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Adaptation and Sustainability in a Small Arctic Community: Results of an Agent-Based Simulation Model

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ABSTRACT. Climate warming and resource development could alter key Arctic ecosystem functions that support fish and wildlife resources harvested by local indigenous communities. A different set of global forces—government policies and tourism markets—increasingly directs local cash economies that communities use to support subsistence activities. Agent-based computational models (ABMs) contribute to an integrated assessment of community sustainability by simulating how people interact with each other and adapt to changing economic and environmental conditions. Relying on research and local knowledge to provide rules and parameters for individual and collective decision making, our ABM generates hypothetical social histories as adaptations to scenario-driven changes in environmental and economic conditions. The model generates projections for wage employment, cash income, subsistence harvests, and demographic change over four decades based on a set of user-defined scenarios for climate change, subsistence resources, development, and government spending. Model outcomes assess how scenarios associated with economic and climate change might affect the local economy, resource harvests, and the well-being of residents for the Western Arctic Canadian community of Old Crow, Yukon. The economic and demographic outcomes suggest implications for less quantifiable social and cultural changes. The model can serve as a discussion tool for a fuller exploration of community sustainability and adaptation issues.

Key words: community sustainability, integrated assessment, local knowledge, mixed economy, tourism, agent-based model, simulation, climate change, Old Crow, Yukon

RÉSUMÉ. Le réchauffement climatique et la mise en valeur des ressources pourraient modifier des fonctions clés de l'écosystème arctique qui assurent le maintien des ressources ichtyques et fauniques exploitées par les collectivités autochtones locales. Un autre jeu de forces à l'échelle mondiale – les politiques gouvernementales et les marchés du tourisme – dirige de plus en plus les économies monétaires locales qu'utilisent les collectivités pour soutenir leurs activités de subsistance. Des modèles informatiques orientés agent (ABM) concourent à une évaluation intégrée de la viabilité des collectivités en simulant les interactions entre les personnes et leur adaptation aux conditions changeantes de l'économie et de l'environnement. S'appuyant sur des travaux de recherche et sur le savoir local afin de fournir règles et paramètres pour la prise de décisions individuelle et collective, notre ABM génère des histoires sociales fictives comme adaptations à des changements dans les conditions environnementales et économiques définis dans un scénario. Le modèle génère des projections pour l'emploi salarié, le revenu monétaire, les prélèvements de subsistance et le changement démographique au cours de quatre décennies. Ces projections sont fondées sur un ensemble de scénarios définis par l'utilisateur concernant le changement climatique, les ressources de subsistance, la mise en valeur et les dépenses publiques. Les résultats produits par le modèle évaluent la façon dont les scénarios associés aux changements économique et climatique peuvent affecter l'économie locale, l'exploitation des ressources et le bien-être des résidents de la communauté canadienne de Old Crow, située au Yukon, dans l'Ouest de l'Arctique. Les résultats économiques et démographiques suggèrent qu'il existe des répercussions sur des changements sociaux et culturels moins quantifiables. Le modèle peut servir d'outil de discussion pour explorer plus à fond les questions de viabilité et d'adaptation des collectivités.

Mots clés: viabilité des collectivités, évaluation intégrée, savoir local, économie mixte, tourisme, modèle orienté agent, simulation, changement climatique, Old Crow, Yukon

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INTRODUCTION

Recent research findings and local knowledge suggest that climate warming may alter key ecosystem functions and associated human uses in the North American Arctic (Cohen, 1997; Krupnik and Jolly, 2002). Small indigenous communities of the North American Arctic maintain a long-standing reliance on fish and wildlife resources as an important food source and as a central feature of their cultural identity (Langdon, 1991; Kruse, 1992; Nuttall, 1998). These communities express concern that the possible effects of climate change on northern ecosystem health could threaten the subsistence way of life (Peterson and Johnson, 1995; Eamer et al., 1997; Krupnik and Jolly, 2002). Today these communities support subsistence activities with a cash economy that is increasingly directed by other global forces for change.

Because of this mixed economy, and because people adapt to changing conditions, the question of sustainability of Arctic communities cannot be answered simply by projecting changes to the ecosystem. Instead, it requires a more holistic approach that encompasses potentially interacting adaptations to changes in social, economic, and environmental conditions (Gunderson et al., 1995; Berkes et al., 2003). Researchers face a challenge to integrate these disparate forces for change. Agent-based computational models (ABMs) allow for such integration by simulating how people interact with each other and adapt to changing conditions (Kohler and Gumerman, 2000). In ABMs, each agent is a decision-making social unit such as an individual, household, or family group that collects information about the environment, makes decisions about actions based on that information, and acts on these decisions. Multiple agents may interact to form complex adaptive systems (Holland, 1992).

Early ABMs were theoretical, examining how stylized spatial relationships resembling institutions emerge through patterns of interactions among agents following simple decision rules (Gilbert and Conte, 1995; Epstein and Axtell, 1996; Axelrod, 1997). More recently, a second type of ABM has generated alternative social histories of use and occupancy of lands, consistent with archeological evidence (Axtell et al., 2002). A third type of model addresses contemporary issues of regional sustainability by embedding decision-making agents in a natural system and allowing them to adapt to its feedback (Carpenter et al., 1999). This type of application may be especially relevant to the Arctic, where people's lives are closely linked with their natural environments (Berkes and Folke, 1998).

Combining elements of the second and third type of application, we model human responses to environmental change to project resource use and adaptation over a period of several decades. Rather than use an ABM to explore what institutions emerge from agents' interactions, or to find parameters that best reconstruct a known history, we instead use the model to project how local institutions shape human adaptations to hypothetical scenarios for economic and environmental change. We built the model to support a larger integrated assessment of effects of development and climate change in the U.S.-Canada Arctic Borderlands region, in partnership with four communities (Kruse et al., in press). Our model projects effects of changes in employment opportunities and environmental conditions, rather than effects of other potential forces for change, to address larger project goals.

