MEASURING VULNERABILITY:

A TRIAL INDICATOR SET

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Many attributes of societies and the environment are potentially vulnerable to climate change. Governments who took part in the IPCC Second Assessment Report (SAR) (Watson et al. 1996) requested information on potential impacts for 18 distinct environmental systems/processes or socio-economic activities, including forests; rangelands; deserts; land degradation; mountain regions; wetlands; the cryosphere; oceans; coastal zones and small islands; hydrology and fresh water ecology; water resources management; infrastructure (industry/energy/transportation); settlements; agriculture; fisheries; forestry; financial services; and health. For the purposes of this exercise, the IPCC SAR classification was too fragmented; potential impacts were aggregated into four domains—food sensitivity; ecosystem sensitivity; settlements/infrastructure sensitivity, and human population health sensitivity. Three categories of coping capacity indicators were created to represent overall economic capacity, human resources, and renewable natural capital. In the process used to construct the index, proxy variables were aggregated to produce scores for each of these seven categories; then separate scores were calculated for each country's overall sensitivity and coping capacity; in the final step of the process, these scores were aggregated into a summary index of climate-change vulnerability. Details will be provided for each indicator category.

Procedures

Indicator computations

Using the proxy variables, sensitivity, coping capacity, and overall vulnerability scores to represent current (i.e., 1990) conditions are calculated for each geographic unit (in this case, sample countries) using 1990 data from a variety of sources. These baseline scores are scaled to US values for 1990 to facilitate comparisons. The seven countries include Brazil, China, India, Japan, Senegal, Spain, and the United States; they were selected to provide a geographically and socio-economically diverse sample of developed and developing countries.

Using these baseline values as a starting point, we then examined the evolution of the vulnerability of the seven selected countries under different socio-economic and climate scenarios. To do this, we scaled the baseline values for the countries using regional outputs from PNNL's MiniCAM (Edmonds et al., 1997) forced by several different socio-economic/emissions scenarios (IPCC, 2000). MiniCAM is a multi-sector modeling framework that includes information on economic activity, energy-related GHG emissions, conventional air pollutants, agricultural production, and land use. It produces projections of atmospheric composition, radiative forcing, temperature, and sea-level rise based on assumptions of socio-economic conditions and energy technology. A post processor (Pitcher, 1997) was used to calculate changes in some socio-economic variables that are not part of the standard model outputs, but for which relationships with model outputs are postulated in the literature. Regional outputs used were from Latin America (Brazil), China, SE Asia (India), Japan, Africa (Senegal), OECD Europe (Spain) and the USA. The percentage change in MiniCAM results for a given period of time was used to scale the national 1990 data, which were then used to recalculate the indicators in 15 year increments. The procedure is broadly analogous to that used to scale the spatial pattern of climate projected by GCMs with outputs from energy balance models.

Socio-economic scenarios

The scenarios used in our experiment are based on the new IPCC scenarios (Nakicenovic et al. 2000) for analysis of greenhouse gas emissions. They are quantitative representations of different human futures in

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which economic growth, demographic trends, technology sets, and other factors (e.g., human preferences) lead to different emissions trajectories, levels of climate change, sensitivities, and capacities for coping. While the scenarios were initially developed for analysis of emissions, the possible futures represented also would be expected to lead to very different levels and types of vulnerability. The challenge in this experiment was to have the indicator reflect these differences. The scenarios are summarized in Table 1 and described in greater detail below.

Table 1: Summary of variants of IPCC SRES scenarios used in this experiment

"Storyline"	Population	Gt C/yr	ΔT	Implications for vulnerability
B2 Local solutions to sustainability	10 billion (UN medium)	22	2.96	+improved local coping capacity +global environmental stress but local resilience
A1 Rapid growth with economic "convergence"	9 billion 2050 7 billion in 2100	17.3	2.47	+high levels of wealth +median global levels of forcing, high levels of local environmental stress
A2 Regional blocks with differentiated success	15 billion	27.1	2.88	+low levels of wealth +high levels of environmental stress both globally and locally
A2 to A1 Delayed development	17 billion (?)	21.3	2.31	Initially high vulnerability, reduced over time

In the "rapid growth" scenario (IPCC A1), economic development is a robust three percent annually to 2100, with per capita income reaching US$21,000 by 2050. Over time, current distinctions between "poor" and "rich" countries are eliminated. Affluence is correlated with low mortality and fertility—global population grows to some nine billion by 2050 and declines to about seven billion by 2100. Most of society experiences great improvement in the health and social conditions. With the rapid increase in income, dietary patterns shift towards increased consumption of meat and dairy products. High incomes also translate into high car ownership, dense transport networks and sprawling suburbanization. These factors along with high wages result in a considerable intensification of agriculture. Several variants reflect the uncertainty in development of energy sources and conversion technologies. In the scenario used here, annual CO_2 emissions are 17.3 GtC in 2100, with average temperature increase of 2.47°C. In this world, social and economic coping capacity would be presumed high, although ecological systems would be expected to be stressed and, for the most part, highly managed.

