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ECOSYSTEMS

Modeling Sustainability of Arctic Communities: An Interdisciplinary Collaboration of Researchers and Local Knowledge Holders

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Abstract

How will climate change affect the sustainability of Arctic villages over the next 40 years? This question motivated a collaboration of 23 researchers and four Arctic communities (Old Crow, Yukon Territory, Canada; Aklavik, Northwest Territories, Canada; Fort McPherson, Northwest Territories, Canada; and Arctic Village, Alaska, USA) in or near the range of the Porcupine Caribou Herd. We drew on existing research and local knowledge to examine potential effects of climate change, petroleum development, tourism, and government spending cutbacks on the sustainability of four Arctic villages. We used data across eight disciplines to develop an Arctic Community Synthesis Model and a Web-based, interactive Possible Futures Model. Results suggested that climate warming will increase vegetation biomass within the herd's summer range. However, despite forage increasing, the herd was projected as likely to decline with a warming climate because of increased insect harassment in the summer and potentially greater winter snow depths. There was a strong negative correlation between hypothetical, development-induced displacement of cows and calves from utilized calving grounds and calf sur-

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vival during June. The results suggested that climate warming coupled with petroleum development would cause a decline in caribou harvest by local communities. Because the Synthesis Model inherits uncertainties associated with each component model, sensitivity analysis is required. Scientists and stakeholders agreed that (1) although simulation models are incomplete abstractions of the real world, they helped bring scientific and community knowledge together, and (2) relationships established across disciplines and between scientists and communities were a valuable outcome of the study. Additional project materials, including the Web-based Possible Futures Model, are available at http://www.taiga.net/sustain.

Key words: Alaska; Arctic tundra vegetation; Canada; caribou; climate change; indigenous communities; integrated assessment; local knowledge; petroleum development; sustainability; tourism.

Introduction

How will climate change affect the sustainability of Arctic villages over the next 40 years? This is the question that motivated a four-year collaboration of 23 researchers and four Arctic communities: Old Crow, Yukon Territory, Canada; Aklavik, Northwest Territories, Canada; Fort McPherson, Northwest Territories, Canada; and Arctic Village, Alaska, USA. We designed the study from the perspective of the field of Integrated Assessment (IA). This emerging field has not yet established an authoritative practice for conducting these assessments; however, there is a broad consensus that it is important to have a diverse portfolio of parallel efforts to advance the field (Parson 1995). Most IAs have been undertaken at a regional, national, or global scale; however, our work starts at the opposite end of the spatial scale—the local community. By working up from the community level, we have been able to focus on IA issues that are difficult to address in studies that work down from national or international scales. One such IA issue is human response to changing conditions; we focus here on the effects of changing environmental and socioeconomic conditions on the sustainability of Arctic communities over time.

Defining Sustainability

A major challenge in IA has been the formal representation of values and meaningful outputs (Risbey and others 1996). Morgan and Dowlatabadi (1996) suggest that the treatment of values in IAs should be explicit and measurable. The term ''sustainability'' is therefore particularly problematic given its ambiguity and normative qualities. To address this potential problem, we asked our four partner communities to define sustainability in terms of their own community goals—the dimensions of sustainability that communities themselves perceive to be most important for their future. The research team rejected the approach of viewing the community as an aggregation of individuals, each with a different definition of sustainability. Because the goal of the project was to help communities make informed policy choices, the team worked with the local organizations most likely to make, or attempt to influence, policy choices relevant to changes considered in this study. We therefore worked primarily with local renewable resource committees and councils. The specific organizations varied by community, and in the case of Aklavik, there were separate Inuvialuit and Gwich' in land claims groups and associated renewable resource committees for each population.

Working with community residents, research scientists in collaboration with local research associates asked partner communities in the first year of the project to define ''sustainability''. Although there were some different perspectives on specific issues of sustainability, all communities expressed five common goals: (1) use of, and respect for, the land and animals in their homelands; (2) a cash economy that is compatible with, and supports, continued local use of the land and animals; (3) local control and responsibility for what is done in village homelands and what happens to resources used by the community; (4) education of younger people in both traditional knowledge and Western science, and education of the outside world about community goals and ways of living; (5) a thriving culture that has a clear identity, is based on time on the land and native language use, and which honors and respects elders.

This contribution of local knowledge served as a key reference point in our overall analysis by establishing the conditions against which possible futures would be assessed. Guided by this definition, we constructed a set of response variables as measures of the five community goals (Table 1).

Table 1. Sustainability Goals of Arctic Communities and Associated Response Variables

Sustainability goal	Response variable
(1) Lands and Resources	Caribou hunting effort
	Caribou distribution and migration
	Caribou herd size
	Vegetation and caribou forage
	Caribou harvest shortfall
(2) Cash Economy	Number of jobs
	Cash income
	Unemployed households
(3) Local Control	Natives living in town
	Outsiders living in the community
	Visitors in town
	Social impacts
(4) Education	Time on the land across generations
	Formal education completed
(5) Thriving culture	Time on the land

Whereas many IAs focus only on climate change, we examined the effects of climate change as well as potential petroleum development, tourism, and reductions in government support to communities.