Our ABM integrates and synthesizes interdisciplinary research and local knowledge to generate indicators for population change, employment, household incomes, and subsistence harvests at the community level. We focus on these outputs rather than the social and cultural implications of change because the latter are difficult to quantify and commonly follow from rapid changes in ecological and economic conditions. Outputs from the ABM provided a set of community-defined sustainability indicators that were used to prompt discussions among community members and with researchers about changes associated with possible futures, including social and cultural changes (see Kofinas, 2003; Kruse et al., in press).

Community partners have stated from the outset that computer simulation models, being highly mechanistic, have limited ability to capture the complexity of real-world phenomena. While such models clearly cannot predict the future, community partners and researchers alike recognize the value of these models for improving understanding of system dynamics and the effects of forces for change on community sustainability.

THE COMMUNITY OF OLD CROW, YUKON TERRITORY

Situated without road access at the confluence of the Old Crow and Porcupine rivers, the settlement of Old Crow (Fig. 1) supports a mixed economy, in which wild food resources and wage-based jobs together provide essential material needs. The community is relatively homogeneous; most of the approximately 275 residents are members of the Vuntut Gwitchin First Nation, the political entity representing a local Gwich'in culture group that has inhabited the region continuously for several thousand years (Morlan, 1977; Acheson, 1981). The Vuntut Gwitchin identify themselves as "caribou people," and the Old Crow community is one of the primary users of the internationally migratory Porcupine caribou herd. Like many communities of the North, the people of Old Crow hold a long-standing and intimate relationship with the land and animals on which they depend (Stager, 1974; Acheson, 1981; Kofinas, 1998). That relationship also reflects a traditional knowledge of the ecological processes of the local region, including observations and explanations of environmental change (Irving, 1958; Kofinas et al., 2002a).

According to a 1993 assessment, Old Crow's cash economy provides about 90 total jobs, most of which are part-time or seasonal, amounting to 53 full-time equivalent

FIG. 1. View of Old Crow, Yukon Territory.

jobs. Settlement of land claims in 1993 resulted in a self-government agreement under which the First Nation provides a broad range of public services to the community with federal government support. Most of the jobs in Old Crow depend directly or indirectly on funds allocated through the land-claim agreement. Subsistence caribou hunting remains strong in Old Crow, with annual harvest averaging about two animals per capita (Yukon First Nations Harvest Surveys, 1988–94; Kofinas, 1998).

A number of factors make Old Crow an ideal Arctic community for investigating the potential contribution of agent-based modeling to the study of sustainability. The community is geographically isolated; it has no road access. Subsistence livelihoods depend to a great extent on the Porcupine caribou herd, for which a large research base exists (Fancy et al., 1988; Russell et al., 1992, 1993; Griffith et al., 2002). The 1993 land-claim agreement gives the Vuntut Gwitchin First Nation substantial authority to influence the community's future. Most important, the community has been willing to participate in this research as a partner and share local knowledge with modelers (Kruse et al., in press).

THE MODEL

The model places artificial agents representing individuals and households in a hypothetical community surrounded by a landscape divided into a number of hunting areas. Individuals reside in five different types of households, representing combinations of working-age men and women, children, and elders with different wage-work and hunting-time capabilities. Table 1 shows the model's specific categories of individual and household demographic characteristics, educational attainment levels, job preferences, and subsistence consumption needs.

Agents make decisions and interact using a set of rules for nine separate activities regarding working for pay, hunting, sharing, and moving (Table 2) in a local economy based on household production, as broadly described by Usher (2003). Individuals form households and seek wage work on the basis of age, gender, and educational attainment. Adult men and women queue for and take jobs according to education and job suitability, and they may move out of or back to the community to achieve greater well-being. Hunters share hunting gear, travel to hunting areas using household time and money resources, and share harvests with other households. The model also considers the option for a community to respond to harvest shortfalls with collectively organized hunts. In practice, sharing of gear and harvests, and even job assignment, often follows familial lines. However, the model abstracts from family organization (beyond the household) in order to focus on how adaptations distribute risk and outcomes in the community as a whole. We construct rules and parameters of the mixed economy from observations of contemporary jobs and workforce attributes generally characteristic of small Arctic communities, using a variety of research data and local knowledge provided by experts from Old Crow and surrounding communities (Kofinas and Braund, 1998). The Appendix discusses details of the methods for constructing rules for job suitability, hunting, and migration.

Given the characterization of agents, the model simulates their decisions sequentially based on qualitative rules, using different time clocks for different activities (Table 3). The model chooses outcomes using logical (if-then-else) statements from a defined set of possible outcomes at each of four decision steps. First, demographic and education characteristics of the population adjust, and people redistribute themselves into households. Second, adults seek and obtain jobs in each of four seasons (starting with fall). Some workers may take jobs located outside the community. Third, hunters go out on the land on the basis of household time and money budgets (from job assignments) and caribou availability. Finally, people move into and out of the community in response to changes in well-being.

Demographic change, household formation, seasonal wage employment, and migration follow a five-year time step to simplify computations while focusing on the modeling objective of understanding long-term patterns of community change. On the other hand, the model recomputes hunting activities dynamically five times per year to capture the effects on harvest success of high seasonal and interannual variability of caribou movements and weather conditions that affect access to hunting areas, as well as seasonal job constraints on hunting time. To ease the computational burden for hunting, the model randomly samples a maximum of 30 households to simulate hunting activities, regardless of the number of households in the community.

To initialize the model for Old Crow, we obtained parameters for contemporary household and workforce characteristics from our fieldwork and from local experts (Table 4). Parameters for subsistence hunting and caribou movements came from interviews with local hunters, Yukon First Nations Harvest Surveys (1988–94), Russell et al. (1992), and Eastland (1991). Local experts defined the

TABLE 1. Attributes of individuals and households (agents).

