing in mind the likelihood of irreversible climatic changes in the future (IPCC 2001b; ACIA 2005).

Population dynamics provide key quantitative indicators of social impacts and well-being

In the arctic, as elsewhere, HD research has a rich history of employing both qualitative and quantitative methods.

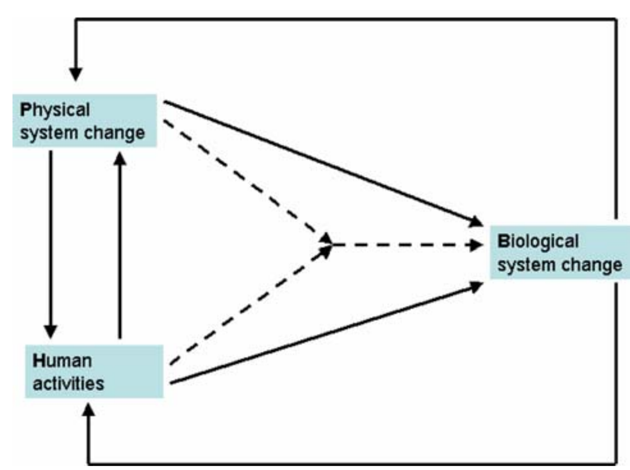


Fig. 2 Effects and feedbacks among physical, biological and human systems. (A variation of this diagram is presented in Huntington et al. (2007))

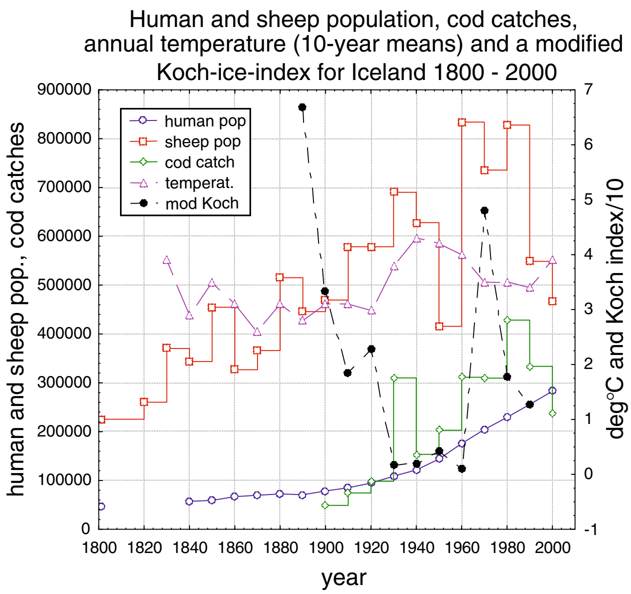


Fig. 3 Human and sheep populations, cod catches, annual temperatures (10-year means), and Koch ice index for Iceland 1800–2000

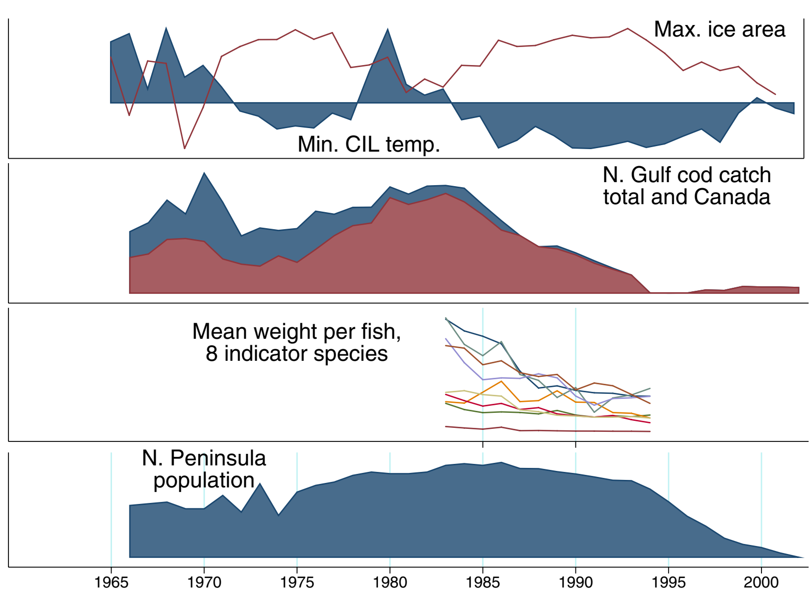
Because the HARC research agenda has self-consciously worked to integrate the natural and social sciences, we have repeatedly found the value of using long-term population indicators, For example, over the twentieth century, the Icelandic population rose sharply, driven by more favorable economic conditions than in the past—in particular, the rise of commercial cod and herring fisheries—even as some environmental conditions such as erosion due to sheep grazing and other factors worsened (Fig. 3). In West Greenland, the collapse of the cod fishery led to outmigration and population decline in one town (Paamiut), while another town (Sisimiut) grew as it made a successful transition from cod fishing to shrimp fishing (Rasmussen and Hamilton 2001; Hamilton et al. 2003). In the Faroe Islands, net migration was closely coupled with cod catches from the 1970s through the mid-1990s. Outmigration by young adults both reduced and rapidly "aged" the remaining Faroes population, until restructuring and economic recovery in the late 1990s reversed this demographic tide (Hamilton et al. 2004b).

