Illustrating the coupled human–environment system for vulnerability analysis: Three case studies

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The vulnerability framework of the Research and Assessment Systems for Sustainability Program explicitly recognizes the coupled human–environment system and accounts for interactions in the coupling affecting the system's responses to hazards and its vulnerability. This paper illustrates the usefulness of the vulnerability framework through three case studies: the tropical southern Yucatán, the arid Yaqui Valley of northwest Mexico, and the pan-Arctic. Together, these examples illustrate the role of external forces in reshaping the systems in question and their vulnerability to environmental hazards, as well as the different capacities of stakeholders, based on their access to social and biophysical capital, to respond to the changes and hazards. The framework proves useful in directing attention to the interacting parts of the coupled system and helps identify gaps in information and understanding relevant to reducing vulnerability in the systems as a whole.

Sustainability science seeks understanding of the coupled human–environment system in ways that are useful to the different communities of stakeholders. A concern for many of these communities is an improved understanding and projection of the vulnerability of people, places, and ecosystems in the face environmental change, global or otherwise. This concern has generated the search for viable templates by which to frame vulnerability analysis. The Research and Assessment Systems for Sustainability (Sustainability Systems) Program's vulnerability framework (http://sust.harvard.edu) and the multidisciplinary research that informed its development are detailed by Turner and colleagues (1).[m] This framework is predicated on the notion that vulnerability resides in the condition and operation of the coupled human–environment system, including the response capacities and system feedbacks to the hazards encountered. It provides a general framing of vulnerability; the specific variables and relationships to be studied, and the methods for studying them, will vary from case to case (2). Here we review three case studies (two well studied cases in the southern Yucatán and the Yaqui Valley of Mexico and one under development in the Arctic) to illustrate how the framework can be applied.

The two Mexican cases draw on studies undertaken for other research purposes and serve as "test" references in the design of the Sustainability Systems Program's vulnerability framework. Both cases cover relatively small areas that have experienced the neoliberal changes underway in Mexico's rural economy. The two cases diverge in that the southern Yucatán represents a development frontier in which agriculture and eco-archaeo-tourism compete for use of tropical forest lands, whereas the arid Yaqui Valley is a rapidly developing commercial agricultural center predicated on irrigation. The third case study, the Arctic, is in the planning stage and emerged from within the Sustainability Systems Program iteratively with the development of the vulnerability framework. The expansive Arctic region experiences changes directly tied to global processes, affecting its sensitive biophysical systems and altering the expectations of its occupants.

The Southern Yucatán Peninsular Region

The Sustainability–Vulnerability Issue. Southeastern Mexico retains parts of the largest continuous expanse of tropical forests in Middle America, stretching across Guatemala and into Honduras (3–7).[n] That part, located in southeastern Campeche and southwestern Quintana Roo, the 22,500-km^2 southern Yucatán peninsular region (Fig. 1), experienced extensive, state-led development beginning in the late 1960s. *Ejidos* established across the region led to a 10-fold increase in population by 2000 and launched significant deforestation (7). In the late 1980s, however, Mexico determined to remake the economic value of the region through the forest and the Maya ruins beneath it. The government established the Calakmul Biosphere Reserve (CBR) in the center of the region (8). El Mundo Maya (EMM), a plan to develop eco-archaeo-tourism throughout the Maya lowlands, and the Mesoamerican Biological Corridor (MBC) program, aimed at the sustained movement of biota across Middle America (9), build on the CBR. The search is now underway to reconcile the decidedly different goals of the principal stakeholders controlling the land resources of the region: to maintain and increase the agricultural food stocks and income of the *ejido* farmer and to maintain a mature forest for the biotic diversity and carbon stocks central to the roles of the CBR, EMM, and the MBC.