Age Structure	Individuals fall into one of six population cohorts: children under 15, men and women aged 15–39 and 40–64, and elders aged 65 and older.
Household Types	Adults reside in one of five different household types: a. Single men b. Single women c. Couples d. Multigenerational (adults living with parents) e. Elders (Single women, couples, and multigenerational households may include children.)
Education	Working-age (15–64) adults possess one of four possible levels of educational attainment, ranging from primary school through college.
Wage Employment	Working-age adults seek an individual-specific number of months of work per year that varies with household type and educational attainment.
Government Transfer Income	Households receive government transfer income that varies with household type and declines linearly with earned income.
Taxes & Subsidies	Households pay taxes or receive subsidies (negative income tax) as a fixed percentage of income.
Subsistence Consumption Target	Households have an annual subsistence consumption target (need), measured in numbers of caribou, which varies with household type.

geography and attributes of hunting areas, as described in Berman and Kofinas (2004).

SCENARIOS FOR CHANGE

Like other small Arctic communities, Old Crow faces multiple forces for change, including global markets, national policies, acculturation pressures, and climate. Petroleum and mineral development drive economic change in many areas of the North. Some oil and gas exploration, with minimal production, has taken place in the Eagle Plains near the Dempster Highway, and the Crow Flats have some natural gas resources. However, the potential for large-scale extractive industry near Old Crow during the next several decades remains relatively slight. Although the community currently receives fewer than 100 visitors annually, tourism has significant, if uncertain, growth potential, with the recently created Vuntut National Park and its visitors' center bringing higher visibility to the area. Some in the community see tourism as a viable option for economic development, given the substantial local control afforded through the land-claim agreement. Although land claims have been settled, funding for public services administered by the Vuntut Gwitchin First Nation remains tied to overall Canadian social policy and the federal commitment to northern development.

In cooperation with local residents, we developed a series of scenarios that examine possible futures for tourism, climate, and levels of government spending in the community over 40 years, documented in Martin et al. (1999). The baseline scenario hypothesizes a market economy that changes little from that of today, with the number and type of jobs and real rates of pay staying constant throughout the projection period. The retrenchment scenario envisions the possibility that the federal government might reduce its commitment to fund public services throughout Canada, leading to a permanent reduction of 30% in real federally financed spending. Since we derive the baseline from a survey of population and employment in 1993—the year for which we have complete data for the community (G. Kofinas, unpubl. data)—projections actually range 30 years into the future. The first decade simulates historical conditions, and scenarios for change begin incrementally during the second decade of the 40-year scenario.

Tourism futures are of great interest to community members, and they raise a number of questions regarding the generation and distribution of jobs, effects on subsistence hunting, and effects on local culture (see Orams, 2002). To address these questions for Old Crow, we identified scenarios for three levels of tourism development greater than the baseline that span the range of "soft" through "hard" ecotourism (Orams, 2001). Through a workshop with adult students at the Old Crow Campus of Yukon College, interviews with key informants, and research, we developed clusters of 19 types of local enterprises that might emerge in each of the three levels of tourism. We then projected associated investment costs, employment, and revenues based on current tourism business data (See Martin et al., 1999).

The ecotourism scenario represents a hypothetically successful effort by the community to attract and serve independent cultural and ecotourists to the area. The ecotourism-plus-road scenario envisions constructing a year-round road leading from the Dempster Highway to Old Crow. The road would bring additional independent travelers to the community and could bring additional impacts from increased access. The mass tourism scenario hypothesizes development associated with large, organized tour groups' visiting Old Crow after a road connection is established. Recent research on ecotourism has linked tourism effects to institutional conditions regarding local participation in planning and the level of local control of development (Fotiou et al., 2002; Vincent and Thompson, 2002; Garrod, 2003). The ecotourism scenarios

TABLE 2. Individual and household (agent) rules.

Subject	Rule
1. Household formation	Individuals are randomly assigned to a fixed number of households of each type determined by the population of men and women and by parameters specifying the percentage of women remaining single and the percentage of elders living with families. Assignment of men and women to couples and multigenerational households preferentially matches individuals with common levels of education.
2. Wage employment	Working-age adults ranked by educational attainment queue for jobs ranked by salary. Jobs are assigned by working down the lists from highest- to lowest-paying position and from most- to least-educated worker. Jobs are offered once to each worker who is not already employed that season, whose education level meets or is one level higher than the job requirements, and whose household wants additional work. A job applicant meeting all these criteria randomly accepts the job with a probability that varies with the job suitability level (described in the Appendix). Part-time jobs not accepted during the first round are offered a second time to the underemployed to permit qualified workers to potentially hold two part-time jobs. Jobs remaining unfilled after the second round are assigned to outsiders. Job assignment occurs seasonally starting in the fall, with year-round and multi-season job assignments carrying over into succeeding seasons.
3. Hunter participation	For each hunting season, starting in the fall, each household whose annual subsistence need exceeds cumulative annual caribou receipts gets a fixed per-season number of chances to take a hunting trip. Households randomly choose whether or not to hunt at each opportunity, with a probability that depends on their household resources, unmet subsistence need, and an index of hunting quality (see Appendix).
4. Household resources, gear sharing	Each household's resources for hunting are measured with an index that is a linear combination of household income and time. Time is measured for each hunting season, starting with a fixed total number of months that depends on household type (i.e., number of hunters) and subtracting months of full-time-equivalent household wage work. The index is then summarized in three levels to classify households as low, medium, and high. A fixed percentage of households with income below a low threshold and time to hunt above a high threshold borrow hunting gear from high-income households. Household resources are adjusted up one level for gear borrowers and down one level for gear lenders.
5. Hunting quality and geographic dispersion of hunting trips	On each hunting trip, hunters choose a geographic area for hunting based on seasonally varying hunting area attributes: • distance (measured in days required to complete the hunting trip, which varies seasonally and with climate conditions) • caribou "seen" that season (an index of animal abundance in three categories: none, few, lots) • specific geographical preferences (see Appendix). The hunting quality index combines the set of attributes for all hunting areas into a single index, summarized in three categories: poor, fair, great.
6. Hunter success	On each hunting trip, hunters harvest a random number of caribou based on caribou seen in the hunting area selected and season (reflecting different travel modes and food preservation constraints).
7. Harvest sharing	A household that borrows hunting gear distributes a percentage of its harvest that season to the lending household. A fraction of the remaining harvest, based on annual time (which depends on employment and household type) and income, goes into a common share pool distributed to all households in proportion to unmet need. The hunting household keeps the remainder of the harvest for its own consumption.
8. Community hunt	A collective (community) hunt may be triggered in any season if the percentage of households meeting a minimum consumption threshold falls below a pre-defined rate. All high-time (unemployed) hunters take one hunting trip in a community hunt. Harvests from community hunts are distributed to households below the minimum consumption threshold in proportion to unmet need.
9. Migration	Each adult randomly moves away from the community with a probability of moving that depends on age and sex, household type, earnings in the community relative to a fixed standard representing opportunities elsewhere, and whether a severe harvest shortfall occurs (see Appendix). A random proportion of a "reservoir population" moves into the community at rates that vary with the same set of factors. Children move in proportion to adult women.