Scenarios of Change

Climate

Our focus on climate change reflects the priorities of the US Human Dimensions of Global Change (HDGC) program (Committee on the Human Dimensions of Global Change 1994) and the NSF Arctic System Science (ARCSS) Program (ARCUS 1993). In the process of understanding the feedbacks between climate and arctic ecosystems, ARCSS-funded scientists have examined the effects of varying climate conditions on tundra plant communities. Field-based studies suggest that increased temperatures increase Arctic vascular plant biomass and productivity at annual time scales, primarily through increased nutrient availability (Chapin and others 1995; Shaver and Chapin 1995). We decided that the most logical relationship between ARCSS program research and northern peoples is the effect of climate change on forage for caribou during the calving season and the subsequent effect on the availability of caribou to communities. Results from general circulation models for Alaska and the western Canadian Arctic project increases in the frequency of years with earlier green-up, higher summer temperatures, more summer precipitation, and potentially deeper winter snows (Maxwell 1992; Rowntree 1997; Serreze and others 2000). Our hypothesis was that early snowmelt and warm summers would increase calf survival during June as a result of increasing availability of high-quality forage for cows and calves.

We also considered an additional climate-related effect on caribou calf survival to one year of ape—increased frequency of high inject harassment years (more warm, wet summers). We hypothesized that the added energy requirements associated with more frequent years of high insect harassment (White and others 1975; National Research Council 2003) and potentially deeper snows would partially offset the gains from increased forage during the calving season.

Availability of caribou to local communities is a function of caribou numbers and location and how easily the hunters can get out on the land to hunt them. In turn, these factors depend on environmental conditions, caribou population dynamics, and caribou movements. We worked with local hunters of our partner communities and used prior research (Fancy and others 1986; Eastland 1991; Russell and others 1992, 1993) to identify relationships between environmental conditions and the seasonal and annual distribution and movements of the Porcupine Caribou Herd (PCH), the range that encompasses the hunting areas of all four of the partner communities. Similarly, through focus groups and mapping exercises with local knowledge holders, we determined how environmental conditions (for example, timing of freeze-up and break-up, shallow snow cover, and the presence of ''candle ice'' on lakes) affected hunters' access to community hunting grounds. We used an iterative process of multiple small-group interviews in each community to generate and refine qualitative propositions about community caribou availability and hunter access and time for hunting as a function of local and regional environmental conditions (Kofinas and others 2002a). We then used historical distribution and movements of the PCH (Russell and others 1992) and local knowledge as the basis for delineating 12 PCH rangewide zones and 38 community-specific hunting zones. For each hunting zone, we drew on this information to assign probabilities of PCH presence and estimated the relative hunting effort required as a function of annual environmental conditions.

In summary, we designed our climate scenarios to take into account the following factors at annual time scales: (1) summer temperature (affecting green-up timing, forage quality and biomass, insect harassment level, and calf survival during June), (2) winter snow depth (affecting overwinter caribou calf survival, caribou distribution, and hunter access to certain distant hunting zones), and (3) timing of freeze-up (also affecting the accessibility of hunting zones). We had insufficient empirical data to model potential climate effects on the duration of the peak in quality of caribou summer forage and the extent to which caribou and their predators may track and adapt their life cycles to climate-induced changes in the environment. We also had limited data on caribou winter ranges and their use of nonvascular plants, the explicit energetic costs of parasite burdens, and any expected increases in catastrophic events. In addition, complex interactions among surface temperatures, precipitation, and cloud cover may negate our expected increase in insect harassment as a result of climate warming.

Petroleum Development

Potential petroleum development on the coastal plain of the Arctic National Wildlife Refuge (ANWR) is probably the most debated natural resource issue in the US and western Canada. Ever since the Alaska National Interest Lands Conservation Act of 1980 (ANILCA) identified the 1002 Area as a potentially significant source of petroleum resources, concerns about the potential effects of petroleum development on the PCH have motivated sustained research programs by both the US and Canada. Recognizing this area of concern, the research team decided to include petroleum development as a potential force for change in the study.

Project researchers constructed a set of hypothetical oil development scenarios based on an analysis of USGS assessments of oil potential in ANWR and changing worldwide petroleum markets (USGS 1998; Tussing and Haley 1999). The scenarios represented a progressively increasing petroleum development presence that ranged from limited oil development just west of the ANWR with some ''drainage'' of oil beneath the Arctic Refuge in the Canning River Delta to petroleum development throughout the 1002 Area. Because these hypothetical development scenarios (Tussing and Haley 1998) were unlikely to be realized exactly, they were used only to generate a distribution of potential displacements of the annual calving grounds of the PCH (Griffith and others 2002).

We initially anticipated that we would model the potential effects of petroleum development on both employment and caribou. However, Kaktovik, Alaska, the only community likely to experience significant employment effects, ultimately chose not to participate as a partner community. We therefore focused on the potential effects on caribou populations and availability of caribou to communities.

Tourism

Partner communities were keenly interested in a more detailed look at alternative tourism scenarios. Working in collaboration with communities, we identified 15 tourist enterprises ranging from small-scale guiding outfits run by locals to large-scale tourist lodges built by an outside company. Each enterprise had specific jobs associated with it (full-time and/or part-time jobs) and an estimate of its required cash investment and profitability. We constructed four tourism scenarios using various combinations of the 15 potential tourist enterprises. The scenarios were: (1) no additional tourist activity, (2) small-scale ''eco/cultural tourism,'' (3) the addition of a year-round road to the community for small-scale eco/cultural tourism, and (4) large-scale tourism, coupled with a road to the community. We hypothesized that tourism-related jobs in the community would add to the wage income of households, but also would reduce the amount of time that people had to engage in subsistence activities. To analyze these effects, we attached attributes to each job such as annual salary, number of months of employment offered per year, which seasons of the year the job was available, its educational requirement, and the relative probability that the job would be filled by a man or by a woman.