Net migration from the most fisheries-dependent regions of Newfoundland turned sharply negative following the 1992 cod collapse. Other social indicators including age structure, sex ratios, fertility, education, income and crime rates showed effects of these population changes as well (Hamilton and Butler 2001). Figure 4 graphs population on Newfoundland's Northern Peninsula together with changes in Northern Gulf of St Lawrence environment (winter ice extent and cold intermediate layer temperature), cod catches and mean weights of eight indicator species of fish—visualizing the connection between ecosystem and social change (Hamilton et al. 2004a).

In the Kola study, changes in outmigration and fertility actually preceded economic and ecological changes. While at first glance one would assume that population changes were driven by economic collapse in this region, in reality a more distant impact of changes in the larger national system is seen. In this case, the outmigration and birth rates were most likely to have been affected by a substantial drop in subsidized northern salary rates that took place during *perestroika* (Fig. 5). This also illustrates the importance of scale in defining appropriate causes and effects.

In the Barrow study, the population growth and accelerated development described in the previous section are linked to the 1971 Alaska Native Claims Settlement Act, and the formation of the Arctic Slope Regional Corporation

Fig. 4 Environment, cod catch, and mean weight of eight indicator species in the Northern Gulf of St Lawrence (*top three graphs*); population of Newfoundland's Northern Peninsula (*bottom*). See Hamilton et al. (2004a)