TABLE 3. Model time steps.

Model Computation	Time Step
Population aging, births, and deaths	Once every five years
Educational attainment	Once every five years
Household formation	Once every five years
Job assignment to workers	For each of four seasons, once every five years, resulting in recalculation of annual income and seasonal time for hunting every five years
Hunting activities, harvest distribution	Five seasons per year (winter split into an early and late, reflecting differences in snow conditions and daylight) every year
Migration into and out of the community	Once every five years on the basis of the job assignments for the preceding five years and whether a severe harvest shortfall has occurred in any one of those years

TABLE 4. Base case parameters for Old Crow.

Individual Characteristics:		Initial population		Annual death rates	
Children under 15		70		0.005	
Women 15–39		40		0.002	
Women 40–64		30		0.005	
Men 15–39		40		0.01	
Men 40–64		30		0.01	
Elders over 64		25		0.08	
		Initial Percent		Percent decadal rate of change	
Annual birth rate, women 15–39		0.13		-10	
Elders living with families		70		-10	
Single women		25		10	
Women with college degree		5		0	
Women with post-secondary education but no college degree		15		0	
Women with high school education but no college		40		10	
Women with no high school degree		40		-10	
Men with college degree		5		0	
Men with post-secondary education but no college degree		10		2	
Men with high school education but no college		35		10	
Men with no high school degree		50		-10	
	High	Medium		Low	Minimal
Probability of obtaining job by suitability level (See Appendix for complete definition.)	50%	20%		10%	1%
Household Characteristics:	Elders	Multigenerational	Couples	Single women	Single men
Average elders per household	1.2	1.1			
Average men per household		1.3	0.9		1.1
Average women per household		0.65	1.25	1.1	
Average children per household		0.6	1.2	0.95	
Work wanted (months per year)	6.15	12.75	13.85	8.15	8.65
Annual caribou need	3	14	10	6	4
Total time (months/season month)	1.0	2.0	1.5	0.5	1
Base transfer funding level	$10 000	$16 000	$12 000	$10 000	$6000
	College		Post-secondary		High school
Additional months of work wanted with education	2.25		1.5		0.75
Job Characteristics:					
Transfer earnings lost per dollar earned			-50%		
Percent of living costs subsidized			30%		
Funding level with cutbacks for transfers and subsidies relative to base period			2% annually during second decade		
Hunting Parameters:	Fall	Early winter	Late winter	Spring	Summer
Maximum hunting trips/season	2	1	6	2	6
Probability of borrowing gear from potential lender			30%		
Caribou harvest per hunting trip	Small kill		Medium kill		Large kill
Probability, caribou seen = none	9%		1%		0%
Probability, caribou seen = few	30%		15%		5%
Probability, caribou seen = lots	40%		40%		10%
Animals harvested, summer or fall	1		2		10
Animals harvested, winter or spring	1		2		5
Percent of harvest shared with gear lender			40%		
Percent of harvest placed in the share pool[1]	Low time		Medium time		High time
Low income	5		25		45
Medium income	10		45		70
High income	15		60		90

[1] Percentages based on harvest sharing as a function of need (-), expected harvest (+), and income (-) and expected harvest as a function of time (+) and income (+) (Berman, 1998).

Harvest Shortfalls:	
Harvest shortfall threshold	50% of annual household need met
Community hunt triggered if less than	50% of total community need met
Households with less than	50% need met receive harvest from community hunt

FIG. 2. Additional year 40 tourism jobs considered suitable for local men and women, compared to baseline and retrenchment scenarios (Baseline: constant over 40 years). "Suitable" is defined as medium or high job suitability (see Appendix for complete definition). The same job can be suitable for both men and women.

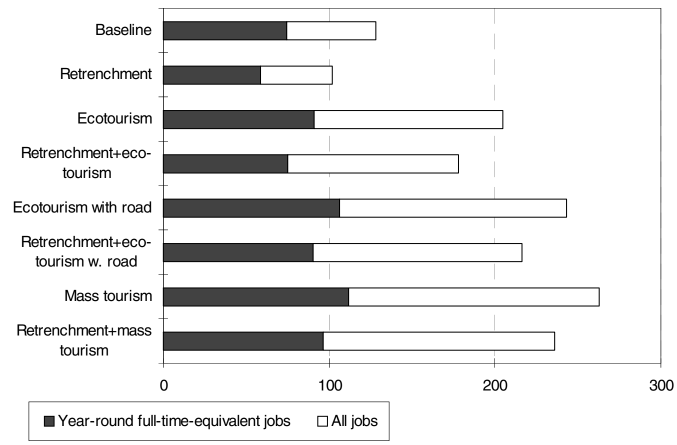

FIG. 3. Year 40 total and full-time-equivalent jobs under eight employment scenarios (Baseline: constant over 40 years).

envision a high degree of local planning and participation. Under the mass tourism scenario, ownership of the large-scale tourism operation would remain with a non-local corporation, with community residents gleaning benefits through employment and spin-off enterprises. Because the Vuntut Gwitchin First Nation has the authority to regulate activities of tourist businesses on settlement lands, the mass tourism scenario is unlikely, but it was included to represent a range of possible futures, as well as to reflect conditions in other Arctic communities that do not hold similar property rights.

