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VULNERABILITY TO CLIMATE CHANGE
A Quantitative Approach

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EXECUTIVE SUMMARY

The PNNL Vulnerability Assessment Program explores approaches for assessing the significance of potential future changes in climate for natural resources and socioeconomic systems. Research on vulnerability addresses two important challenges identified in the recent impact assessments of the Intergovernmental Panel on Climate Change (IPCC) (Watson et al. 1996, 1998, McCarthy et al. 2001). The first challenge is to improve approaches for comparing and aggregating impacts across diverse sectors and populations. The second challenge is to model socioeconomic transformation as well as climate change in assessing the future significance of climate change. Vulnerability assessment must account for multiple dimensions: the physical-environmental impact of changed climate; a region's capacity to recover from extreme events and adapt to change over the longer term; and the degree to which international trade, aid and other connections assist a region in its coping and adaptive efforts.

Multifaceted, interdisciplinary quantitative approaches to vulnerability assessment are essential for improving our understanding of the environmental, social, and economic effects of different stabilization targets for greenhouse gases. Improved understanding will be essential for identifying a quantitative stabilization objective within the context of the United Nations Framework Convention on Climate Change (UNFCCC). It is also important for the process of developing priorities for adaptation. Research on vulnerability seeks to address both of these issues by developing quantitative and qualitative frameworks for assessing the interaction of socioeconomic conditions and environmental changes.

To meet the challenges identified by the IPCC, we have constructed a prototype computer-based methodology for assessing vulnerability and resilience to climate change given present circumstances and for three alternative scenarios of the future. The model calculates indicators of sensitivity to climate change, and coping-adaptive capacity. It aggregates these into our overall indicator of vulnerability in a three-level, transparent process.

Background

Previous research that has laid a foundation for quantitative and qualitative vulnerability assessment spans the literatures on impacts of climate change, adaptation strategies, natural hazards and responses (e.g., floods, droughts), sustainability, and social indicators – as well as the recent studies of vulnerability itself. Vulnerability is also related to issues of economic development, sustainability, disaster mitigation and relief. The statistical data, case studies, and comparative analyses in these related areas provide analytic resources for vulnerability assessment. In addition, they provide results that can be used in evaluating the new methodology.

Vulnerability and adaptive capacity are useful integrative concepts for evaluation of the potential effects of climate change, but they are also complex concepts that cannot be directly measured or observed. Therefore, we identify proxy variables for use in modeling or observation. Desirable proxies are variables that summarize or otherwise simplify relevant information; make visible or perceptible phenomena of interest; and quantify, measure, and communicate relevant information. Proxies should simplify or summarize a number of important properties rather than focus on isolated characteristics of a system. They must be based on measurable or at least observable information, and the methodology used to construct indicators from them should be transparent and understandable.

The development of quantitative indices for vulnerability is an important part of the vulnerability assessment program. Developing proxy variables and indicators for use in modeling or observation enables sophisticated vulnerability analyses that integrate environmental and social perspectives. Within the UNFCCC, indicators of vulnerability have been proposed not only to assist in determining what levels of climate change might be "dangerous" but also to identify countries or groups that are especially vulnerable for the purposes of targeting multinational assistance to the most needy.

Model Description

Table ES-1 lists the indicators, sectors, and proxy variables used in the vulnerability-resilience indicator prototype (VRIP) model.[1] The sensitivity sectors include settlement, food security, human health, ecosystems, and water. The coping capacity sectors include economic capacity, human resources, and environmental capacity. Each sector, in turn, is composed of one, two, or three proxies. Our choices of sectors and proxies were limited by available data, and the initial effort in further development of the model will be to review these choices and evaluate other data sources. However, this set of indicators and proxies illustrates the sort of relationships that will need to be explored in greater depth in the process of moving from testing this prototype indicator system to development of an expanded model.