Change and Variability in the Coupled System. The region is a rolling, karstic upland, ranging from 100 to 350 m above mean sea level, interspersed with large solution sinks or *bajos*. A north to south rainfall gradient ranging from 900 to 1,400 mm·yr^{-1}, respectively, supports a seasonal tropical forest (7, 10). A mature upland forest takes ≈25 yr to regain species abundance after being cut for cultivation, and forest biomass recovery can take 55–90 yr (3, 7, 11). Late-stage successional growth and mature upland forests increase carbon stocks and, ostensibly, wildlife abundance, and apparently provide the conditions required for the seasonal migration of some larger fauna (12).

Abbreviations: CBR, Calakmul Biosphere Reserve; EMM, El Mundo Maya; MBC, Mesoamerican Biological Corridor.

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[m]This case study assessment does not repeat the literature reviewed by Turner and colleagues (1), and the reader is directed to that paper for the literatures relevant to the general observations made in this study.

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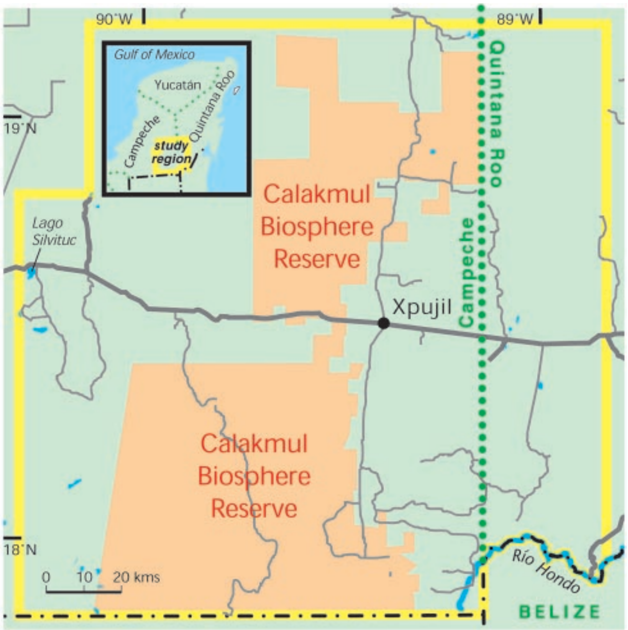

Fig. 1. Southern Yucatán Peninsular Region, Mexico.

Deforestation in the region escalated in the late 1960s with planned occupation, leading to the region's placement on various lists of "hot spots" of tropical deforestation (4). Between 1969 and 1997, the area cleared for cultivation and pasture, including successional growth, increased in by 974 km^2 (287%) within the central portion of the study region alone. This and subsequent deforestation followed from the growth in the number of *ejidos* (usufruct tenure) from 14 to 45 between 1967 and 2000, accompanied by a "legal" population that increased to 39,000 (3).

Almost all *ejido* farmers cultivate maize for subsistence and, increasingly, undertake commercial chili production, giving rise to a fragmented landscape of opened and successional forest land. After three crop–fallow cycles, reduced forest productivity suggests soil or land degradation (3, 11) and, along with burning to clear land, may contribute to plot invasion by bracken fern (*Pteridium aquilinium* L.). The region conservatively holds $\approx$6,000 farming households cultivating, on average, $\approx$4.6 ha·yr^{-1}, and thus requiring a minimal total of 276 km^2 of cropped land annually (7). This area is further enlarged to nearly 1,500 km^2 (year 2000) by lands given to pasture, invaded by bracken fern, and in fallow.

Despite the recent authorization to privatize *ejido* lands and various Non-Governmental Organization (NGO)-sponsored initiatives promoting agro-forestry, few commercial agricultural activities have proven economically viable in the region. Of these, chili production for the national market has had the most success. By the mid 1990s, >50% of the households across the region grew commercial chili and as much as 85% of those in *zonas chileras* did so (3, 7), generating high rates of deforestation and landscape fragmentation along the southern road skirting the eastern border of the CBR (Fig. 1). Increasing reliance on commercial chili production has raised household income but simultaneously driven large swings in this income. Chili is water-, pest-, and disease-sensitive and subject to crop failures. In addition, the price of chili in the region is highly variable. In good years (sufficient rain, few pests, and a strong chili market) *chileros* yield as much as $N18,000 ($\approx$$1,800 U.S.) per household. In a bad year, however, they may not harvest their crop and may lose all of their investment (3).