In the "local sustainability" scenario (B2) there is increased concern for environmental and social sustainability, with an emphasis on strengthening the community and achieving local self-reliance. International and national institutions decline in importance and local decision-making structures and institutions are greatly enhanced. Human welfare, equality, and environmental protection all have high priority and are addressed mainly through community-based social rather than technical solutions. Income per capita grows at a moderate rate to reach about US$12,000 by 2050. International income differences are reduced considerably. Education and welfare programs lead to reductions in mortality and fertility, with the population reaching about 10 billion people by 2100. Environmental protection is a priority, although strategies to address global environmental challenges are less successful than in other scenarios. There is a gradual reduction in the current reliance on fossil resources, but the energy supply is still predominately hydrocarbon-based even in 2100. In the variant of the scenario we use, this scenario results in annual CO_2 emissions of about 22 Gt C by 2100, corresponding to mean temperature change of 2.96°C. In this world, there is less wealth for adaptation, but social networks would be presumed to be more effective. Ecosystems would also be under less stress than in the rapid growth scenario.

The third scenario we used was a variant of two scenarios called "delayed development" (A2 to A1). In this scenario, economic development in Africa and parts of Asia and Latin America is retarded because of continuing institutional setbacks. There is more international conflict and less cooperation. People, ideas,

and capital are less mobile so that technology diffuses slowly, with the result that international disparities in productivity, and hence income per capita, are maintained or increased. Fertility rates decline only slowly, although they vary among regions, and high population growth results in a population of 15 billion by 2100) with low income per capita, at US$7,000 in 2050. Some attention is given to potential local and regional environmental damage (sulfur and particulate emissions are reduced in Asia) but this is not uniform (SO_2 emissions increase in Africa as a result of the intensified exploitation of coal). The delayed development world is one of high energy and carbon intensity, and correspondingly high GHG emissions (21.3 GtC/yr in 2100), with corresponding temperature change of 2.31°C in 2100. Vulnerability would be expected to vary from location to location but would be particularly high in those areas where economic development is delayed, population growth remains high, and environmental problems are not addressed.

"Backcasting" test for plausibility

To test whether the projections developed were plausible, we used historical data to conduct a "backcasting" exercise. Historical trends were calculated from linear fits to data as a first approximation, and the rates of change in the historical series were compared to those in the model-based projections.

Proxy variables used in calculating the indicators of sensitivity and coping capacity

Table 1 lists the proxy variables and key hypothesized relationships that were used in constructing the subcomponents of the vulnerability index. The point is not to argue that these selections are necessarily the final or "best" choices for proxies, but to illustrate the sort of relationships that will need to be explored in greater depth in the process of moving from testing of this prototype indicator system to full-scale implementation.

Sensitivity indicators

Food sensitivity

Food sensitivity is defined as the potential for changes in the availability of food in a particular geographic area. It encompasses both production of principal foodstuffs (e.g., crops, livestock, fish) as well as socio-economic issues such as type of production system, access to production inputs that can offset changes in climatic conditions, and access to markets for purchase of food. Climate variability and change can affect food sensitivity through a variety of mechanisms, particularly related to food production. Variability in temperature and precipitation affects crop production directly, as well as through impacts on soils (e.g., erosion), pest and disease outbreaks, and other mechanisms. In addition, floods, droughts and periods of extreme temperatures can affect livestock and fisheries production (Stern and Easterling 1999). Climate change is projected to have impacts on agricultural production through these mechanisms, as well as through changes in atmospheric concentration of CO_2, which affects productivity and water use efficiency, particularly in C_3 plants. Impacts on agricultural production may also be felt through changes in availability of water resources for irrigation. (Reilly et al., 1996). Climate variability and change also cause changes in livestock and fisheries production through a variety of mechanisms (Reilly et al., 1996; Allen-Diaz, et al., 1996; Everett, et al. 1996).