To project changes from the baseline distribution of jobs by education level and gender for different scenarios, we examined the proportion of indigenous men and women of differing educational attainment levels that held similar jobs in occupational employment data from rural Alaska. We found that although new ecotourism jobs would attract both men and women, high-paying jobs associated with road construction and maintenance in the road-plus-tourism scenarios would mostly be "men's jobs" (Fig. 2). Comparing total and year-round full-time-equivalent jobs at the end of the 40-year simulation horizon generated in each of the eight potential combinations of tourism and government spending scenarios (Fig. 3), we found that ecotourism provides a large increase in part-time seasonal jobs but relatively modest gains in full-time employment. While all eight scenarios represent plausible futures, none is "most likely" to occur; the future may combine parts of any of these scenarios. One could say that they bound the probable futures, but certainly not all possible ones.

Climate change also challenges the community, both through potential ecological effects on subsistence resources and through changes in access to lands. Current projections for the Arctic from climatological models call for warmer, longer summers and greater variability: more variable snow conditions (more years of deep and low snow) and fewer "average" years (Zhang et al., 2000). Over the past decade, the Porcupine caribou herd has been declining by about 3.2% annually while regional climate has warmed (Griffith et al., 2002). Nicolson (1999) modeled caribou populations using a stochastic energetics-based approach that takes into account changes in forage, snow conditions, and insect harassment (White et al., 1999; Kruse et al., in press). He projects that under a warming climate, the herd is more likely to decline from its current level than to increase. Future caribou population projections are highly uncertain. To explore the potential vulnerability of Old Crow subsistence harvests to a declining Porcupine caribou herd associated with climate warming, we consider a decline of 2% per year, or about two-thirds the current rate of decline. This leads to a herd size of about 40% of the current level after 40 years.

Climate-related changes in caribou movements could affect the community as much as (if not more than) changes in herd size. Following Nicolson (1999), who used caribou distribution data from Russell et al. (1993) and local knowledge analyzed by Berman and Kofinas (2004), we assume that under a warmer climate, caribou would more often follow migration routes taken during historically warmer years. A warmer climate is likely to be associated with more years during which complete freeze-up is delayed, preventing safe overland travel to more distant hunting areas until late December (see Appendix, Table A-2).

Continuing penetration of mainstream North American consumerism through the mass media and the Internet could cause a variety of effects in Old Crow unrelated to scenarios of economic, policy, and climate change. These effects could include, but not be limited to, a reduced interest in subsistence hunting, greater mobility of residents, and in-migration of non-indigenous people. The model can represent potential effects of changes such as these through hypothesized shifts over time in parameters for household caribou need, hunting participation, and migration rates (see Appendix). We hold these parameters constant over our 40-year projections to address the interests

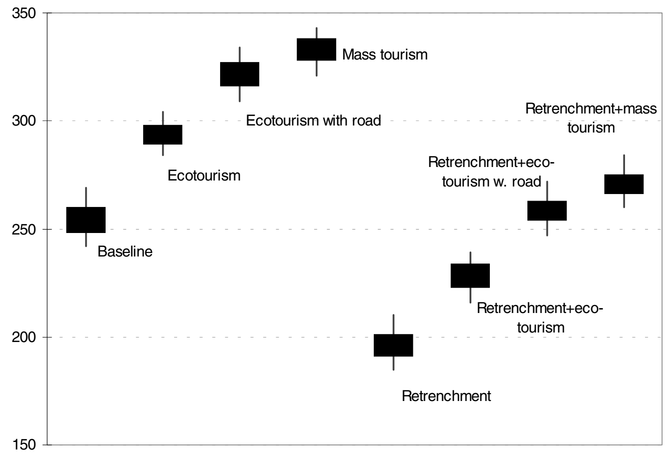

FIG. 4. Year 40 community population under eight employment scenarios, (Monte Carlo Simulation, 100 runs: year 1 population = 235). Bars bracket the 30th and 70th percentiles; lines bracket the 10th and 90th percentiles.

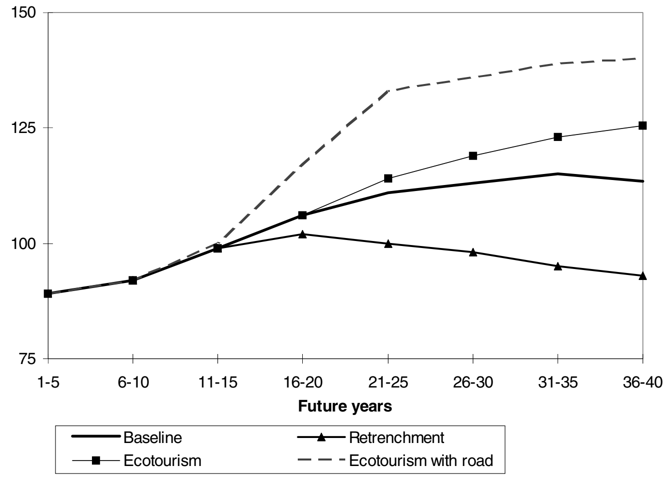

FIG. 5. Median resident households over 40 years under four employment scenarios (Monte Carlo simulation, 100 runs).

of Old Crow and other partner communities, for whom maintaining subsistence hunting and a viable community economy and population remain important goals, despite decades of social change (see Kruse et al., in press).