With the establishment of the CBR in the 1990s, Mexico officially recognized most of southeastern Campeche as a "green" district, complete with the goal of "sustainable development." Variously enforced rules pertaining to land use within and adjacent to the CBR and part of the MBC followed, intended to reduce deforestation and intensify the use of extant open land. PROCAMPO (a federal program assisting in the neoliberalization of rural Mexico), for example, provides direct payments based on 1994-cultivated land in maize and several other crops (7, 13). Household-controlled land is thus under cultivation more frequently than in the past, although farmers use much of the payments to clear additional forest for pasture, an unintended consequence of a program seeking to intensify cropping.

The Application of the Vulnerability Framework. The southern Yucatán peninsular region experiences at least two readily apparent environmental hazards (water stress and hurricanes). Seasonal tropical forests are adapted to water stress, dropping foliage during the dry season (14). Farmers respond to this stress by taking an early dry-season catch crop. Severe hurricanes knock down large stretches of forest, as Janet did in 1955, and subsequent dry-season fires can open large tracts of land ripe for bracken fern invasion, arresting forest regrowth for multiple decades. Hurricanes arrive during the main harvest period, damaging crops, especially chili, by winds, rain, and floodwater. A fragmented landscape creates more forest edges exposed to severe winds, damaging near-edge trees, and a more open landscape yields less wind protection for crops.

Households seek to reduce the risk of crop losses and increase output. Land-use intensification, however, increases vulnerability to several hazards, such as crop pest and diseases, exacerbated by the sensitive chili crops and the volatile farm-gate prices for chili. In contrast, the CBR, EMM, and the MBC seek to reduce losses of mature forest cover and its carbon and biotic stock. Beyond hurricanes, vulnerability for these entities involves farm-driven deforestation, including unintended fires, and the landscape conditions created by it.

More farming households means more forest cleared for cultivation, and while new lands awarded for *ejidos* have been reduced dramatically with the creation of the CBR, landless migrants have increased in number, increasing land pressures on *ejidos* or illegally squatting on CBR lands. Land pressures also mount from increasing commercial chili production in terms of the amount of land taken to and the frequency of cultivation (3). Increasing proportions of household production are more sensitive to drought, disease, pests, thin markets, and the risk of losses to the investments made in fertilizers, pesticides, labor, and even tractor-tilling for chili cultivation (3).

Agricultural changes underway throughout the region, including those along the edges of or within the CBR, not only open and fragment the landscape, they may be depleting soil nutrients, as identified by reported losses in crop yields since the 1970s (3). Large-scale landscape burning is related to bracken fern invasion. Once established in large areas, farmers may refuse to combat it and compensate for lost croplands by clearing more forest land. From 1987 to 1997, the area covered by bracken fern increased by 74 km^2 to consume 92 km^2 (7), much of it along the edge of the CBR.

These landscape changes, and the vulnerabilities that they carry, run counter to the goals of those programs mandated to protect forest cover and ecosystems or seeking to transform the region into a "green" economy. These changes threaten to reduce forest cover, biota, and carbon stocks. In turn, various rules and programs designed to make farming compatible with the goals of the CBR, EMM, and the MBC and the region a sustainability exemplar for Mexico have contributed to the frequency of cultivation on *ejido* lands, in many cases without the necessary inputs to sustain it, and to the unintended outcome of pasture expansion.