The structured relationships of these model elements are illustrated in Figure ES-1 and discussed in more detail in the full report. The difference between aggregated sensitivity (the negative value) and adaptation capacity (the positive value) yields a vulnerability-resilience indicator. If the indicator value is positive we are dealing with resilience and when negative the indicator denotes vulnerability. Importantly, the vulnerability-resilience indicator can easily be decomposed into all its contributing aspects and therefore remains transparent to analysts.

We positioned the VRIP model in a framework for Monte Carlo analysis that allows for analysis of the implications of the model structure and the contributions by the changing proxies to the uncertainty of the calculated vulnerability-resilience indicators over time. Moreover, it allows for the identification of dominant or leading proxies over time.

We define dominant or *leading proxies* as those proxies that are the most important in determining the composite vulnerability-resilience indicator for a particular case. We identify leading proxies by evaluating the correlations between the sampled proxies and the calculated indicators; proxies with the highest explanatory power of the variance of the calculated indicators are determined to be leading proxies. By basing the uncertainty ranges of the proxies on their projected changes over time, we capture through our sampling from those ranges the different pathways the proxies might take over time, and which of the proxies will be most dominant (leading) in determining the final indicator values.

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[1] Vulnerability is defined as the *sensitivity* of system or process to climate change (the degree to which outputs or attributes change in response to changes in climate inputs) and the *adaptability* of that system (the extent to which changes are possible to take advantage of the new conditions).

Table ES-1. Indicators, sectors, and proxies used in the vulnerability-resilience indicator prototype (VRIP) model

Sensitivity or Adaptive capacity category	Proxy variables	Proxy for	Functional relationship
Settlement/ infrastructure sensitivity	Population at flood risk from sea level rise Population without access to clean water/sanitation	Potential extent of disruptions from sea level rise Access of population to basic services to buffer against climate variability and change	Sensitivity ↑ as population at risk ↑ Sensitivity ↑ as population with no access ↑
Food security	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 ↑
Ecosystem sensitivity	% Land managed Fertilizer use	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
Human 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 ↓ Sensitivity ↓ as life expectancy ↑
Water resource sensitivity	Renewable supply and inflow Water use	Supply of water from internal renewable resources and inflow from rivers Withdrawals to meet current or projected needs	Sensitivity calculated using ratio of available water used: Sensitivity ↑ as % water used ↑
Economic capacity	GDP(market)/capita Gini index	Distribution of access to markets, technology, and other resources useful for adaptation	Coping-adaptive capacity ↑ as GDP per capita ↑ 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-adaptive capacity ↓ as dependency ↑ Coping-adaptive capacity ↑ as literacy ↑
Environmental capacity	Population density SO_2/area % Land unmanaged	Population pressure and stresses on ecosystems Air quality and other stresses on ecosystems Landscape fragmentation and ease of ecosystem migration	Coping-adaptive capacity ↓ as population density ↑ Coping-adaptive capacity ↓ as SO_2 ↑ Coping-adaptive capacity ↑ as % unmanaged land ↑