Two proxies have been selected to represent food sensitivity in this experiment. Cereals production per unit area is intended to capture the degree of modernization in the agriculture sector and the access of farmers to production inputs that can be used to buffer against the effects of climate variability and change. Systems with higher production per unit area are presumed to be less sensitive than those with low production. Animal protein consumption per capita is an imperfect proxy for the degree of modernization in processing and distribution of agricultural goods for consumers. Populations with high levels of animal protein consumption are presumed to have lower food sensitivity than those with low levels of consumption. The food security sensitivity index is calculated as the geometric mean of the scaled proxies for cereal production per unit land area and animal protein consumption per capita. Baseline estimates of the food sensitivity index are calculated for 1990 using data from FAO (1999) and the World Bank (1998). Future projections of cereal production/area are calculated from the MiniCAM forecasted crop production/region and area of country , which are then scaled to the USA baseline value for 1990. The animal protein

consumption/capita projections are calculated from MiniCAM forecasts of animal demand/region and assumed population growth/region, which are then scaled to the USA baseline value for 1990.

Table 1: Proxy variables for sensitivity and coping capacity

Sensitivity or Coping capacity Category	Proxy variables	Proxy for:	Functional relationship
Food sensitivity	• Cereals production/ area • Animal protein consumption/capita	• Degree of modernization in the agriculture sector; access of farmers to inputs to buffer against climate variability and change • Access of a population to markets and other mechanisms (e.g., consumption shift) for compensating for shortfalls in production	• Sensitivity ↓ as production ↑ • Sensitivity ↓ as consumption ↑
Ecosystems sensitivity	• % Land managed • Fertilizer consumption	• Degree of human intrusion into the natural landscape and land fragmentation • Nitrogen/phosphorus loading of ecosystems and stresses from pollution	• Sensitivity ↑ as % land managed ↑ • 60-100 kg/ha is optimal. X<60 kg/ha, sensitivity ↑ due to nutrient deficits and potential cultivation of adjacent ecosystems. X>100 kg/ha (capped at 500 kg/ha), sensitivity ↑ due to increasing runoff
Settlements/infrastructure sensitivity	• Population at flood risk from SLR • Population no access clean water/sanitation	• Potential extent of disruption from SLR • Access of population to basic services to buffer against climate variability and change	• Sensitivity ↑ as population at risk ↑ • Sensitivity ↑ as population with no access ↑
Human population health sensitivity	• Completed fertility • Life expectancy	• Composite of conditions that affect human health including nutrition, exposure to disease risks, and access to health services	• Sensitivity ↓ as fertility ↓ and life expectancy ↑
Economic capacity	• GDP(market)/capita • Gini index	• Distribution of access to markets, technology, and other resources useful for adaptation	• Coping capacity ↑ as GDP/cap ↑; at present GINI held constant
Human and civic resources	• Dependency ratio • Literacy	• Social and economic resources available for adaptation after meeting other present needs • Human capital and adaptability of labor force	• Coping capacity ↓ as dependency ↑ • Coping capacity ↑ as literacy ↑
Renewable natural capital	• Population density • SO2/area • % land unmanaged	• Population pressure and stresses on ecosystems • Air quality and other stresses on ecosystems • Landscape fragmentation and ease of ecosystem migration	• Coping capacity ↓ as density ↑ • Coping capacity ↓ as SO_2 ↑ • Coping capacity ↑ as % unmanaged land ↑

Ecosystems sensitivity

Ecosystems and the functions they provide to individuals and society (e.g., providing food, fiber, medicines and energy; processing carbon and other nutrients; purifying and regulating water resources; providing recreation and intrinsic value) are sensitive to variation and change in climate. The composition and distribution of ecosystems has changed in the past in response to shifts in climate, and models project future shifts in response to both the rate and magnitude of climate change. Mechanisms through which climate impacts are felt are similar for agriculture, i.e., variation or change in precipitation and temperature, changes in atmospheric composition which affect the competitive balance among different types of plants, changes in soils, and changes in the incidence of diseases and pests. Ecosystems are also influenced by other environmental stresses, including pollution (both runoff in water courses and deposition from the atmosphere), increasing extraction of resources, and incursion/fragmentation. These factors have also been shown to affect the sensitivity of ecosystems to climate variability and change.