Gains and Gaps in Understanding. Changing federal vision and policy concerning the value and use of the southern Yucatán have significantly shaped the human–environment conditions present in the region today, contributing to the contrasting vulnerability

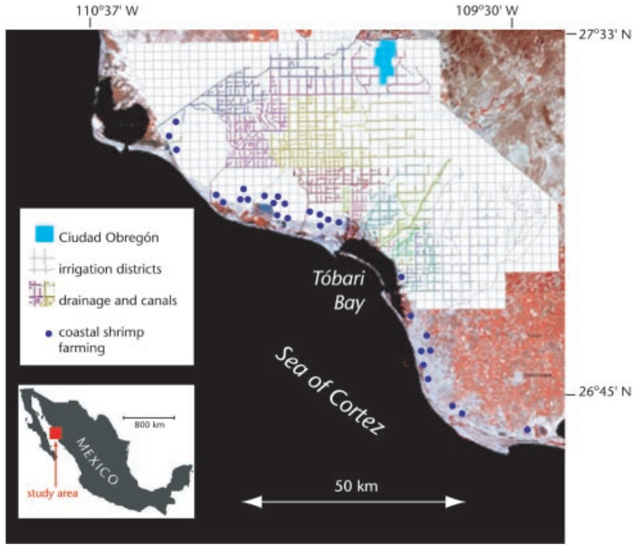

Fig. 2. Yaqui Valley, Sonora, Mexico.

concerns of farmers and "green" managers and signaling the complexity and scalar dimensions of vulnerability analysis. Although hurricanes and droughts are transparent hazards, the amplification of their impacts by land-use decisions that create a more open and fragmented landscape and the expansion of bracken fern are not. Indeed, bracken fern emerges as a "new" hazard in the operation of the coupled system. These linkages and dimensions are revealed regardless of a hazards-to-consequences or consequences-to-hazards orientation of study, although the last may direct more attention to the decision rationales of the several stakeholders in the human subsystem. Use of the vulnerability framework suggests that response options require attention to the dynamics of coupled systems to facilitate the identification of potential perverse outcomes, such as the expansion of pasture created with funds intended to intensify land use and reduce forest cutting and burning.

The Yaqui Valley

The Sustainability–Vulnerability Issue. The lower Yaqui Valley of Sonora, Mexico (Fig. 2), includes a 235,000-ha irrigation district and surrounding desert and coastal lands in southern Sonora and is home to ≈500,000 people.[o] The district hosted the birth of the Green Revolution for wheat and remains a productive breadbasket with 235,000 ha of irrigated, wheat-based agriculture critical to the Mexican economy (15). The Yaqui River and the valley's drainage network empty into the estuaries of the Gulf of California (Sea of Cortez), transferring effluents from agricultural run-off, urban centers, and pig farms. The coastal systems provide critical habitat for migratory and resident waterbirds, marine mammals, and fish (16), and constitute an important center for both subsistence and export fishing industry. Valley stakeholders (farmers, fisherfolk, and land–water managers) are concerned about sustaining yields and maintaining household incomes in the face of globalized markets, reduced subsidies and price supports, drought, and other forces, while being confronted with reductions in water quality and quantity, the salinization of agricultural soils, and "downstream" impacts of agriculture and other forms of development. Vulnerability to these hazards appears to vary across Yaqui Valley stakeholders.

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Variability and Change in the Coupled Human–Environment System. The entire northwest coast of Mexico is arid. Winter monsoons trigger highly variable annual and decadal rainfall averaging 270 mm·yr^{-1}. The natural ecosystems of the valley are likely to be adapted to variable climates and occasional prolonged droughts; the agricultural system is far more sensitive to these variations. High winter rainfall lowers yields in winter wheat. Prolonged droughts, such as the unusually extended period of low rainfall since 1994, lead to dramatic declines in total reservoir volume. Currently installed groundwater wells do not have sufficient capacity or quality to buffer reduced surface water storage, and delivery of water to farmers has declined from a long-term average of 2,655 million m^3 to 1,100–1,700 million m^3 over the past 5 yr (17).