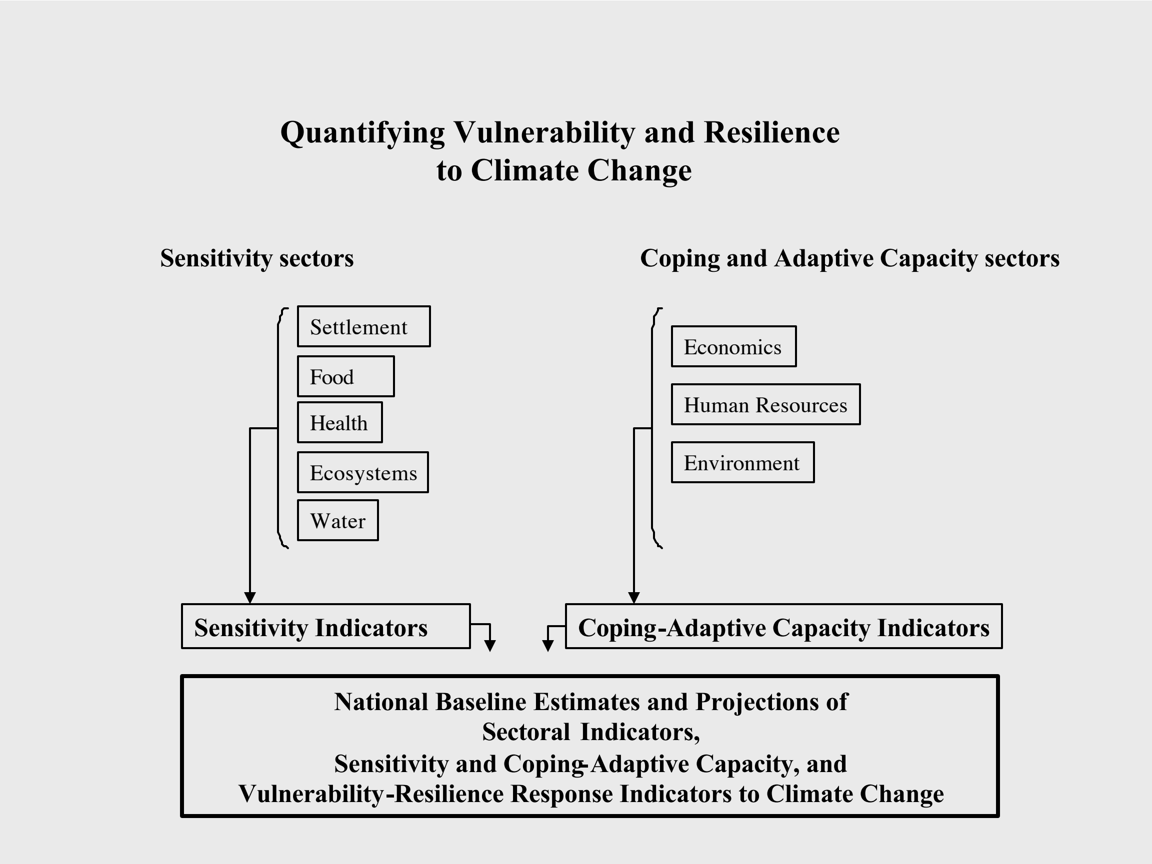

Figure ES-1. Developing quantitative vulnerability indicators: the structured relationships of model elements.

Results

We calculated indicator scores for both current and potential future conditions for 38 countries and the world. We based the calculations of the current indicator on 1990 national data. For the calculations of indicators for future conditions, we used regional outputs (11 regions and global outputs) forecasted by the MiniCAM, an integrated assessment model (Edmonds et al. 1996, 1997) and its post-processor Sustain (Pitcher 1997). To drive these projections, we used variants of the new IPCC emissions scenarios (Nakicenovic et al. 2000), called rapid growth (A1v2), local sustainability (B2h), and delayed development (A2A1). These scenarios provide consistent assumptions about socioeconomic factors that both force climate change and affect adaptive capacity.

To test the relationships within and structure of the model, we examined the effects of indexing against different baseline data, the projections of different scenarios of the future, and the contributions to uncertainty of each of the proxies to the overall uncertainty of the vulnerability-resilience indicators.