Reductions in Government Support to Communities

To the first three forces for change—climate, petroleum development, and tourism—we added potential reductions in government support to communities, Huskey and Knapp (1988) estimated that federal and state transfers to households and local governments accounted for 46% of village income in western Alaska in 1984. Based on our review of economic data for Old Crow (G. P. Kofinas unpublished), we estimate government funds directly supported 69% of the wages and salaries in 1992. Reductions in overall government spending in remote northern settlements could be among the most significant forces for change to affect Arctic communities over the next 40 years.

Scenario Combinations

Scenarios for change can arise as a result of various policy initiatives implemented from local to international levels. The warming scenario assumes continuation of the observed (Serreze and others 2000) northern latitude warming, whereas the no-warming scenario assumes the warming abates by natural processes or reductions in greenhouse gas emissions. Petroleum development scenarios assume opening of the 1002 Area by US Congressional action. We envision all the tourism scenarios as results of community-controlled policy decisions. To explore interactions and cross-linkages among the four forces for change, we examined the various combinations of climate change, petroleum development, tourism, and government spending. There are a total of 80 scenario combinations (2 climate scenarios × 5 development scenarios × 4 tourism scenarios × 2 government-spending scenarios).

Model Descriptions

Spatial and Temporal Scales

Our modeling simulations operate at four spatial scales: (1) the calving ground of the PCH on the coastal plain, (2) the entire range of the herd's annual migration, (3) a single community, including the hunting areas of its surrounding homelands, and (4) the household. Relationships pertaining to all four scales are represented in our integrated model, which we call the Arctic Community Synthesis Model, because it *synthesizes* data and relationships from several disciplinary perspectives. To date, we have developed the Community Synthesis Model to reflect conditions in the community of Old Crow, Yukon Territory, Canada.

The principal tension in choosing a time scale came between the 100-plus-year horizon over which vegetation composition changes might be expected to affect the caribou population and the 20-year time scale over which we might venture to anticipate technological changes. We decided to focus most of our attention on a 40-year time scale. Given the uncertainties, 40 years appears to be the outer limit at which we could hope to model with any semblance of relevance to the perceived problems of today. What ultimately made the 40-year time scale an overall reasonable choice is that year-to-year variations in timing of green-up, potential snow depths, levels of insect harassment, and caribou harvests, in addition to the multidecadal response of arctic vegetation to warming, appear to have significant effects on caribou population trends over a 40-year period.

Vegetation and Caribou

We developed a model called ArcVeg that simulates transient dynamics in Arctic vegetation and the response of tundra plant communities to climatic warming (Epstein and others 2000). The model incorporates a relatively detailed set of plant functional types including mosses, lichens, grasses, and a variety of forbs, sedges, evergreen, and deciduous shrubs. This degree of detail was necessary due to the day-to-day and seasonal dynamics of caribou diets and the quality of forage items (Thompson and McCourt 1981; Russell and others 1993; Griffith and others 2002; Johnstone and others 2002) and the importance of diet to reproductive success of caribou. Plant types were distinguished in the model by a set of five parameters that described a wide range of growth, competition, and survival strategies. Climate and disturbance were stochastic elements in the model. The model was nutrient-based because many Arctic ecosystems are limited by plant-available nutrients, especially nitrogen (Shaver and others 1992; Shaver and Chapin 1995; Schime and others 1996) and respond relatively quickly to changes in nutrient availability (Shaver and others 2001).

For caribou population dynamics, the project built on 15 years of Porcupine Caribou energetics modeling work (Hovey and others 1989; Kremsater and others 1989; Kremsater 1991; Russell 1991; White 1991). This included refinement of CARIBOU, an existing research model designed to assess the energetic and population effects of harvesting, climate change, and petroleum development within the range of the PCH. We incorporated new research findings from concurrent and recently completed projects (Russell and others 1998; Chan–McLeod and others 1999; Russell and White 2000) into the model structure. We used validation data to assess the ability of the model to accurately reflect caribou body conditions measured in the field (Gerhart and others 1996) and to more closely link body condition to reproductive performance (Cameron and others 1993; Gerhart and others 1997a). We linked the CARIBOU model with the vegetation model ArcVeg to explore the implications of predicted increases in vegetation biomass and changes in plant species composition on cari-

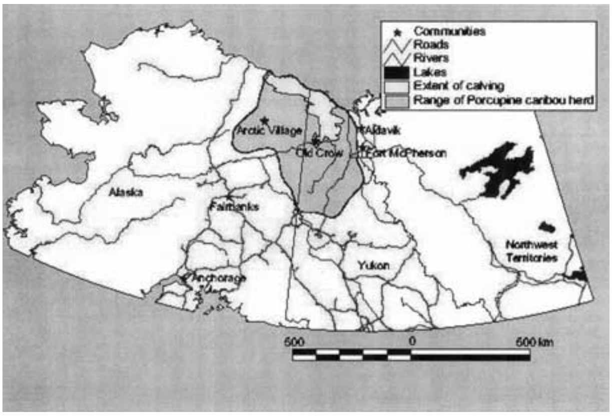

Figure 1. Map of the range of the Porcupine Caribou Herd (PCH), the PCH calving grounds, and the four partner communities.