Winter wheat dominates production and has done so for four decades, growing from an average area of 130,000 ha in the late 1970s to 190,000 ha in 2002 (15). However, some farmers continue to diversify and experiment with new crops in response to market and policy signals, as well as pests (15). Planted hectares of cotton have declined since the 1950s, while alfalfa, garbanzo beans, vegetables, and fruit crops have increased. The proportion of vegetables planted increased 8-fold from the early 1980s, and the proportion of fruit trees quadrupled over the past 10 yr. Soybean cultivation dropped from 120,000 ha to 20 ha in a 3-yr period in the mid-1990s because of a whitefly infestation (18) and was replaced largely by summer maize requiring more water and fertilizer input.

The use of fertilizer N has increased markedly; between 1968 and 1995, fertilizer application rates for wheat production rose from 80 to 250 kg of N per ha. The current fertilization practices lead to large N losses to the atmosphere, ground, and surface waters (19–21). Canals drain tillage water rich with N and other agricultural chemicals directly to the gulf (22), potentially posing a threat for economically important coastal ecosystems (23).

As agricultural development and intensification proceeds, concerns about salinization increase for about one-third of the valley's soils situated in the lower-lying portions of the valley and often associated with poor drainage and high water tables. Today, salinity levels threaten to reduce productivity by over ≈19,000 ha; management practices that reduce ground water tables, along with the use of large amounts of relatively low-salt freshwater in irrigation, prevent much broader salinization problems but rely on large supplies of freshwater.

These conditions prevailed throughout the 1980s and early 1990s within a protective federal policy of price supports for crops and input subsidies on water, credit, and fertilizer (15). Neoliberal reforms have effectively shifted responsibility for agriculture from the government to the private and *ejido* sectors, the impacts of which include (15):

- development of a 15-yr program of direct income payments to farmers (PROCAMPO), linked to the abolition of subsidies and price supports;
- reduction in the government's involvement in agriculture, including privatization of the Mexican Fertilizer Company (FERTIMEX) and removal or reduction of government credit subsidies (BANRURAL);
- decentralization of operating authority and funding responsibilities for irrigation systems to local water user groups via the Water Laws of 1992 and 1994;
- amendment of Article 27 of the Constitution of Mexico, which made possible the legal sale, rental, and mortgage of previously inalienable *ejido* land, providing *ejido* members transferable titles to their land; and
- adoption of the North American Free Trade Agreement (NAFTA), which led to large changes in the prices of many agricultural inputs and outputs.

Application of the Vulnerability Framework. Irrigation supports the large-scale agricultural economy of the arid Yaqui Valley; thus a major hazard–consequence linkage in the system is water and production/profit shortfalls. The current 7-yr drought has reduced reservoir levels and allocations to farmers (see above). Farmers have adjusted to this stressor by reducing the number of irrigations and the hectarage in crops, primarily by eliminating summer production and experimenting with less water-intensive crops like sunflower and safflower (15). In addition, the pumping of water from aquifers has increased. Too saline to apply directly to fields, most aquifer water is mixed with surface water until acceptable salinity levels are reached. In addition to the use of publicly owned wells, the irrigation district "purchases" water from ≈50 private well owners by providing them access to additional deliveries of surface water for use or sale. The variation in access to low-saline water may contribute to differential vulnerabilities to drought among the valley farmers.

The irrigation districts of the valley have recently augmented their groundwater pumping capacity through new wells and are considering increased pumping of saline groundwater to provide additional flexibility in water allocation. The variable salinity characteristics of the valley's soils, however, suggest different responses to the "mixed" irrigation water, with some soils potentially more sensitive and easily salinized than others. Thus, soil characteristics constitute another form of natural capital that affects vulnerability to drought.