Figures ES-2 and ES-3 illustrate the differences among countries and scenarios in projected response to climate change impact with proxies indexed against 1990 world baseline data. While in 1990 (Figure ES-2) 16 countries out of the 38 are considered more vulnerable to climate

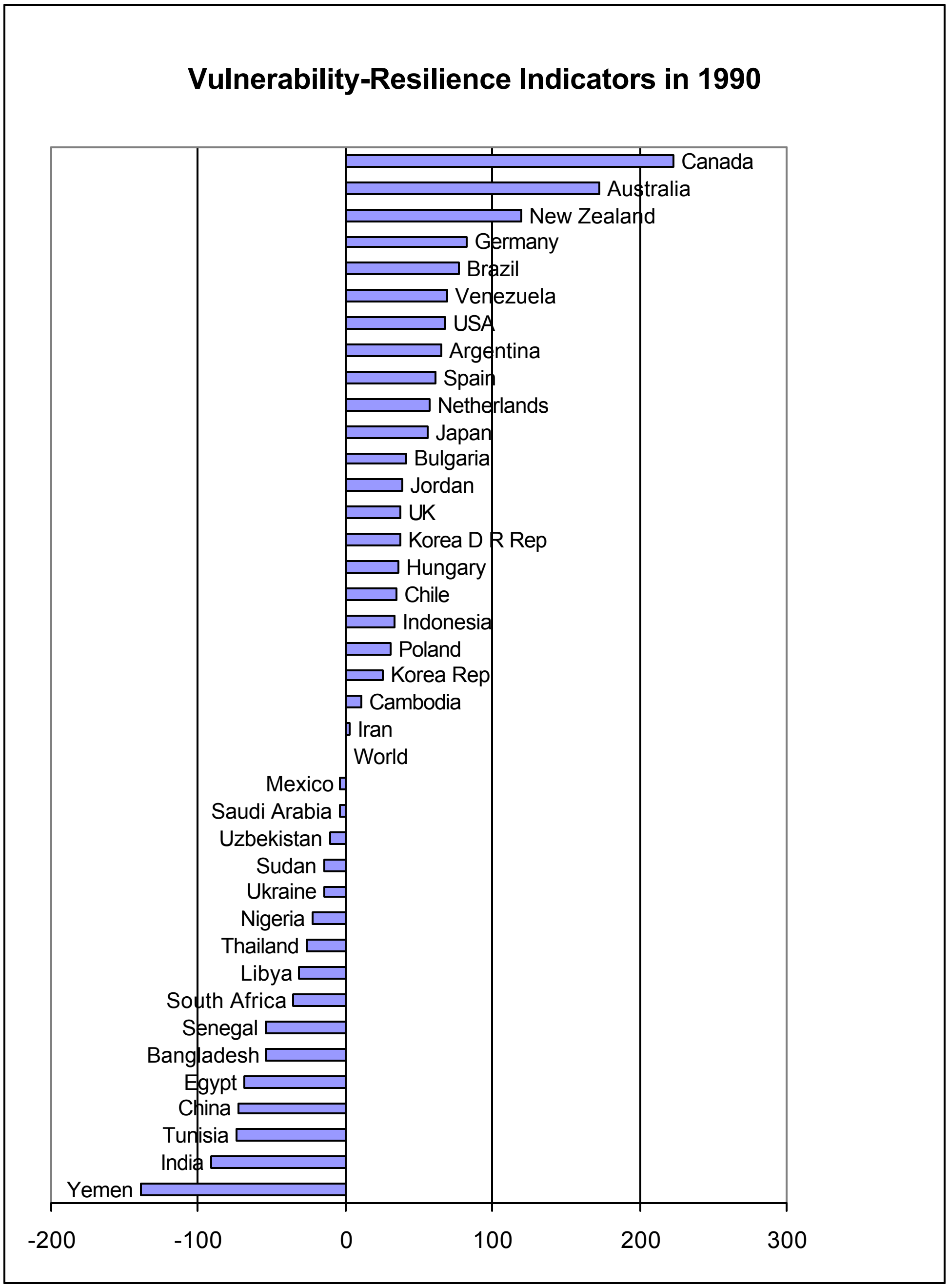

Figure ES-2. Vulnerability-Resilience Indicators; proxies indexed against world data

impact than the world as a whole, by the year 2095 (Figure ES-3) only one country remains vulnerable in the rapid growth scenario, three countries in the local sustainability scenario and nine countries in the delayed development scenario.