SIMULATION RESULTS

The model has many randomly varying outcomes, including household assignments, employment, caribou numbers and distribution, climate effects on access, hunting decisions, harvest success, and migration. These uncertainties compound each other, so that the outcome of random variables in one simulation period affects opportunities in future periods. Monte Carlo simulations allow us to view probabilistic outcome paths under such conditions of cumulative uncertainty, or path dependency.

Monte Carlo simulations of the baseline economy show that although employment remains constant, population increases slowly during the first decade. This increase is consistent with observed trends that show a population increase in Old Crow from 235 in 1993 to 276 in the 1996 census. After another decade of slow increase, out-migration begins to exceed natural increase, with population declining in 40 years to a level about 10% higher than the initial level. The number of households increases somewhat more because of long-term demographic changes that imply a gradual aging of the population.

Migration into and out of the community keeps the range of variation in long-term community size under each employment scenario within a surprisingly narrow band (Fig. 4), in spite of the many uncertainties built into the model. The time paths of the median projected number of resident (indigenous) households (Fig. 5) and per-capita income (Fig. 6), however, differ substantially among scenarios. (These figures show results for four representative scenarios out of the eight analyzed.) Expanded tourism development increases community population by as much as one-third if a road is constructed. Government retrenchment without road-supported tourism leads to a substantial loss of income, with subsequent population decline. Ecocultural tourism without a road expands job opportunities but adds little to per-capita income, as most tourism jobs are part-time, seasonal, and relatively low-paid. The large number of part-time, seasonal jobs, however, does enable an adult from virtually all households to find some cash employment.

Jobs and incomes dramatically increase during road construction in road-plus-tourism scenarios, which attract non-indigenous workers as well as indigenous in-migrant households. Upon completion of construction, however, incomes return to near the baseline level, leaving the community larger, but not much better off. Relatively little difference appears between the effects of "hard" and "soft" road-enabled ecotourism, although mass tourism provides slightly greater long-term economic benefits (as Weaver [2002] suggests). Economic and population effects projected from all scenarios involving road construction could lead to adverse social impacts, even without considering the effects of greater access to the community afforded by a road itself. The model does not directly calculate social impacts. However, its economic and demographic outputs provided a basis for discussion among community members about the likely social impacts and ecological pressures of various types of tourism development, and whether the community could take mitigative measures to keep outcomes consistent with community goals.

The caribou harvest varies substantially from year to year in the baseline case, but median per-capita harvest remains virtually constant, at around 3.6 caribou annually. Monte Carlo simulations show that the distribution of outcomes for the lowest annual harvest per decade rises slightly for the first three decades, then declines slightly in the fourth decade (Fig. 7), tracking the community population. Under the baseline economy and assumed effects of climate change on herd size and movement and on hunter access, the range of lowest annual caribou harvest per

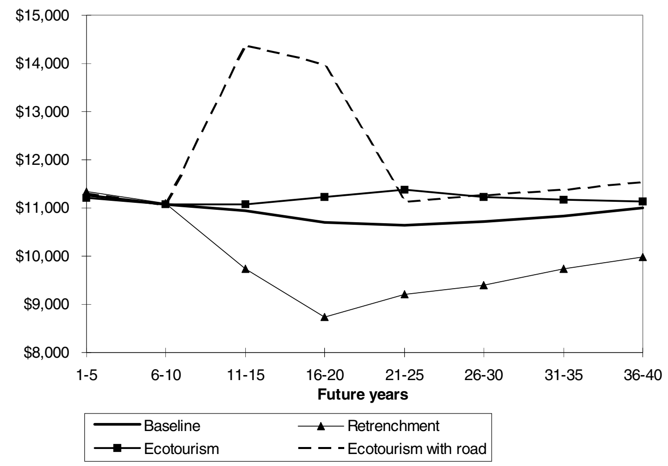

FIG. 6. Median per-capita household income over 40 years under four employment scenarios (Monte Carlo simulation, 100 runs).

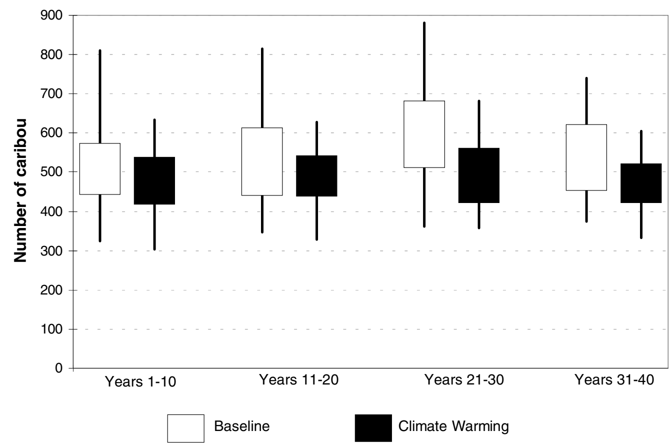

FIG. 7. Lowest annual caribou harvest per decade with baseline economy and baseline and warming climate scenarios (Monte Carlo simulation, 100 runs). Bars bracket the 30th and 70th percentiles; lines bracket the 10th and 90th percentiles.

decade gradually slips toward the lower portion of the distribution of baseline outcomes (Fig. 7). These simulations assume no compensating change in management that might affect Porcupine caribou harvest levels if the population fell this low. In fact, such a fall without a management adjustment is unlikely (see Kofinas et al., 2002b). However, a policy to restrict harvest throughout the range to help maintain the population under an increasingly adverse environment might also require Old Crow hunters to limit harvests. Given the high degree of uncertainty surrounding our prediction of climate effects on caribou, care should be taken with interpreting this result. However, the model does suggest how people might adapt to one possible combination of environmental changes that could occur with climate warming.