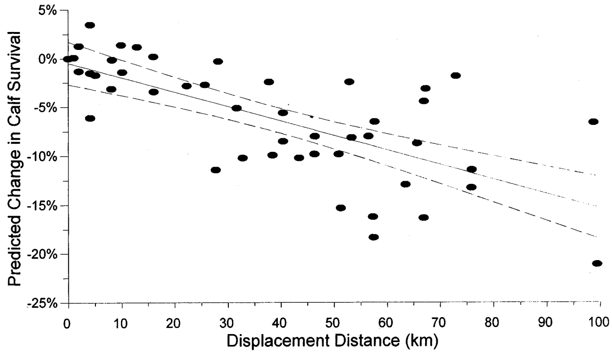

Figure 2. Estimated change in caribou calf survival during June (% change) as a function of hypothetical annual calving ground displacement distance (km); adapted from Griffith and others (2002).

bou over a 40-year time horizon (White and others 1999).

The 1002 Area of the ANWR overlaps the area used most heavily by the PCH for calving (Figure 1). We modeled (Griffith and others 2002) the potential influence of petroleum development in the 1002 Area on caribou distribution and resulting calf survival during June. Our model was based on the documented separation of high-density calving areas of the Central Arctic caribou herd from petroleum development infrastructure (Cameron and others 1992; Lawhead and others 1993; Wolfe 2000) and empirically based functional and numerical responses of parturient PCH female caribou and their calves to forage availability and predation (Griffith and others 2002). Caribou selected annual and concentrated calving grounds with high-quality forage and high-forage biomass, respectively. Calf survival during June was positively related to forage biomass within the calving ground and negatively related to predation risk at birth sites (Griffith and others 2002). Using these empirical relationships we estimated calf survival before and after hypothetical displacements and generated a dataset relating potential changes in calf survival to displacement distance (Figure 2) (Griffith and others 2002).

We also have evidence that caribou in proximity to oilfield infrastructure have a different pattern of energy use than those further from development (Murphy and others 2000). We used the CARIBOU energetics model to simulate the effect of these altered energy budgets on cow fat weights, pregnancy rate, and calving success. We ran combinations of climate and oil development scenarios within the CARIBOU energetics model to develop sets of caribou population parameters that served as inputs to the synthesis model.

Household Economies

Our interdisciplinary social science approach to community modeling embedded the local economy within the institutional framework of the study communities (Polanyi 1944, 1957; Halperin 1994), but it also followed empirically based rules of household and individual behavior (Quigley and McBride 1987). We derived theories by integrating a rational choice analysis of economic behavior with qualitative propositions based on local knowledge to explain observed patterns (Berman and Kofinas 2004). This approach enabled us to model a set of dynamic interactions between institutions and individuals over time. We focused our efforts on several issues critical to the community sustainability goals; these included the interaction of the wage economy with the subsistence economy (VanStone 1960; Stabler 1990; Kruse 1991; Kirkvliet and Nebesky 1997), sharing of wildlife harvests (Wolfe and others 1984; Brown and Burch 1992; Sahlins 1972), and human migration (Hamilton and Seyfrit 1994). Because the changing role of institutions in distributing risks and rewards may be crucial to achieving community sustainability, our model disaggregated the community into component parts—individuals and households—in order to assess explicitly the distribution of outcomes within the community.

The structure of the household economies model included three socioeconomic components: (1) local wage labor market, (2) subsistence harvest, and (3) community population (Berman and Kofinas 2004; Berman and others in press). The local labor market component allocated household time to wage work and subsistence, based on job opportunities, environmental conditions, and development scenarios (Kirkvliet and Nebesky 1997). It probabilistically allocated jobs based on resident and nonresident education and job preferences over four seasons using a five-year time step. The subsistence harvest component projected hunting participation and harvest success in each of five seasons per year based on environmental conditions and labor market outcomes, taking into account different probabilities of harvest success, time for accessing hunting areas, and a set of rules (based on local knowledge) for sharing of gear and harvest among households. The harvest component incorporated spatially explicit hunting relationships and interactions among wage employment, hunting participation, and harvest sharing based on data for Alaskan North Slope Iñupiat communities. The village population component projected household formation, births, deaths, aging, educational attainment, and migration of First Nation members into and out of the community on a five-year time step, using migration probabilities based on demographics, income opportunities, and caribou harvest shortfalls during the previous time period (Huskey and others 2004). Finally, the model assigned remaining unfilled jobs to non-First Nation migrants.

We implemented the household economies model for the community of Old Crow, YT. We obtained data for model assumptions from a variety of sources, including Statistics Canada, harvest surveys, local hunters, and household surveys (Kofinas 1998; Kofinas and others 2002a). We validated the model by comparing simulated community outcomes for 1995 and 2000 with survey data on local employment, income, historical caribou harvest, and community population. Although the lack of complete data precluded a formal test of detailed outcomes for individuals, all aggregate measures fell within the margin of error of the available survey data.