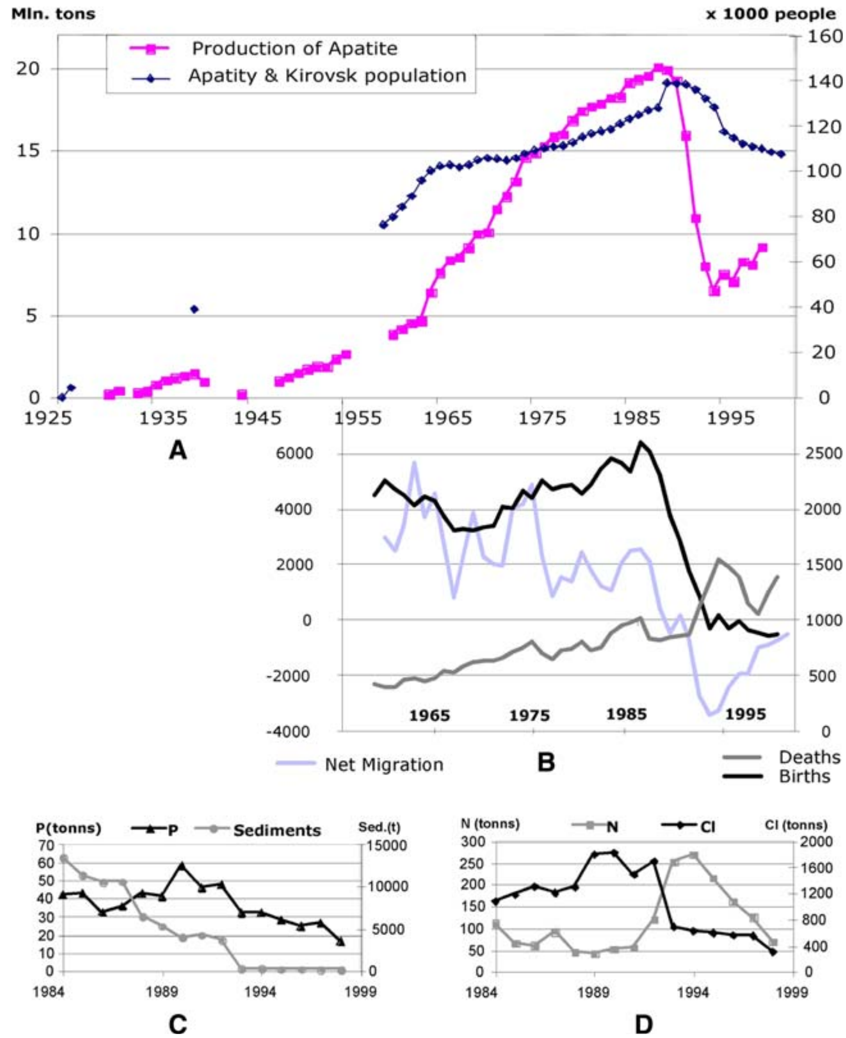


Fig. 5 Trends in Imandra watershed mining and population (**a**); births, deaths and migration (**b**); and Imandra Lake phosphorus and total sediments (**c**) and nitrogen and chlorine (**d**); see Voinov et al. (2004)

and the Ukpeagvik Iñupiat Corporation (Lynch and Brunner 2007). With the 1972 founding of the North Slope Borough came the ability to issue bonds for capital projects. People migrated to Barrow to work for local government and native corporations. Well-paid jobs were available, enabling many residents to afford purchases previously out of reach, including trucks, snowmobiles, motor boats and ATVs. The even more rapid development that commenced in the early 1980s coincided with the end of a decade and a half with relatively few severe storms in Barrow. Only the elders remembered the big storms of the 1950s and early 1960s. Many younger residents considered the 1970s and early 1980s normal from a weather and climate standpoint. This complacency ended with major storms on 12 and 20 September 1986, but already a pattern had been set for the building and rebuilding of potentially vulnerable infrastructure.

In each case, population response serves as a key social indicator. Because population data are routinely collected in censuses or national registers, such data are widely available. Interpreting population changes may not always be straightforward, but such data nevertheless provide strong evidence that society is responding to a stimulus of some sort. Detailed demographic analyses help to discern causal factors, such as whether they might be due to shifts in births, deaths, or in or out-migration among particular population sectors. These elements in turn affect other indicators. Thus, for example, outmigration by young adults and families raises the median age of the population left behind, with secondary implications for social indicators such as crime rates (decline), median education (decline), and mortality rates (increase) (Hamilton and Butler 2001). However, the hierarchy of systems remains crucial, since in many cases the signals that are observed at one level are actually generated by processes at other levels or scales. As Feibleman posits in his theory of integrative levels: "For an organism at any given level, its mechanism lies at the level below and its purpose at the level above" (Feibleman 1954). Multilevel modeling, a statistical approach employed in several arctic research projects, provides analytical tools that should prove useful in studying such cross-scale relationships (e.g., Skrondal and Rabe-Hesketh 2004).

Environmental change in the arctic creates winners and losers, but specific impacts and responses are highly context sensitive

In the Sustainability study, the five communities were all in relatively close geographic proximity (at least in arctic terms) and shared a similar climatic regime. In spite of being near to one another and sharing a deeply held consensus on the goals of sustainability (Kofinas et al. 2002; Kruse et al. 2004), environmental changes are projected to lead to quite different consequences for the five communities. For example, caribou migration patterns depend on a set of environmental conditions such as deep or shallow snow depth in the herd's winter range, or whether the timing of spring snowmelt was early or late in the season (McNeil et al. 2005). In deep snow years, caribou are more likely to spend the winter in the southern Yukon, and not to be present near Arctic Village, Alaska. Because of the typical migration patterns, if caribou do not winter in Alaska, Arctic Village are not only unable to hunt caribou over winter, but would have no opportunity either to hunt them on their spring migration. In contrast, the community of Fort McPherson has better caribou hunting if caribou overwinter in Canada and take longer on their spring migration (early snowmelt seasons).