The dominance of the agricultural economy in the valley makes production and profit shortfalls a dominant concern. Working from these consequences reveals other critical linkages in the system, and hazards. As water conditions and commodity markets change, farmers experiment with new crops and are faced with insufficient cropping system information, new pests and diseases, and new interactions with global and local policies. The effects of and uncertainties related to markets and policy reforms are additional stressors, and again, there appears to be differential ability to respond to them. In particular, they may have differential and significant impact on *ejidos*, which before 1990 accounted for ≈56% of the total agricultural area and 72% of producers in the valley (24). For example, banking reforms affected BANRURAL (National Rural Credit Bank), leading to a reduction in the number of *ejido* farmers receiving credit and total expenditures on subsidized interest, and making it difficult for small private and *ejido* farmers to secure loans and access credit (a form of social capital; ref. 15). At the same time, changes in Article 27 allowed *ejido* land to be rented, sold, and mortgaged. By 1999, 70% of interviewed *ejido* farmers rented their land, largely to private landholders (25), and almost all of these farmers reported difficulty in accessing credit as a primary reason for renting. Likewise, increased real prices for water and fertilizer inputs were noted as impediments to farming. For Yaqui Valley *ejido* farmers, therefore, the high production costs of cultivation were not adequately compensated in the restructured political economy (15, 25), making renting or selling of land attractive. In some case, rental rates raised household incomes relative to their own engagement in farming (25), but the longer-term impacts on these households is not known, especially with the sale of land and the potential break-up of *ejidos*. The impact of the "concentration" of farm production among fewer farmers with regard to the efficiency of water use and other inputs is not known.

Gains and Gaps in Understanding. Even a cursory assessment of vulnerability in Yaqui Valley reveals the need to address multiple and interacting hazards from the perspective of stakeholders operating with different levels of natural and social capital. Recent shifts in federal policy stimulated by international pressures have changed the economic structure of agriculture, incidentally at a time of prolonged drought, leading to changing farm impacts and responses and giving rise to an additional stressor on farming: irrigation water salinity. By focusing on the coupled system, the complexity of many dimensions of vulnerability analysis is revealed. We see that household sensitivity and responses to hazards depend in part on household access to biophysical resources, as well as to social resources. In turn, distinctions in access lead to significant differences in individual household vulnerability and response options. The structural changes in the economy, directed from afar, portend significant impacts on farmers, especially *ejido* farmers, but the long-term consequences for the coupled systems are uncertain. Potential shifts in precipitation patterns with climate warming raise signals about the long-term viability of large-scale irrigation as it is practiced today, and the responses to drought and policy changes underway in the valley have implications not only for the agricultural sector but for Gulf of California systems.

The Arctic

The Sustainability–Vulnerability Issue. Environmental and social changes have had and are expected to have significant effects on the sustainability of coupled human–environment systems in the Arctic.[p] These systems experience climate change and variability, ozone depletion, and environmental pollution, as well as transformations associated with self-determination, technological innovation, global trade, urbanization, oil and gas exploration, and tourism (26). The Sustainability Systems Program vulnerability framework guides the development of a comprehensive study of these factors and the challenges they pose for the Arctic region. Preliminary analysis and site visits have led to refinements in the framework itself and to the formulation of methodologies to facilitate its application. Here, the framework is explored for two locales in the Arctic: Uummannaq, Greenland, and Finnmark, northern Norway.

Variability and Change in the Coupled Human–Environment System. The Arctic is undergoing rapid and dramatic changes. Winter temperatures in many inland Arctic regions have warmed 2°C per decade over the past 30 yr (27), as evidenced by the thawing of once permanently frozen ground (28–30) and changes in the geographic ranges of animals. Storm surges have increased coastal erosion in the Bering Sea. Arctic Sea ice extent has decreased by 3% per decade between 1978 and 1996, and summer sea ice thickness has decreased by 40% since the 1950s (31). Since the early 1990s, northern latitudes have episodically experienced up to 20% reductions in stratospheric ozone and >40% increases in UV radiation (32). Over the past century, precipitation in high latitudes increased by 15%, with most of the increase occurring during winter months within the last 40 yr (33). The Arctic Monitoring and Assessment Program (AMAP) concluded that although the Arctic is a relatively clean environment, it continues to suffer from significant pollution hazards (34), especially with regard to heavy metals (HM) and persistent organic pollutants (POPs). Levels of pollutants in native populations are some of the highest measured in the world. Native Arctic peoples have also experienced significant social changes over the past 30 yr (35, 36), establishing new relationships between local and national governments, becoming more closely connected to external markets and ways of life, and asserting their identity, rights, and culture in legal and policy forums.