Synthesis Model Structure

Our central focus on developing a single synthesis model proved to be the most important factor in achieving an integrated assessment. The synthesis exercise of this project challenged modelers to combine the interactions among the different subsystems (vegetation ecology, caribou ecology, human economics, and population dynamics) over a regional scale in a way that effectively addressed the four forces for change (Figure 3). There is a tension in any modeling effort of this kind between simplicity and detail (Costanza and Sklar 1985; Starfield and Bleloch 1991; Rolling 1999). Many system models take a bottom-up approach, that is, start with the finest level of detail in the hierarchy and build the model upward. Starfield and others (1993) argue that this approach locks one early on into possibly unnecessary and potentially confusing details. They argue for a top-down approach where one starts with a very simple model that reflects gross dynamic changes and then successively refines this model down to the appropriate level of detail, defined by the goals or objectives of the project, to address the relevant science or policy questions. We took a top-down approach in the development of our synthesis model.

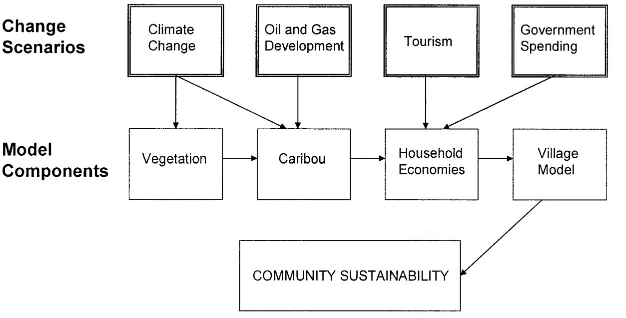

Figure 3. Diagram of the Arctic Communities Synthesis Model outlining the four aspects of change and the four integrated model components.

The Arctic Community Synthesis Model is best understood as an interacting cluster of four components (Figure 3). The vegetation component integrates changes in climate with plant growth characteristics and controls on nutrient cycling. It simulates the interannual changes in the biomass of the major plant types in the tundra plant community. The caribou component integrates the effects of climate, vegetation changes, petroleum development, and hunting. It models caribou population size, herd distribution, and the relative abundance of caribou for hunting by communities. The household economies component integrates the effects of tourism, government spending, and caribou availability. It models the mixed wage–subsistence economy, the distribution of household income, and household caribou harvest and consumption. The village population component integrates the effects of employment, income, time on the land, and rural–urban migration. It models village population, household formation, and movement of both local people and outsiders to and from a village. Taken together, these four components represent major social, economic, and environmental processes affecting the human dimensions of change in Arctic communities. In keeping with community sustainability goals described earlier, the Arctic Community Synthesis

Model generates outputs that are indicative of communities' sustainability goals, including caribou harvest, time on the land, employment, and proportions of local and nonlocal populations in the community (see Table 1). Although the outputs of many of these variables would have possible implications for the difficult-to-quantify effects of change on communities (for examples, loss of identity, intergenerational transmission of cultural traditions, respect for elders), we decided early in our IA process that the model would not attempt to calculate ''indicator values'' for these areas of assessment, leaving them instead to be addressed through the discussions among local knowledge holders.

Modeling Results and Discussion: Implications for the Sustainability of Arctic Communities

Vegetation

The simulations of climatic warming suggested an increase in total plant biomass for high and low Arctic tundra ecosystems over 200 years (Epstein and others 2000) (we extended the vegetation simulations past the 40-year time frame of the synthesis) and a long-term increase in shrub biomass at the expense of other plant functional types. The initial responses of vegetation to climatic warming (approximately 0–50 years) were controlled by the existing dominant plants and were not indicative of predicted long-term changes in plant community composition (approximately 50–200 years). To explore the short-term transient vegetation changes for the 40-year time scale, we first ran the model for 400 years under current, stable climate conditions (to ensure that the initial vegetation community was at equilibrium), then for an additional 40 years under the climate-warming scenario, and recorded changes in total biomass and plant community composition during this time. Simulations for the coastal plain (caribou calving ground) projected an increase in total biomass of approximately 150 g/m^2 (a 37.5% increase) with increases in mosses and sedges and slight increases in both evergreen and deciduous shrubs (Epstein and others 2000). The 40-year vegetation data were inputs to the caribou component of the synthesis model.

Caribou Population

Caribou are an important food source for indigenous communities in and adjacent to the range of the PCH (Wein and Freeman 1992, 1995). More than 20 years of research have shown that northern people choose to continue to harvest and consume substantial local resources despite an increasing importance of a cash economy (Kruse 1991). The PCH also has a cultural importance beyond its food value (Kofinas 1998). People share resources to hunt, they hunt together, and they share harvests. Children learn cultural values by observing and participating in hunting and processing activities. Moreover, in Old Crow, Arctic Village, Aklavik, and Fort McPherson, caribou are closely linked to cultural identity and community well-being. Perceived threats to the continued presence of caribou and to the integrity of the environment they occupy are taken very seriously by communities of the region.

Changes in the size of the PCH are therefore of great interest to communities that depend on the herd. The sequence of interannual variations in summer temperatures, forage availability, snow depth, harvest by humans, and insect harassment strongly influenced the 40-year simulation results for the herd. We conducted 200 repeated executions of the Synthesis Model while keeping the probability of warm summers, high insect harassment, deep snows and high harvests constant. These simulations predicted 40-year caribou populations under current conditions that varied from increases in excess of 5% per year to decreases of the same magnitude, as well as intermediate trajectories. In some simulations, chance occurrences of a sequence of ''bad'' years set in motion a large population decline. In other runs, an absence of such strings of bad years produced a large population increase. These results raise the important point that random annual variations can potentially mask or accentuate the apparent effects of any of the change scenarios. Climate alone induced a high degree of variability in our modeled projections of the size of the PCH over the next 40 years. This climate variability set the stage for analyses of the potential effects of petroleum development and tourism on community sustainability.