Details of the results are given in the body of the report, along with percentage changes in sensitivity and adaptation capacity and actual changes in the vulnerability-resilience indicator values. The model results and analysis of the interactions among proxies and sectors provide insights about where countries might focus their efforts in building resilience to climate change.

For example, the results for Spain (Figure ES-4) show water sensitivity dominating over time, while for Brazil (Figure ES-5) many proxies contribute to the vulnerability-resilience indicator. The extent of which a proxy dominates is shown clearly in the scale of the radius on the two figures. For Spain the scale ranges up to 2800 units, for Brazil only to 800. (Note that these results are illustrative of the vulnerability indicators model, but not necessarily a firm foundation for a vulnerability assessment of Spain or Brazil.)

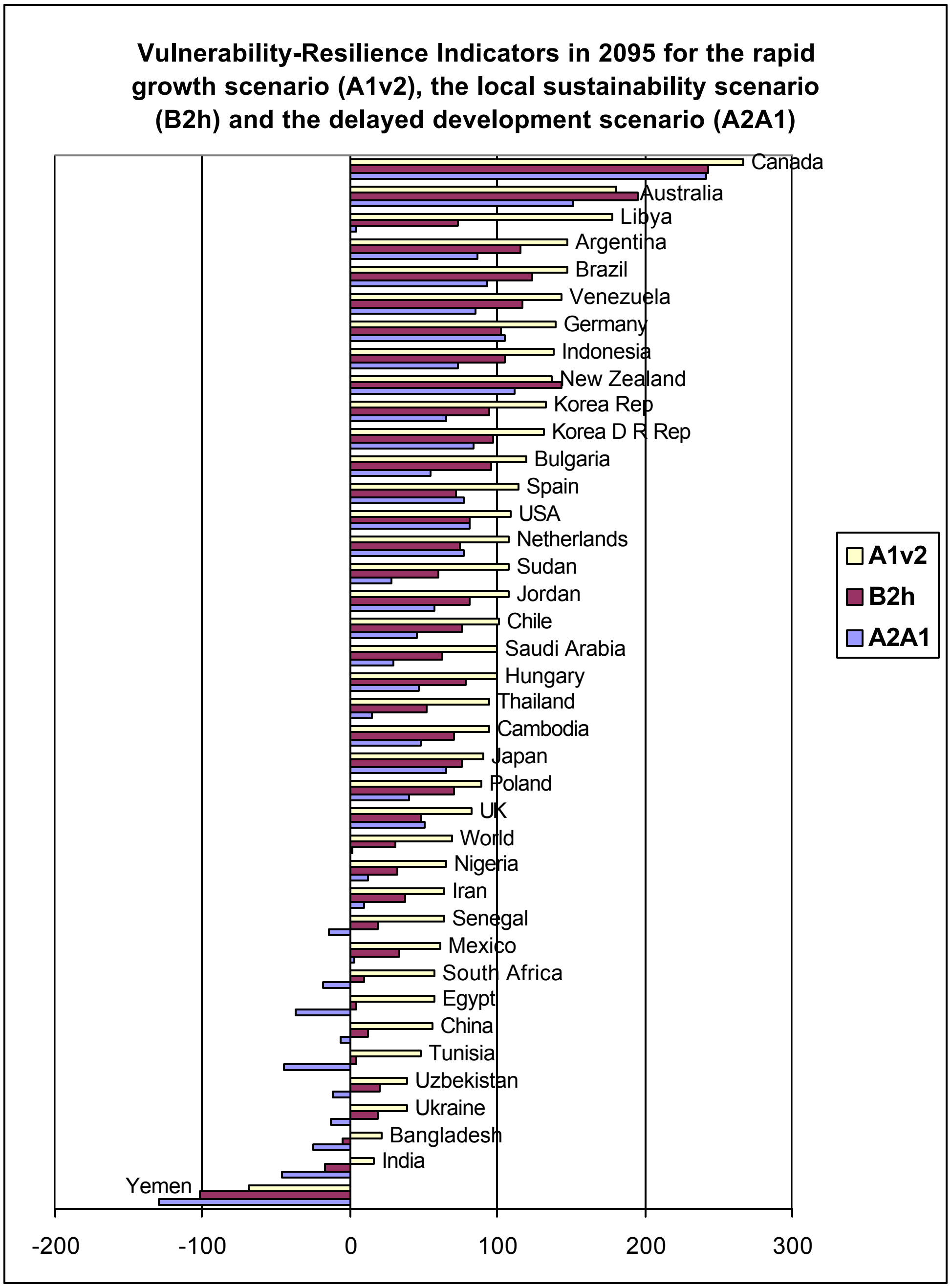

Figure ES-3. National Vulnerability-Resilience Indicators in the year 2095 for all three scenarios; proxies indexed against world baseline data.

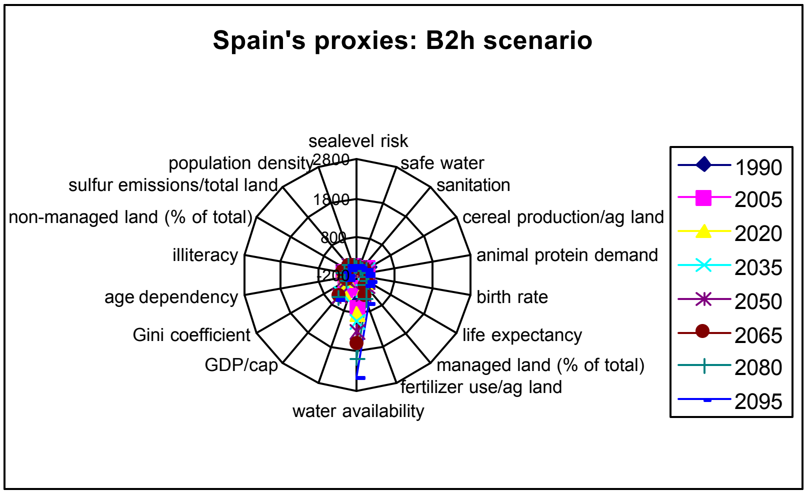

Figure ES-4. Spain's proxies in the local sustainability scenario over time after indexing the proxies against 1990 world baseline data

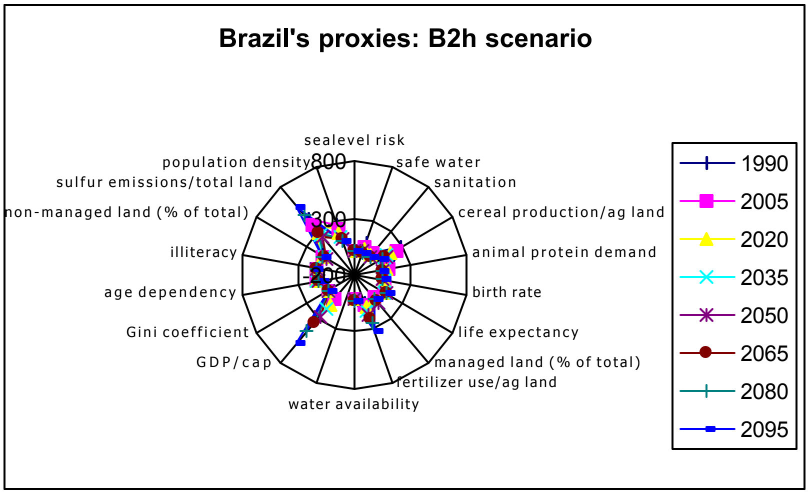

Figure ES-5. Brazil's proxies in the local sustainability scenario over time after indexing the proxies against 1990 world baseline data