In the face of these developments, four overarching research questions guide the Arctic study:

- How are Arctic social and biophysical systems suitably characterized and coupled for analysis within a vulnerability framework?
- What social and biophysical conditions contribute to the major hazards affecting the coupled systems?
- In what ways are the coupled systems most vulnerable?

[p]Activities supported by the Sustainability Systems Program at Harvard University, the National Oceanic and Atmospheric Administration, University Center for Atmospheric Research, the Office of Naval Research, and in-kind sources associated with international and national institutions in the Arctic and other locations.

- What can be done on local, regional, and global scales to address these vulnerabilities?

Based on preliminary consultation with a sample of local stakeholders regarding the Arctic region as a whole, three kinds of stressors are identified for further analysis: (*i*) variability and change in climate and climate variability and UV radiation (e.g., snow cover, permafrost, sea ice, and extreme weather events), (*ii*) environmental pollution [dichlorodiphenyltrichloroethane (DDT), polychlorinated biphenyls (PCBs), hexachlorocyclohexane (HCH), and lead, cadmium, and mercury], and (*iii*) human and societal trends (e.g., consumption, governance and regulation, and markets and trade). The significance of these changes among different cultures, age groups, and economic sectors appears to be large. A cursory but on-going dialogue with several stakeholders in two locales (below) reveals several broadly constructed consequences to be avoided. These are threats to human health and well-being, indigenous cultures and food security, and human settlements and development.

An evaluation of the hazards and their consequences for different coupled systems is planned based on an analysis of change from 1980 to present, and prospectively to 2020 (± 10 yr). Information on hazards and impacts will be combined in a participatory phase in which residents of each site take part in the research process through workshops, interviews, focus groups, and other mechanisms by, in part, describing the changes observed in the biophysical system they occupy, their coping and adaptive capacities, and the major outcomes they seek to avoid. Using this information, site- or region-specific vulnerabilities of coupled human–environment systems will be examined by the hazard-to-consequence and consequence-to-hazard approaches illustrated below for two example cases.

Application of the Vulnerability Framework. Uummannaq is a municipality covering 93,000 km^2 (12,500 km^2 ice free, 64,500 km^2 ice covered, and 16,000 km^2 water) on the west coast of Greenland, located 590 km north of the Arctic Circle (Fig. 3). The Inuit dominate the population of nearly 3,000 engaged in a mixed market-subsistence economy. Seals and whales are hunted primarily for local consumption. Fishing is undertaken also for local consumption and by capital-intensive commercial businesses. The coupled human–environment system in Uummannaq is exposed to potential risks from multiple hazards operating at different scales. Climate change affects the distribution and movement of animals as they respond to changes in temperature, sea ice, and snow cover.

Fig. 3. Uummannaq, West Greenland.

Fig. 4. Finnmark, Norway.

Pollution, largely from sources outside the Arctic, leads to the bioaccumulation of contaminants in fish, seal, and caribou. These changes combine with those related to "globalization" (increasing international trade, the broadening scope of resource policy, and externally influenced values and attitudes) to create opportunities and constraints for the residents. Many biophysical changes, for example, interfere with the ability of the Inuit to interpret environmental indicators, with implications for the diminishing size and quality of their harvests. These dynamics interact with growing dependence on distant fish markets and the increasing authority of local-to-state governance in setting quotas and otherwise regulating the harvesting of marine resources. The changes underway could overtax the adaptive capacities of the Uummannaq's coupled systems (37), reducing the importance of kinship and family as the center of social organization around fishing and leading to divisions within and between fisher and hunter organizations.