Caribou populations are quite sensitive to a warming climate through its influence on summer forage and resulting calf survival (Griffith and others 2002) and through its effect on late summer insect harassment and winter snow depths which may influence body condition and subsequent parturition rates (Gerhart and others 1997b). Our simulations of the effects of climate warming on the PCH suggested it was likely that the herd would decline over the next 40 years (Figure 4). Our initial expectation was that warming would tend to increase herd size as a result of earlier spring green-

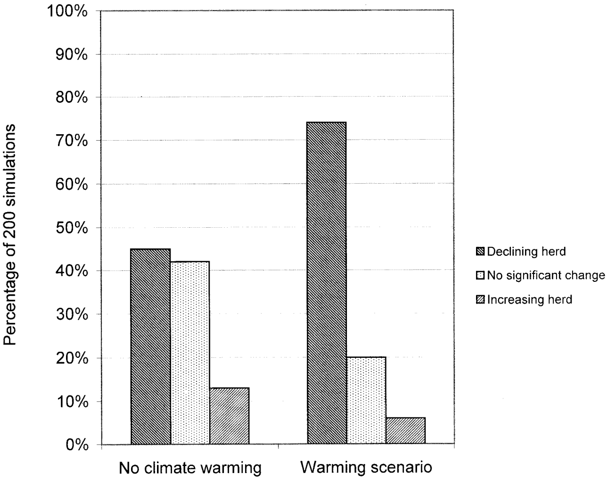

Figure 4. Estimated effect of climate change scenarios on caribou population size.

up and greater forage quantity. When we combined the warming effects on caribou forage with an increased frequency of years of deep snows and high insect harassment, however, the net effect was to increase the chances of population decline.

Current general circulation models appear to be better at predicting temperatures than precipitation, and the latter is relevant to both snow depths and insect harassment levels. Community residents who have reviewed our model noted the shortfalls in making broad generalizations with regard to possible changes in snow depth and suggested that regional variability in precipitation levels, as well as average values, is also an important factor.

The Synthesis Model simulations suggested that the most important potential relationship between petroleum development and caribou is the hypothesized effect of reduced access to forage during peak lactation demand and increases in predation losses brought about by a potential displacement of concentrations of cows and calves during calving. Forage quality and predation are both important components of calf survival; these relationships are mediated by climate and may be affected by petroleum development (Griffith and others 2002). There was a significant inverse relationship between hypothetical displacement distance and calf survival (Griffith and others 2002; $r^2 = 0.665$, $P = 0.0017$; Figure 2). There was an estimated 1% reduction in calf survival for each 6 km of displacement (Figure 4). Previous stochastic simulation modeling (Walsh and others 1995) suggested that a 4.6% reduction in calf survival would be sufficient to halt growth of the PCH during the best conditions observed to date. The variability in these modeled relationships suggested that it will be difficult to statistically demonstrate such an effect, if it does occur, unless large numbers (much greater than 100) of cows are radio-collared and intensively monitored. This exercise assumed that calving ground mortality was additive to calf mortality during the remainder of the year and that there were no other compensatory mechanisms that would negate the simulated effect.

Caribou Availability to Communities and Caribou Harvest

Porcupine Caribou user communities are dispersed widely in and around the range of the PCH. We constructed probabilities for different herd movement patterns based on documentation of past herd movements and local knowledge. For example, participants in focus group discussions in Old Crow reported on their use of the Porcupine River in the fall hunting season to intercept migrating caribou at their traditional river crossings. Elaborating on their hunting activities, local residents also reported on the environmental conditions that are likely to affect the location and rate of caribou migration through community hunting grounds (for example, late-summer storms, fall icing events). The Arctic Community Synthesis Model incorporated local knowledge and science-based understandings of caribou distributions and movements to simulate year-to-year differences in herd concentrations. These probabilities varied between no-warming and warming scenarios. Hunters in the model see "lots," "few," or "no" caribou in a given area and season, depending on the herd distribution and overall population size. The number of caribou seen affects the likelihood of hunting, the effort required (treated in the model as day, overnight, or multinight trips), and hunting success. Hunters also need time to hunt and enough money to buy equipment and supplies. Employment conditions affect both time to hunt and money, depending on the types and numbers of jobs. Sharing of equipment and harvests are important ways in which the community tries to optimize hunting effort and meet household needs for caribou.

We modeled the community of Old Crow where fall is the primary caribou hunting season. Although hunters may try to make up for poor fall hunting in winter and regularly participate in spring hunts for fresh meat supply, we can obtain an indication of changes in caribou availability over time by counting the number of fall hunting seasons in which hunters see only a few caribou. In our simulation model, about one in four years