The Monte Carlo uncertainty analysis (Figures ES-6 and ES-7) demonstrates that both the model structure and the proxy values themselves determine the contributions to uncertainty in the final indicators. Initially, before 2005, the variance of Spain's vulnerability-resilience indicator is mainly determined by settlement and infrastructure sensitivity (Figure ES-6). (Backcasting is done by means of available historical data of the proxies.) Between 1961 and 1990 reported access to safe water and especially sanitation greatly improved. By the year 1990 the reported full access results in minimal uncertainty in those proxies by 2005. From 2005-2035, changes in the vulnerability-resilience index for Spain are driven primarily by the forecasted change in sulfur emissions, which affects environmental coping capacity. After 2065, changes in the index value for Spain are primarily driven by changes in age dependency (the percentage of people dependent on people in the work force), which affects civic and human resources coping capacity.

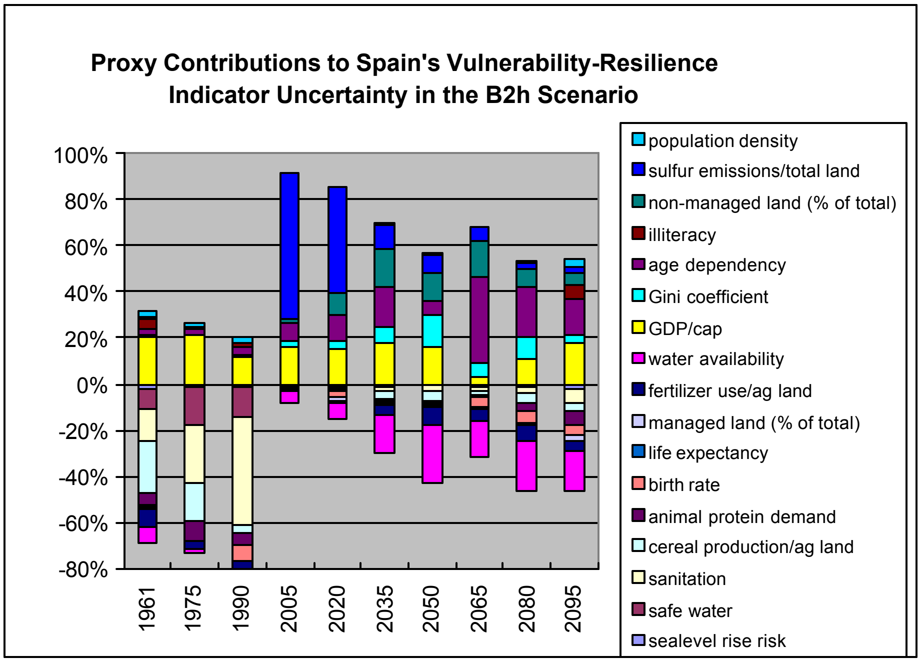

Figure ES-6. Percentage contribution by proxies to the uncertainty of Spain's vulnerability-resilience indicator from 1961 through 2095 for the local sustainability scenario with proxies sampled from ranges determined by changes in proxy values over time.