The way in which local context affects the impacts of change on communities was also seen in the Sustainability project through the response of several partner communities to a policy change regarding oil development in the Arctic National Wildlife Refuge (ANWR). For the community of Kaktovik, economic benefits of oil drilling include new employment opportunities and a share of oil revenues, and these benefits help offset the ecological risk of negative impacts on the caribou population (potentially leading to imposed harvest reductions). In addition, Kaktovik depends more on marine mammal harvest (particularly on bowhead whale) that on caribou, and they have access to two different caribou herds, only one of which would be affected by oil drilling in ANWR. On the other hand, the community of Old Crow depends strongly on a single caribou herd, does not have access to marine mammals, and because they would not gain economically from ANWR oil development, the change offered high levels of risk to their subsistence economy with little or no compensatory benefit.

In the Faroes, net migration and the cod catch were closely correlated for a period, but then diverged as other factors increased in significance (Hamilton et al. 2004b). In Greenland, for both ecological and social reasons, Sisimiut was able to capitalize on the change in fisheries from cod to shrimp, while Paamiut was not (Rasmussen and Hamilton 2001; Hamilton et al. 2003). These differences in time and space are not readily explicable by large-scale variables such as climate or culture. Instead, they draw attention to social, historical, and geographical factors that vary from place to place and time to time.

In the Imandra watershed, industrial activity produced substantial discharges of a wide range of pollutants, such as heavy metals (nickel, zinc, copper, chromium, chlorine, nitrogen, etc.), which contributed to a decay of ecosystem and human health (Moiseenko et al. 2006). During the *perestroika* years with the collapse of the economy, substantially less pollution was discharged into the environment. The social stress turned out to be an ecological gain. At the same time poaching has increased dramatically. As a result, in the case of the fish population it is not clear whether the overall impact is positive or negative. This is another example of a complex response of a hierarchical system, where external forcings cause internal reactions from the system that are difficult or impossible to predict.

The Iceland study demonstrated the causal sequence of favorable environmental conditions leading to increased fish populations and thus increased catches, which in turn had a very positive effect on the Icelandic economy. The prosperity engendered undoubtedly had an influence on the human population, as which may be seen from Fig. 3, has continued to rise throughout the twentieth century. Fluctuations in the sheep population may also be seen in Fig. 3. Apart from fisheries, sheep farming has been the mainstay of the Icelandic economy, both in the past and in the present. However, grazing by sheep contributes greatly to Iceland's perennial erosion problem and there is currently disagreement among farmers as to the most appropriate stocking mix and its relationship to pasture conditions. Clearly, some relationships between the data sets shown in Fig. 3 are easier to define than others. The correlation between climate and sea ice, for example, is well established. The relationship between fisheries and climate, although complex, is indisputable. The prosperity of the population, and hence its growth, is undoubtedly tied to the development of the fisheries in the twentieth century, and is hence a second-order effect of climate. Fluctuations in the sheep population are also linked to the growth of the human population, but are also a function of changing economic priorities.

When it comes to predicting the effects of environmental change on human society, the five projects illustrate a key challenge for policy makers. Accurate predictions about complex systems (i.e., those with multiple feedbacks) are not possible to make on theoretical grounds. Rough estimates can be elusive if the direction and magnitude of key changes cannot be ascertained with confidence. As noted by Nobel Laureate Philip Anderson, “life is shaped less by deterministic laws than by contingent unpredictable circumstances” (Horgan 1995). Even in the relatively predictable world of physics, “The ability to reduce everything to simple fundamental laws does not imply the ability to start from those laws and reconstruct the universe” (Anderson 1972).

The examples given above reinforce the point that the specifics of the context matter greatly in complex interactions. Recognizing the limitations of knowledge or available information can help research projects to focus on realistic targets and also help researchers working with communities and individuals better understand the local context, for example the factors that allowed one Greenlandic town to flourish while another declined. The growing complexity of systems requires a more adaptive and iterative approach, which is based on strong stakeholder participation and frequent rethinking of the course of the study. When dealing with open and evolving systems, models may be impossible to test if the data collected become outdated sooner than the models are completed and ready to use (Oreskes et al. 1994).