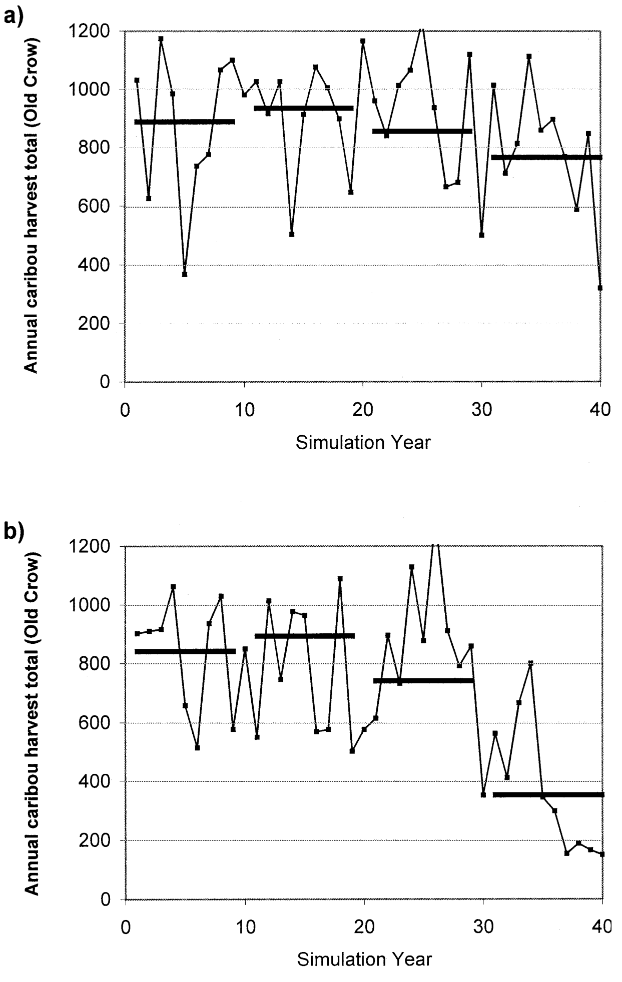

Figure 5. Estimated total caribou harvest by humans under (**a**) current climate and (**b**) climate warming plus an approximate 50-km calving ground displacement across the 40-year simulations.

showed bad fall hunting under a no-warming scenario.

The simulations started with a high degree of uncertainty about what would happen to the caribou herd size. However, under most simulations, producing a decline in community harvests would likely require climate warming coupled with a substantial eastward displacement of the annual calving grounds during a two- to three-week period in June (Figure 5).

The Synthesis Model simulations with climate warming assume that communities continue efforts to meet their caribou needs. It is important to point out that the assumption that no self-regulating harvest policy will be implemented to limit the number of caribou harvested is unrealistic. Our rationale was to highlight the kinds of changes in harvest strategies that might be necessary under various scenarios of change. Modifying our model to reflect the adaptive harvesting strategies of a comanagement system is a priority as we advance this work (Kofinas and others 2002b).

With warming, the herd size could decrease as much as 85% over 40 years (that is, declining to about 20,000 animals by year 40). Simulating the potential effect of such a large reduction in herd size on harvest was problematic because we had no empirical data on harvest success or harvest strategies for herd sizes below about 100,000 animals. Some accommodations for low caribou populations by communities would be expected because "community hunts" have been organized when harvest shortfalls occur. When enough hunters experience poor hunting success (which we estimated in the model as the point when less than 50% of the community need for caribou is met), the model implements a community decision to pool resources, hunt collectively, and travel to the areas where caribou have been seen in sufficient numbers. Over a long enough time period and without a policy limiting total take of caribou, such a harvest strategy might further depress herd size, but if yield per unit effort declined enough, harvest might ultimately be reduced.

Employment

Potential changes in tourism and reductions in government spending can affect employment conditions. Communities prefer tourism scenarios that increase local employment without bringing large numbers of tourists through the community. We designed an "eco/cultural tourism" scenario to include combinations of enterprises (for example, outfitters, wilderness camps, gift shops) based on the experiences of other communities, management planning documents, and through discussions with partner community members. In the Synthesis Model, local residents compete with each other and with nonlocals for jobs based on their educational qualifications and job preferences. If Old Crow were successful in implementing an eco/cultural tourism industry, we estimated that the percentage of households in which no adult had a job in 2040 dropped from the 2000 figure of 8% to less than 1% in most simulations, compared with an increase to 15% if tourism remains at the 2000 level. On the other hand, per-capita income remains virtually unchanged, despite a 60% increase in the number of jobs. The reason is that the new jobs would attract First Nation members not currently living in Old Crow, increasing Old Crow's local population from about 235 to 300. The types of jobs created would on average pay lower wages

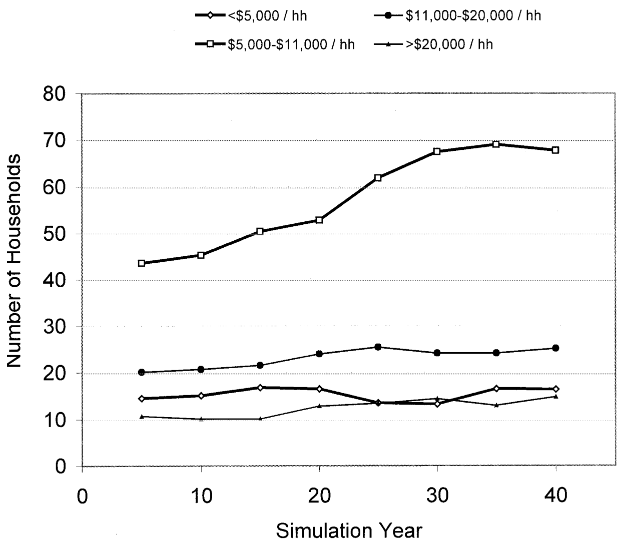

Figure 6. Number of households by average per capita income across the 40-year simulations.