Finnmark, the northernmost, largest, and least populated county of northern Norway covers nearly 46,000 km^2 and is inhabited by $\approx$74,000 people (38). Finnmark is located within Fennoscandia, a region that extends across 300,000 km^2 of northern Norway, Sweden, and Finland, and is inhabited mainly by the Sami (Fig. 4). Reindeer herding constitutes the most important form of land use in the Eurasian Arctic and among the Sami. Herders from 24 different ethnic groups in the study area move their animals over a heterogeneous environment of mountain and tundra/taiga pastures (39). Climate variation, which appears to play a major role in determining the productivity of northern grazing systems, shows high amplitude and significant unpredictability, and may contribute to fluctuations in herd size (40). Other potentially important factors that could interact with climate impacts include: changes in the availability and quality of herding habitat, particularly losses to infrastructure (e.g., roads and pipelines); international conservation treaties and herding-related regulations (e.g., rights to grazing lands); the presence and regulation of markets, including effects on subsidies and import tariffs; the adoption of new technologies, such as the snowmobile, accompanied by increased desires for material goods and greater inflows of cash, affecting production requirements for herders and contributing to larger herd sizes and changes in herd structure (41); and widespread commercialization of reindeer husbandry, making herders more integrated in Scandinavia's cash economy and more sensitive to market fluctuation in the price of reindeer meat (41).

Gains and Gaps in Understanding. Preliminary analysis suggests that the coupled human–environment systems of Uummannaq and Finnmark are affected by decisions and activities conducted at both great distances from the Arctic and different governance levels within the Arctic. These decisions and activities are often beyond the direct control of the inhabitants of the two study locales, but they affect ecosystem function and human–environment interactions, potentially giving rise to new, system-wide vulnerabilities.

Pilot work demonstrates that a comprehensive vulnerability analysis in the Arctic must draw on qualitative and quantitative information, and novel approaches. For example, some climate data for the Arctic region must be translated to more local-scale climate information by downscaling from General Circulation Model output. Pollutants in various media are measured directly, and statistical information exists for certain socioeconomic factors. These data and the methods to produce them, however, insufficiently cover the range of issues that must be considered, especially with regard to the impacts on and adjustments of livelihood systems that require the use of qualitative information. Understanding of livelihood as well as ecosystem dynamics requires input from Arctic inhabitants.

Reflections on the Vulnerability Framework

A full vulnerability assessment is no easy task given the complexity of factors, processes, and feedbacks operating within even relatively simple coupled human–environment systems. The difficulties of the task are amplified by scalar dynamics, be they global processes operating on the local system of assessment, the asynchronous character of important social and natural processes, or the various, even incompatible goals of the different stakeholders in the system. Indeed, a full vulnerability assessment following the framework developed by the Sustainability Systems Program may lie well beyond the capacities of most research efforts. Yet this general conceptual framework provides a useful point of departure for examining vulnerability. For practical and theoretical reasons, such frameworks should be modified (simplified) to suit the specifics of a given application. The framework presented here also directs assessments to consider the gaps in their understanding and the variation in views held by and impacts on stakeholders. Thus, it affords insights about additional information and understanding required in the assessment and the possible uncertainties and potential "surprises" that might be encountered.

The three case studies illustrate these points. These distinct coupled human–environment systems prove to be quite complex with regard to their vulnerability (exposure, sensitivity, and resilience) to environmental hazards, affected by social and biophysical processes and flows within and across the boundaries of the systems. In each case, external political and economic forces are reshaping regional and local environmental uses and coping capacities. Local stakeholders voice different concerns about these changes and are active agents responding differently based on their individual understanding and capacities.

The vulnerability framework used steered the case studies toward integrated analyses, linkages and feedbacks within and beyond the coupled system in question, and the complexity involved in reaching a comprehensive vulnerability assessment.

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