Two proxies have been selected to represent the sensitivity of ecosystems: percentage of land area that is managed, and fertilizer use per unit land area. The percentage of land under management is a proxy for the degree of intrusion of human activity into the natural landscape and the potential fragmentation of land, which would increase the sensitivity of ecosystems to climate variability and change. The percentage of unmanaged land in a country consists of unmanaged and old forest lands. For the projections, the percent change in managed land is calculated from MiniCAM's projections, and the recalculated percentage of managed land/country is scaled to the USA baseline value for 1990; an increase in managed land will result in an increase in ecosystem sensitivity. Fertilizer consumption/unit area captures nitrogen and phosphorus loading of ecosystems and is a proxy for ecosystem stresses resulting from pollution. The relationship between fertilizer use and sensitivity to climate variability and change is non-linear. Values of 60-100 kg/ha are considered to result in lowest ecosystem sensitivity. If fertilizer use is less than 60 kg/ha, the deficiency in fertilizer use is projected to increase sensitivity because nutrient deficits and low productivity in agricultural systems may potentially result in cultivation of adjacent lands. As use increases above 100 kg/ha up to a cap of 500 kg/ha, sensitivity increases, due to increasing loads of pollutant runoff. Projected changes, calculated as percent change from 1990 values by MiniCAM forecasts of cereal production per forecasted cropland area, are used to calculate changes in projected fertilizer use/unit area. When projected fertilizer use reached above 500 kg/ha, MiniCAM's forecasted increase in crop production was assumed to result from other agricultural management changes than fertilizer use given that at present fertilizer use above a 500 kg/ha does not increase crop yield in general. The projected values are scaled against the USA baseline values for 1990. The ecosystem sensitivity index is then calculated as the geometric mean of the scaled proxies for land use (the inverse of the % unmanaged land and old forest) and fertilizer.

Settlements/infrastructure sensitivity

This category includes effects on economic activities in the industrial, energy, and transportation sectors, as well as effects on human settlements. Climate variability and change have direct impacts through flooding, droughts, changes in average temperatures (e.g., leading to thawing of permafrost), temperature extremes, and extreme weather events (e.g., hurricanes). In addition, climate variability and change can affect markets for goods and services in these sectors, as well as natural resource inputs important to production (Acosta-Moreno and Skea, 1996). Settlements in coastal margins and on small islands are affected through sea level rise and through storm surges, while these areas and inland settlements can be affected by weather-related events that act directly on infrastructure (e.g., leading to river basin flooding, landslides, and the like) and indirectly through effects on other sectors (e.g., water supply, agricultural activity; human migration patterns). Patterns of effect are different for urban and rural settlements, but both have been shown to be sensitive to climate variability and change (Scott et al., 1996).

Two proxies are used for approximating sensitivity of settlements and infrastructure in industry, energy, and transportation: population at flood risk due to sea-level rise, and population without access to clean water and sanitation. The projected number of people affected by potential rise in sea level is based on the estimated number of people in each country affected by sea surges. Data on current population at risk and population projected to be at risk after different magnitudes of sea level rise are developed by scaling the number of additional people estimated to be at risk from sea surges after a 1 meter sea level rise by

MiniCAM's sea level rise projections. As the size of population potentially affected increases, sensitivity increases. The population in a country without access to safe water and sanitation is obtained from historical data; projections are derived by scaling these observations using MiniCAM's projection of regional GDP/cap, and then indexing this to the USA baseline value for 1990. The settlement sensitivity index is calculated as the geometric mean of the scaled proxies for sea-level rise and the geometric mean of the two scaled proxies for population without access to basic needs.

Human population health sensitivity

The health of human populations is affected by climate variability and change through both direct mechanisms (e.g., heatwaves in conjunction with episodes of poor air quality, especially in urban areas) and indirect pathways (e.g., changes in prevalence of vector-borne and non-vector-borne infectious diseases). Populations with different levels of technical, social, and economic resources would differ in their sensitivity to climate-induced health impacts. Sensitivity to climate variability and change would be expected to be higher for those populations with poor basic living conditions such as overcrowding, malnutrition, and inadequate access to health services. Thus sensitivity of human population health to climate conditions can be expected to be highest in developing countries and among the poor in transition and developed countries.

We used two proxies to represent sensitivity of health to climate variability and change: completed fertility and life expectancy. These variables represent a variety of conditions that affect human health, including nutrition, exposure to disease risks, and access to health services. The 1990 baseline data are obtained from WDI. The fertility rate for a country is calculated from the total completed fertility rate and is scaled as number of births/woman to the USA baseline value for 1990. Projected life expectancy for the region is used, scaled to the USA baseline value for 1990. The health sensitivity index is calculated as the geometric mean of the scaled proxies for the fertility rate and life expectancy.