Common approaches taken in HARC projects

Multivariate time plots aid the integration of data

Figures 3, 4 and 5, from three different studies, illustrate the use of multivariate time plots. The North Atlantic study used time-series data on sea temperature and ice cover, fisheries catches, biological surveys, human population and other social indicators (Fig. 4). The Imandra study examined outmigration, birth and death rates, and apatite production, among other indicators (Fig. 5). The Iceland study compiled time-series data for several parameters, including human and sheep populations, sea-ice severity, temperature, and cod catches (Fig. 3). In all three cases, analytical graphics helped investigators explore the magnitude, direction, and detailed timing of changes in environmental and social domains. Integrated research in the Arctic must deal with data representing diverse analytical units, at different spatial and temporal resolutions, and originally gathered with the purposes and tools of separate disciplines. The changes we see in human and natural systems often have multiple, interacting causes which are difficult to untangle analytically. Sometimes, details about timing provide clues—which variables changed earlier, and which later? Visual inspection of time plots provides a simple but powerful tool starting point for exploring such questions.

Further steps would be to test competing hypotheses and estimate the magnitudes of different causal effects. Such tests and quantification requires more formal analytical tools. Time series methods such as autoregressive moving average models with exogenous variables (ARMAX), well developed in econometrics, provide one possible direction. These methods are data-hungry, however, requiring long time series that in many cases do not exist, and might not even be definable, for human-dimensions indicators in the North. As more years of data become available, or where finer temporal scales such as daily resolution make sense, the ARMAX approach looks quite promising (for an integrated although non-arctic example, see Hamilton et al. (2007)). Another approach is to assemble multilevel data such as short time series of social and environmental indicators across each of many different places, or individual-level information (such as surveys) nested within place-level information (such as census or environmental variables). Investigators can then apply techniques for multilevel modeling to estimate and test cross-level effects. [Multilevel data and analyses are currently in development under two NSF-sponsored arctic projects, Humans and Hydrology at High Latitudes (H3L) and the Study of Environmental Arctic Change—Human Dimensions (SEARCH—HD).]

In the arctic system, retrospective and prospective studies are part of a continuum and reinforce each other

Four of the five early HARC studies mentioned above are primarily *retrospective*, looking backwards in time. They aim to learn about causal processes and thereby shed light on the future, and they accomplish these aims by examining complex stories that unfolded in the distant or immediate past. What are the patterns of observed physical and biological changes in the study region? What are the patterns of observed societal change? In what ways are these changes connected? The North Atlantic fisheries, Iceland landscapes, Kola watershed and Barrow storm projects all take primarily retrospective approaches.

The Sustainability project, in contrast, centers around a *prospective* simulation model, offering integrated perspectives of future scenario outcomes based on a variety of ecological, economic and social indicators (Fig. 6). User interactions and stochastically-driven processes in the model provide clear elements of contingency so that the alternative “futures” are not simply mechanically-determined forecasts. Detailed statistical analysis of vegetation change, caribou energetics and migration and northern household economies informed the various component submodels, thereby linking understanding gained from retrospective studies with future projections. This systems modeling approach parallels the way that climate system modelers have combined disciplinary-derived knowledge of heat transfer physics, albedo effects, and ocean and atmospheric circulation into systems models that allow