The model's rules incorporate a number of social adaptations that mitigate the effects of adverse individual job and subsistence outcomes and thereby increase the resilience of the community to change. Workers unable to find jobs have higher probabilities of leaving the community to find work elsewhere, while new higher-paying jobs attract in-migrants. Gear sharing mitigates the effects of the unequal distribution of rewards in the market economy on household hunting resources. Harvest sharing and community hunts mitigate effects of harvest uncertainties. These adaptations reduce differences in the distribution of economic and subsistence outcomes under differing combinations of job scenarios and climate-related environmental conditions (Table 5).

Men earn slightly more than women in the median runs for all job scenarios (men work less but earn higher wages when working), but the result varies widely because of uncertain assignment of high-paying jobs. Employment by gender affects the model's rules for time and money for hunting, and household income affects the rule for sharing. Nevertheless, the projections suggest that the subsistence economy mitigates risk in the cash economy. Less favorable economic scenarios appear no more likely to contribute to moderate or severe harvest shortfalls (defined as one-fourth or one-half of households, respectively, meeting less than half of defined need). Under the retrenchment scenario, more time substitutes for less money in hunting, and sharing increases when incomes fall.

On the other hand, the subsistence economy has more difficulty mitigating the effects on harvest shortfalls of climate warming (Table 5) or any environmental change that significantly reduces the caribou availability or impedes access to hunting areas. Caribou movements are highly variable. During years when caribou are relatively accessible, harvests remain adequate even with a reduced herd. However, the smallest median projected annual harvest during the final decade is 18% lower in the warming case than in the baseline: 465 animals compared to 559. While the model allows households to substitute time for money in hunting, redistribute gear, share harvests, and undertake a community hunt, these mechanisms together are insufficient to prevent shortfalls during years of low aggregate community harvest.

CONCLUSION

While the eight job scenarios bracket the likely range of future economic opportunities for Old Crow, the ultimate effects of climate change in the region are highly uncertain. Oil development in the coastal plain of Alaska's Arctic National Wildlife Refuge and other as yet unknown resource development projects could affect Porcupine caribou herd size and movements (Griffith et al., 2002). The model makes numerous parameter assumptions for demographic change representing current trends, and it relies on rules for agent behavior under past and present conditions. All of these could change. Despite these shortcomings, the model generates results for near-term outcomes that appear consistent with recent trends. It integrates information from disparate sources and disciplines to generate a set of possible long-term futures with a richness and detail

TABLE 5. Selected sustainability indicators for Old Crow (median of 100 Monte Carlo simulations).

	Baseline	Ecotourism	Retrenchment	Retrenchment + ecotourism
Tourism development	Same as today	Expands gradually	Same as today	Expands gradually
Government spending	Same as today	Same as today	30% decline	30% decline
Population change over 40 years (%)	+8	+23	-15	-3
S.D. (%)[1]	4	4	4	4
Ratio of per capita household income, years 36–40 to years 1–5	98%	100%	88%	90%
S.D. (%)	1	1	1	1
Men's as a percentage of women's average annual earnings, yrs. 36–40	112%	107%	105%	111%
S.D. (%)	23	18	28	20
Percent of households with no one employed, years 36–40	15%	0%	15%	0%
S.D. (%)	2	0.4	3	0.5
Percent of households with inadequate time to hunt, fall, years 36–40	29%	29%	23%	25%
S.D. (%)	2	2	2	2
Climate warming does not occur				
Average caribou harvest per household, years 36–40	8.4	8.4	8.1	8.3
S.D.	1.3	1.2	1.0	0.8
Number of years in last decade in which:				
1/4 of households meet less than 50% of need	1	1	1	1
1/2 of households meet less than 50% of need	1	1	1	1
Climate warming occurs				
Average caribou harvest per household, years 36–40	6.9	7.1	6.7	6.8
S.D.	1.0	1.0	0.9	0.9
Number of years in last decade in which:				
1/4 of households meet less than 50% of need	3	3	2	3
1/2 of households meet less than 50% of need	2	2	2	2

[1] All standard deviations were estimated as one-half the difference between the 84th and the 16th percentiles.

that would be difficult to imagine otherwise. The model is readily generalized, with appropriate changes in baseline parameters and scenarios, to other Arctic communities with similar mixed economies.

Model projections of changes in economic, demographic, and hunting conditions raise questions about whether and how projected changes may affect the social dimensions of sustainability. Will population migration and demographic change affect overall social stability of the community? Will an influx of non-community members for short-term employment in road construction increase community exposure to drugs and alcohol, or can local policies to control alcohol and limit public access to the year-round road adequately mitigate these problems? Community members in Old Crow currently express concern about possible threats to caribou by climate change and industrial development. How might a dramatic decrease in caribou availability affect the psychosocial health of a community that identifies so closely with Porcupine caribou? Could harvest policies help restore the herd, and if so, what is the likelihood that there might be adequate social capital to implement those policies effectively? Although the model does not address these questions directly, it does help identify issues to stimulate discussion among community residents and researchers about possible futures.

Simulation results for Old Crow reveal several insights about adaptation to change that might be explored further. Decentralized risk-sharing mechanisms, including sharing of hunting gear and harvests and migration of individuals unable to succeed in the market economy, increase resilience to economic change. The model suggests that communities like Old Crow appear to be more vulnerable to climate change or other environmental risks than they are to probable economic changes. Households seeking to continue subsistence lifeways must rely substantially on place-based mitigation measures for aggregate harvest shortfalls, such as community hunts, that provide only limited assistance when subsistence resources become less available. The land-claim agreement provides a high level of local autonomy in Old Crow; other Arctic communities with less local control may be more vulnerable to change. Future research with integrated systems models should consider whether the findings are robust after scaling up to a larger region and considering how regional institutions might intervene to mitigate or exacerbate effects of climate change and development.