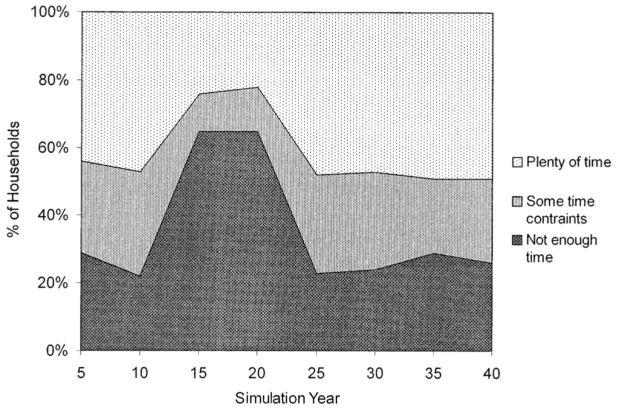

Figure 7. Time to hunt in the fall by households across the 40-year simulations.

than current jobs in Old Crow. This would mean that the number of below-average income households may increase, both in absolute numbers and as a proportion of all households (Figure 6). This model of community employment was also affected by an anticipated demographic increase in the number of adults in the community 20 years from now.

The first ecotourism scenario assumed that Old Crow would remain off the Yukon road network. If we assumed that, in addition to ecotourism, Old Crow decided to build an all-season road to the community—and was successful—we estimated the population increase in Old Crow to be another 50–60 people, an increase in both population and in number of households of more than 50% by 2040.

The major people-to-environment feedback in the model is the demand for caribou. Under the "ecotourism-plus-road" scenario, the increased human population would increase demand for caribou by perhaps 30%, assuming that per-household needs for caribou do not change and that regulations or local policies would prohibit road hunting. With these conditions, over half the simulations showed a decline in the herd, but not enough over the next 40 years to cause more shortfalls in caribou harvest. The Arctic Community Synthesis Model did suggest a relationship between the increased employment demand during potential construction of a road in the second decade and increased numbers of households not having enough time for fall hunting (Figure 7). The reason the decreased time for hunting for some households did not result in a decline in the overall community harvest is that households with employed hunters and no time for hunting were able to use their wage income to help hunters of other households who had more time to hunt. This is an example of a social feedback within the model.

The potential effects of a reduction in government support would obviously depend on the scale of any cutback. We assumed about a 30% reduction in government support and a reduction by 20% in subsidies and transfer payments to households in the "retrenchment" scenario. Interestingly, our simulations show about the same high level of unemployment in 2040 (40%) with and without reduced government support, but with two differences. First, simulations with cutbacks show the percent of households with no one employed increasing to 25% by 2020 before declining to 15% by 2040. Second, with cutbacks, the human population dropped significantly due to out-migration and ended with less than 200 residents. As the cutbacks occurred, the average wage income in the community continued to drop. Jobs in cities would become increasingly attractive as their wage rates would be comparatively higher. The Synthesis Model suggests that the difference in relative wage rates is a major factor in determining the amount of in-migration and out-migration. Eco/cultural tourism would probably not offset the unemployment effects of government cutbacks because most of the jobs created would pay too low a wage.

Conclusion

The Arctic Communities Synthesis Model and an associated, user-friendly Possible Futures Model (designed for the partner communities and found at http://www.taiga.net/sustain) were intended to advance our understanding of relationships across disciplines, building on both scientific and local-based knowledge. We learned a great deal in the research process itself. Nicolson and others (2002) reflect on what we learned about interdisciplinary modeling and offer some heuristics so that others might avoid our mistakes. For example, although we adopted a top-down modeling paradigm, the caribou energetics and household economics components of the model were essentially bottom-up in their design, leading to an imbalance in the model between too much detail in some components and too little in others. Elsewhere, Berman and Kofinas 2004 note that it is difficult for simulation models to incorporate the nuances of local knowledge but that the IA can facilitate a productive conversation among scientists and indigenous peoples regarding forces for change.

We chose to model a single Arctic community, Old Crow, largely because we had to build the household economics component of the model from the ground up. This raises the question of applicability of our conclusions to other Arctic communities. Four partner communities contributed to the development of our operational definition of sustainability. This definition has since been reviewed informally by representatives of communities in the range of the Beverly and Qamanirjuaq caribou herds of Canada and the Western Arctic Herd of Alaska; the definition appears to have widespread applicability. Results from, and relationships contained in, the Single Community Synthesis Model served as the principal basis for discussion with residents of four PCH user communities. They readily identified likely differences in outcomes between Old Crow and their own community; mostly, however, they focused on relationships common to all Porcupine Caribou user communities (for example, climate–caribou relationships). A principal research objective in a second phase of the Sustainability of Arctic Communities project is to focus on the regional level and include all primary PCH communities in a new version of the Synthesis Model that highlights community differences in outcomes and opportunities for collective action. Although some of the model details may not apply to other communities, the basic framework of the model is likely very applicable, particularly for communities that subsist at least in part through caribou harvests.

At a project wrapup meeting in Old Crow, researchers and community residents agreed that the models do not take everything into account. Partners also agreed that any single projection of the future is probably imperfect. Models, to be useful, have to cope with both of these limitations: one can never take everything into account and projections of the future are only if–then statements (if our assumptions are correct, then these are the consequences). A thoughtful sensitivity analysis is therefore essential for gaining insight from a modeling exercise (Nicolson and others 2002). Nevertheless, scientific and local knowledge holders concurred that although simulation modeling is only at best an incomplete abstraction of the real world, it can help us all to bring existing scientific and community knowledge together to consider the future.

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