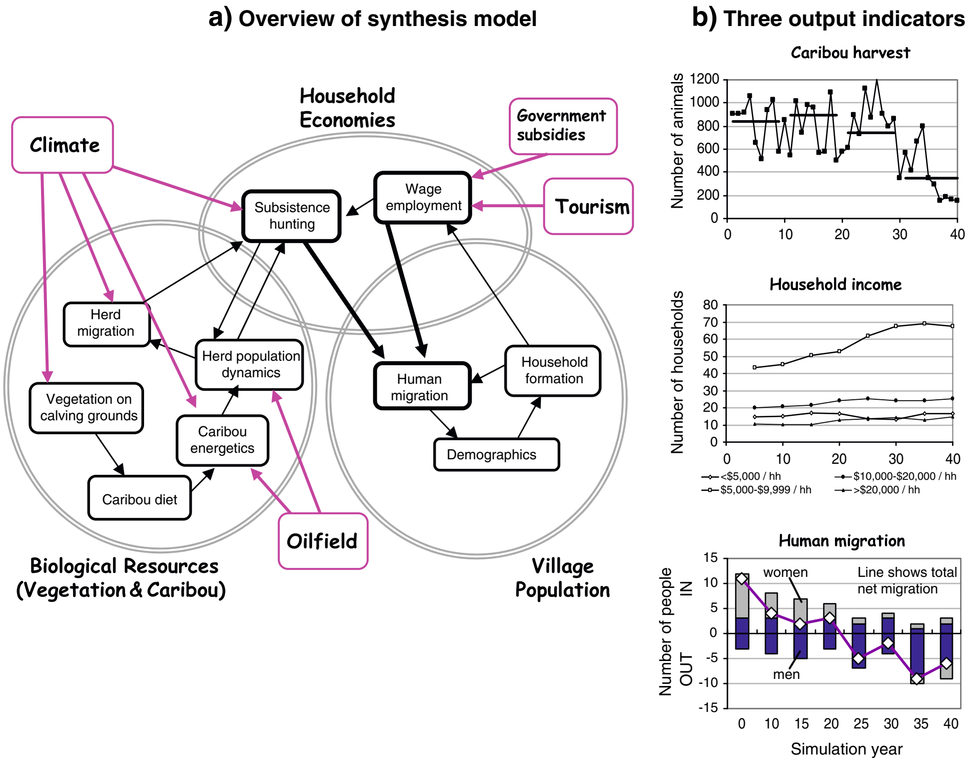


Fig. 6 **a** Diagrammatic representation of the sub-modules represented in the synthesis model for the Sustainability study (see Kruse et al. 2004); **b** selected output indicators from a scenario run of the synthesis model showing examples of ecological, economic and social indicators

scientists and policy-makers to project the outcome of different scenarios (e.g., doubled CO2 forcing, reduced levels of emissions, etc.) for future decades.

As with all studies of complex systems, research within the domain of the arctic system moves back-and-forth between field research on specific *components* of the system and *synthesis* of those components in order to understand how the arctic functions as an integrated *system*. We would argue that in this regard, human–environment interaction research is not much different to the natural sciences. Furthermore, because of way that humans are affected by and indeed drive environmental change in the arctic (Huntington et al 2007), it is important wherever possible that HD research continues to develop dynamic simulation models that can integrate our knowledge gained from retrospective studies in various disciplines and that allow both the past and the future to be modeled and explained.

Even within the relatively well-constrained arctic system, comparative studies are essential for understanding general principles of human dimensions

The North Atlantic study, in particular, took a comparative view of fisheries-dependent communities in the region. Stepping back from the community case studies led to more general ideas about relationships between fisheries dependence and the human response to ecosystem change; the role of innovation in buffering variations in specific natural resources; and the recurring theme of overexploitation both driving and compounding large-scale ecological change. This paper is itself a small step towards broader comparisons among and beyond the five studies discussed herein. Further comparative work, within and beyond the Arctic, is likely to help distinguish additional general principles of human dimensions from localized effects and responses.

General principles, however, must be distinguished from generalizations. The former are useful lessons that can help illuminate processes or interactions. The latter are statements or conclusions intended to apply to across specific situations. As noted above, the results of human–environment interactions are highly specific to context, which is one reason for the emphasis on place-based approaches (e.g., Schröter et al. 2005). Even in a single location, responses at different times may vary greatly, as in the case of the Faroese population response to fisheries catches. For the present at least, general principles are an appropriate goal of comparative research. Whether generalizations are possible is another question entirely.

Arctic residents have played a vital role in research as well as action

A major component of the Iceland project was the incorporation of local knowledge from farmers, stakeholders, and land managers in both study areas, Mývatn and Heimaey. Icelanders are unusually literate, reading more books per capita than any other nation, and include many meticulous observers of nature, both in the past and the present. In Mývatn, as elsewhere in Iceland, land use is changing rapidly. Agricultural production requires less labor than before, so more land and labor is available for alternative use such as reclamation and conservation programs. It was noted that, during the last two decades, modern Icelandic land managers have drastically reduced stocking levels for sheep and, at the same time, "freed" more land from grazing, thereby halting the centuries-old tendency towards deforestation, vegetation decline, and erosion. However, linked to the issues of conservation/preservation, farmer informants showed widespread disagreement on the means, objectives, and shape of such efforts, not least among farmers who have different stocking mix and pasture conditions.