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APPENDIX. DETAILS OF HUNTING AND MIGRATION MODEL COMPONENTS

Job Suitability

Job suitability is an ordered index of the likelihood that an unemployed local man or woman who has the educational qualifications for a job would be offered, accept, and keep that job. Dividing jobs into 17 occupation categories, the suitability index for each job category is the product of the proportion of males (or females) in a job category and the proportion of Alaska Natives in that job category, calculated from the 1990 Public Use Microsample (PUMS) from the U.S. Census for the rural Alaska region (PUMS region 300). The resulting proportions are then adjusted to the ethnic mix of the labor force in Old Crow from that of rural Alaska by multiplying by the ratio of the proportion of indigenous residents in Old Crow to the proportion of Alaska Natives in rural Alaska.

Hunting Decisions

Each household has the same number of chances of taking a hunting trip, equal to the maximum number of trips for each season. The probability of taking a hunting trip at each opportunity is given by the equation:

$$\text{Hunt probability} = (\alpha \bullet \text{unmet need})^{\beta \bullet \text{multiplier}}$$

where α is assumed to be 0.1 and β is set at 0.3. Unmet need is defined as the household's annual need minus its accumulated consumption, measured as cumulative annual harvest (starting in the fall of each year), minus shares given away plus shares received. Table A-1 shows the values and derivation of the hunt probability multiplier and one of its two components, the household resource index. The weights for the household resource index are derived from Berman (1998) and summarized into three categories: low, medium, and high.

The other component of the hunt probability multiplier is the hunting quality index. This index is derived by placing into three ordinal categories the sum of the area-choice quality indexes for all hunting areas, where each area's index is defined by the loglinear equation:

$$\text{Log (area choice index)} = c_1 \bullet \text{caribou seen} + c_2 \bullet \text{access} + c_3 \bullet \text{area preference}$$

Caribou seen is measured in three categories: none (0), few (1), and lots (2). Table A-2 shows the parameters for the area-choice index weights c_1, c_2, and c_3, as well as the assumptions for accessibility values for the hunting areas modeled in the simulation, derived from Berman and Kofinas (2004).

Migration

Migration into and out of the community is modeled with four probit equations that produce normalized probabilities (z scores) for adult men and women moving out of and back into the community. Return migrants consist of adults who are members of the Vuntut Gwitchin First Nation and their immediate families who had been living outside Old Crow (the reservoir population). The parameters represent incremental effects on the z score for the probability of moving.

TABLE A-1. Parameters for hunting participation.

Hunt Probability Multipliers:	Poor hunting	Fair hunting	Great hunting
Low HH resources	0.03	0.08	0.1
Medium HH resources	0.21	0.56	0.7
High HH resources	0.3	0.8	1
	Low	High	
Thresholds for household resource index	1	3	
	Poor	Great	
Thresholds for hunting conditions index	2	4	
Household Resource Index Parameters:		Index weights	
Scale factor		-1	
Income category (low = 1, med = 2, high = 3)		0.05	
Time category (low = 1, med = 2, high = 3)		1	
	Low	High	
Time thresholds: season months	1	3	
Time thresholds: annual months	7	11	
Income thresholds for harvest sharing ($000s)	25	40	
Income thresholds for gear sharing ($000s)	6	15	
Female/male contribution to hunting time		0.5	

TABLE A-2. Parameters for hunting area choice multinomial logit equation.

Area Choice Index Weights:

	Caribou seen (c_1)	Accessibility (c_2)	Area preference (c_3)
	5	-0.45	1

Hunting Area Accessibility (Days To Complete A Hunting Trip) By Season:

Old Crow hunting area	Summer, fall	Summer-fall, high income	Early winter	Early winter, late freeze-up	Late winter	Spring
Near community	1	1	1	1	1	1
Up Porcupine River	2	2	2	*	2	2
Down river	2	1	2	*	2	1
Crow Flat	3	1	3	*	2	2
South, Lone Mountain	4	3	4	*	3	3
Dempster Highway	4	4	4	*	4	4
North Rampart	4	3	3	*	3	3
Far NE corner	4	3	4	*	3	3

* Not accessible

Specific Area Preference:

Near community	1.6
Down river	-1.1

	Decade			
	1	2	3	4
Probability of late freeze-up if climate warms	0.05	0.1	0.2	0.3

TABLE A-3. Parameters for migration probit equations.

	Women Out-migration	Women In-migration	Men Out-migration	Men In-migration
Scale factor	0.46	0.32	-0.09	-1.30
Ratio of out/in expected earnings	1.15	-1.69	1.99	-0.57
Multi-generational household	-0.64	0.17	-0.80	0.33
Couple household	0.04	-0.51	0.91	-0.31
Single women household	0.65	-0.21		
Single men household			1.54	-0.04
Age 15–39	0.56	-1.14	1.01	-1.05
Age 40–64	1.40	-2.00	2.38	-1.87
Age 65 and older	-1.79	-1.29	-2.92	-1.38
College graduate	-5.96	2.57	-10.00	2.50
Post-secondary	-4.83	2.12	-8.11	2.07
High school graduate	-4.36	1.88	-7.33	1.83
Primary school	-3.99	1.68	-6.69	1.63
Harvest shortfall	0.50	-0.50	0.50	-0.50
Ratio of outside “reservoir” to community population	2.0			
Expected earnings outside ($000s)	College	Post-secondary	High school	Primary
Men	$58	$40	$31	$25
Women	$35	$24	$19	$15

Positive numbers represent increased probability of moving; negative numbers represent decreased mobility (Table A-3). The “expected earnings” numbers at the bottom of Table A-3 are adapted from estimates for Old Crow by Huskey et al. (2004), by converting from U.S. to Canadian currency and adjusting earnings levels to reflect Yukon Territory earnings by gender and education in the 1996 Statistics Canada census. When combined with current gender-based earnings differentials, the equations predict generally higher net out-migration rates for women than for men, consistent with the observations of Hamilton and Seyfrit (1994) for rural Alaska.

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