Coping capacity indicators

Economic capacity

Wealth generally provides access to markets, technology, and other resources that can be used to adapt to climate variability and change. Hence we have included GDP (market[1])/capita as one of the proxies for economic capacity. The 1990 GDP/capita (World Bank 1998) for a country is used as a starting point. Projections are calculated using MiniCAM projections of GDP and assumed population growth in the region in which the country is located; the GDP/cap for each country is then scaled to the USA baseline value for 1990. However in societies where the distribution of wealth is very unequal, coping capacity will also be unequally distributed. Thus we attempted to include unequal distribution of wealth within a society as a component of our indicator of coping capacity. Neither historical data nor forecasts are readily available for income inequality. We identified 1990 values for our sample countries, and then scaled these to the USA baseline for 1990. We held these values constant during our projections on the assumption that changes in the distribution of wealth had a complex set of causes and correlates, and that present understanding of these relationships, even in the development economics or sociology literatures, is inadequate to postulate a set of relationships scaled to such factors as GDP/capita. The economic coping capacity index is calculated as the geometric mean of the scaled proxies for GDP/capita and the index of income inequality.

Human resources

Human and civic resources are another critical component of coping capacity. This category includes literacy, level of education, access to retraining programs, and other factors that determine how flexible individuals may be in adapting to new employment opportunities or shifts in living patterns brought about

[1] We did not use purchasing power parity adjusted GDP/capita because over the course of the century for which we make projections, the PPP adjustment wildly inflates that level of wealth in countries that are currently poor to the point that their GDP/capita dwarfs that of those countries that are currently economically developed.

by climate variability or change. As proxies, we selected the dependency ratio and the literacy rate. The dependency ratio measures the proportion of economically active and inactive individuals in a population; a higher rate of dependency would indicate that economically active individuals had many others to support, and resources for adapting to changes in climate would be more limited. Data for 1990 (World Bank 1998) are used to calculate the baseline for each country, and the projections are developed from forecasts for the region in which the country is located. The dependency ratio is scaled to the USA baseline value for 1990 with the result that an increase in the dependency ratio decreases coping capacity. The literacy rate (World Bank 1998) was also included as a measure of the skills that individuals would have to adapt. Development of historical data on illiteracy/literacy at a country level requires interpolation from available information; consistent data are not available and forecasts are not readily available (and in our case 1990 values were held constant). Illiteracy data were recalculated as percentages of a population which are literate and scaled to the USA baseline value for 1990, so that higher literacy rates imply better coping capacity. The human and civic resources coping capacity index is calculated as the geometric mean of the scaled proxies for age dependency and literacy.

Closely related to human resources are civic resources, which include associations among individuals, either informal or formal, through kinship relations, civic associations, or other institutions that would lead to feelings of obligation to help those who may be negatively affected by climate. In future iterations of this work, this set will clearly need to be included.

Renewable natural capital

As discussed above, natural systems are sensitive to climate stimuli and thus will need to adapt to climate variability and change. Adaptation may involve a variety of eco-physiological changes, changes in species mix, migration, or even the loss of some species or ecosystems. The survival of current ecosystems will depend not only the degree of climate variability or the rate and magnitude of climate change but also on the baseline condition of the systems themselves. For proxies of the resilience or coping capacity of ecosystems we take three measures of the amount of natural capital that is available: population density; SO_2 emissions/area; and the percentage of unmanaged land in a country. Percent unmanaged land baseline values are calculated from 1990 FAO data (FAO 1999), and the projected percentage of unmanaged land in a country is calculated using MiniCAM projections of land use; the resulting values are then scaled to the USA baseline value for 1990. Baseline SO_2 emissions by country per unit area are developed using 1985 data from CDIAC. Projections are based on the percentage change in emissions in a region as projected by MiniCAM, and then scaled to the USA baseline value for 1990 for purposes of standardization. Baseline population density for each country is calculated from 1990 data from the World Bank (1998). Forecasts are developed by scaling national baselines using MiniCAM scenario assumptions for the region in which the country is located, scaled to US 1990 baseline. The environmental coping capacity index is calculated as the geometric mean of the scaled proxies for landscape fragmentation (percentage unmanaged land and old forest), air pollution (SO_2 emissions) and population pressure (population density).

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