One example is the case of the Icelandic horse, so vital in past times for travel and transport, but which no longer serves such purposes. In spite of this, the horse population is on the increase to meet demands for recreational purposes, both among the Icelandic public and the growing tourist industry. On one side, farmers argue for the need to reduce production and protect the land from erosion etc., and on the other, they hold to the view that more arable land should be used to increase fodder production or to make enclosures for grazing animals. Changes in agricultural practices may be seen in the context of a changing climate, and also in the context of the current crisis in North Atlantic fisheries and by the impact marine mammal conservationists have had on small-scale fishermen and hunters.

Unlike Mývatn, the island of Heimaey forms a community which is based almost entirely on fishing. The warm ocean currents around the islands have made the region one of the best fishing grounds off Iceland. The people of Heimaey have been great innovators in the fishing industry in Iceland, being the first to set up, for example, boat insurance and a lifeboat association (Allansson 2004). In the 1950s the traditional trade in salted fish to Spain decreased and in its place came the export of frozen fish to other European markets. With the decline in cod catches, catches of other species have supplanted them to a certain extent, only to run the risk of being overfished in turn. One informant noted, for example, his concerns regarding catches of redfish. The change from small fishing vessels to a much larger fishing fleet appears to have had, in the short term at least, a far greater impact on catches than the climate.

Informants on Heimaey were not simply fishermen, but may be said to be accomplished scholars. All had their own theories and opinions on how the fishing quotas should be determined and allocated. They were all willing to share their opinions and to show their catches to the researchers. A prime example of a meticulous observer is Óskar Sigurðsson, the lighthouse keeper. In addition to being a keen ornithologist, he makes observations far beyond the call of duty. His meteorological and other environmental measurements are sent to Reykjavík and beyond. He is carrying on a profession and tradition established by his father and grandfather, who kept careful notebooks of climatic and environmental observations. The tradition of the careful observer of the sea and the weather is not the same as it used to be, however. In the past, a good fisherman would carefully evaluate factors such as the weather, the state of the sea, and the behavior of seabirds. Now, he is more likely to consult the Internet and the weather forecast from Reykjavík.

The Imandra study found that local input is valuable, but not always easy to obtain. In a town dominated by the local nickel smelter, few people were willing to discuss the impacts of that industry on the environment and health or alternatives for future economic opportunities. In other towns, local input provided valuable insight. It was also clear that the study itself, through the questions asked during the surveys and workshops, influenced the system and affected the answers that were obtained. The interactions between researchers and human subjects flow in both directions. For example, project goals must sometimes be modified in order to reflect participant input, insights, or expectations.

In Barrow, the researchers recognized their limitations, as outsiders, in offering sound and well-grounded advice. Seeking input and regular feedback from local leaders and residents helped broaden the research perspective, adding valuable knowledge and insights from Barrow residents. It was evident early in the project that sound policies to reduce Barrow's vulnerability must go beyond science to incorporate the profound uncertainties, the multiple values of the community, and the resources available. The primary role of the researchers was to bring a broader range of alternatives to the attention of community members to expand the range of informed choice. Some alternatives previously considered became more attractive to community members as the context evolved. In particular, the experience of beach nourishment turned out to be disappointing in Barrow, and increasingly severe fiscal constraints precluded a program of comparable direct cost. Meanwhile, each additional severe storm that hits Barrow, like storms in the past, reinforces community interest in protecting itself from coastal erosion and flooding.

The Sustainability study, similarly, benefited from local input from the design stage onwards, and through into the actual co-production of knowledge. For example, community partners were responsible for the study adding ecotourism as one of key drivers of change (in addition to climate change, oil development, and government policy on northern communities). Furthermore, community members framed a set of propositions regarding caribou movement and environmental variables (Kofinas et al. 2002) and economic trade-offs involved with hunting and working. These propositions included statements such as "Those with full-time jobs have equipment that allows for fast access to hunting grounds distant from the community", or "Hunting upriver is more efficient because it allows travel upstream with an empty boat and a return home downstream fully loaded with meat" (for further propositions and a discussion on the way in which local knowledge provided a grounded empirical critique of existing economic theory, see Berman and Kofinas 2004).

Engaging local residents in research is a complex undertaking, requiring time, patience, communication, and careful planning. The results, however, more than justify the effort required. The research is typically improved by a sharper focus on relevant topics and parameters as well as more relevant data and information on which to draw (e.g., Schröter et al. 2005). Acceptance of the results is also enhanced when local residents feel that they have been part of the process and that their views have been taken into account. Although ethnographic studies have long been an important anthropological research tool, it is perhaps the development of "human dimensions" studies that has facilitated an understanding of the value of local knowledge, specifically "traditional ecological knowledge" (TEK) as a complement to "scientific" knowledge (e.g., Fox 2003; Huntington et al. 2004; Huntington 2005). Furthermore, in recent times, much valuable groundwork has been laid for the gathering of such knowledge (e.g., Berkes 1993; Wenzel 1999; Huntington et al. 2002; Krupnik and Jolly 2002; George et al. 2004; Oozeva et al. 2004).

Discussion

The five studies discussed in this paper were conceived and conducted separately. Nonetheless, they have converged on a number of common methods and themes, as described above. These results indicate emerging commonalities that have contributed to understanding of how arctic system change affects arctic society. More broadly, as regional case studies and sources for empirically grounded general principles, they contribute to our thinking about human dimensions of global environmental change, and encourage further comparative work to include local and regional case studies from elsewhere.

With regard to changes in the arctic system and their impacts, a common feature of all five case studies is that the communities in question lie on the economic and political margin. Income derives either from production of natural resources or from transfer payments such as government subsidies. They have limited ability to influence the broad governmental or international policies that affect them. If they supply global markets, they are subject to the fluctuations of those markets. For example, it is fortunate for Greenland that shrimp are popular, or the demise of the cod fishery would have left them with nothing. The communities in the Sustainability project depend in large part on government funds for infrastructure and more, but political support for those expenditures is far from guaranteed. As a metaphor, Barrow's lack of high ground is a suitable image of the lack of options available to most arctic communities.

Even if the largest drivers of environmental and economic change lie outside arctic communities, local human activity still has the potential to influence the local environment, often in synergistic ways that can lead to surprisingly large impacts (as described above and in, e.g., Huntington et al. 2007). Such impacts may be exacerbated by a desire for commercial exploitation of available resources to increase earned income and financial self-sufficiency, creating incentives for unsustainable practices that place short-term results over long-term impacts. As climate changes, the consequences of such decisions may become apparent more quickly and more severely. The human dimensions of the arctic system thus incorporate local, regional, national, and global influences in both society and environment.

In this sense, the connection between human dimensions in the Arctic and human dimensions elsewhere is readily apparent. Few groups live in self-sufficient isolation today. Instead, the majority of human affairs entail a mix of influences from the local to the global. Studies elsewhere in the world have illuminated some of the ways in which communities and societies are vulnerable or resilient in the face of environmental and other change (e.g., IPCC 2001a; Turner et al. 2003; Walker et al. 2004). The studies described here illuminate some aspects of human–environment interactions in places where such connections are especially close. The time is ripe for comparative research to explore the degree to which both sets of findings are consistent and applicable across a range of conditions and contexts, providing additional direction for case studies that can help shed further light on common features of human dimensions worldwide. As one simple example, is the synergistic combination of human and environmental change shown by the double-tailed arrow in Fig. 2 a useful concept elsewhere in the world, too, or is it for some reason particularly apt in the Arctic?

Comparisons could be extended geographically (across regions and between communities in different regions), sectorally (i.e., across industries), and temporally (archeological, historical, and contemporary). In future work, more detailed data and models are needed to analyze more formally the interactions between physical and social changes. Such models could support the evaluation of policy alternatives, and systematic exploration of other mechanisms by which human choices mitigate or adapt positively to changes. Anecdotal discussions of social "versus" environmental causation can progress to more fruitful studies that characterize specific interactions, feedbacks, and the complexity of linked systems.

Because of the nature of climatic and social changes currently occurring in the Arctic, and because of the emphasis placed on this area in research programs like HARC, the region has much to offer in terms of lessons and examples for human dimensions research. Clearly there is also much more to learn, both in studying the Arctic and in comparing arctic results with those from other parts of the world. Future arctic projects can be expected to present more detailed case-study analyses, and also to integrate more closely with physical-system models. Synthesis of research findings from the Arctic and other regions provides an open door for new insight into and understanding of the complex relationships between humans and their environment.

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