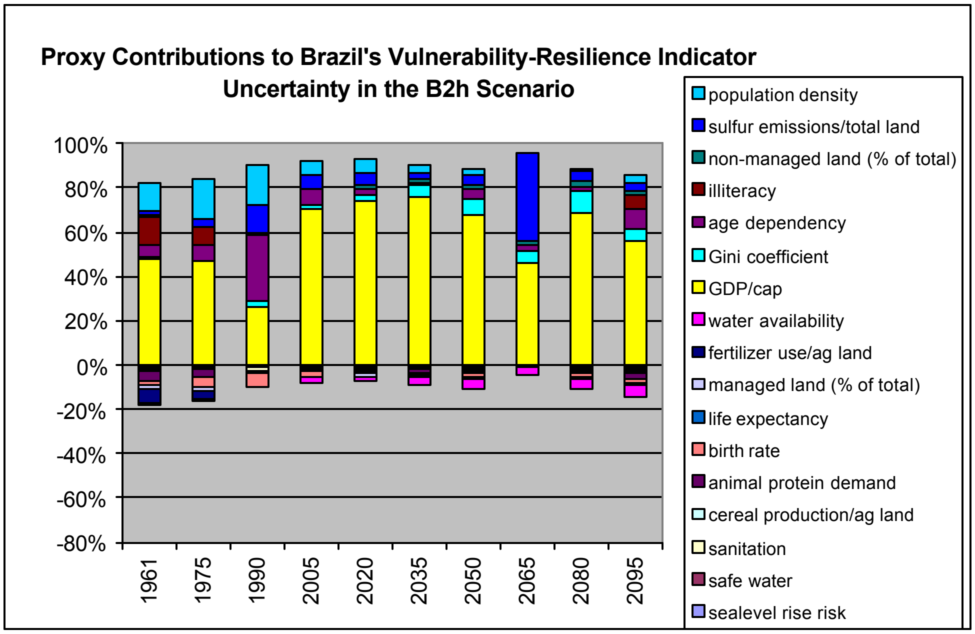

Figure ES-7. Percentage contribution by proxies to the uncertainty of Brazil's vulnerability-resilience indicator from 1961 through 2095 for the local sustainability scenario with proxies sampled from ranges determined by changes in proxy values over time**.**

For Brazil, GDP per capita is the dominant proxy over the total period, historically and into the future (Figure ES-7). Changes in population density, illiteracy and sulfur emissions also are projected as affecting uncertainty in the vulnerability-resilience indicator.

Conclusions

Quantitative vulnerability indicators are a theoretically sound and technically feasible way of assessing vulnerability and resilience to a first approximation. The results of modeling vulnerability-resilience indicators could be used for identification of leading proxies, directing research and analysis toward sectors where resilience-building and adaptive strategies are relative priorities.

The transparency of the model, its processes, and the results is an important and useful attribute for researchers and policymakers. If facilities analysis of which factors most affect the vulnerability-resistance of a society at different points in time. In contrast, comparing single numbers among nations is likely to be irrelevant, if not misleading, since the single numbers represent a complex reality with highly diverse circumstances and likely highly diverse policy strategies and costs.

A framework for vulnerability assessment that includes both quantitative indicators and qualitative, local data can be extremely useful at regional and local scales, both in assessing vulnerability and in pointing toward appropriate and feasible adaptation strategies.

Decomposing the vulnerability-resilience indicator into its sectoral indicators or into its proxies assumes equal contributions to the final indicator by its components. However, the model structure results in unequal contributions. For instance, in a sector comprising three proxies, each proxy contributes only one-third of what a proxy in a single-proxy sector contributes. So decomposition is only a first step in analyzing proxy contributions to the final indicators of interest. By positioning the calculations of the vulnerability-resilience indicator in a Monte Carlo framework, we illustrate a means of capturing the impact of the proxy values, their projected changes over time and the structured relationships of the model elements. Through this approach we can identify those proxies with the largest impact on the final indicator and thus can identify leading proxies that subsequently can be verified, at least historically.

In summary:

- The prototype model yields unique vulnerability pathways for countries, even those within the same MiniCAM regions, from which projections are derived. These results are broadly consistent with our intuitive understanding of vulnerability. But they also contain some unexpected results. For example, some developing countries are less vulnerable than some developed countries. These unexpected results seem logical or plausible when examined in detail.
- The assumptions made about what individual proxies represent and the meaning of their changed values over time (increases/decreases) are shown in Table ES-1. For the whole set of indicators, we looked for possible domination of one or several proxies through their implicit representation in other proxies; for example, wealth or population may drive the overall results if several proxies are driven by either wealth or population. Similarly, proxies might have to be represented in more than one sector; for example, water availability may influence how agricultural proxy values ought to change over time, while water sensitivity may be represented as a sector in its own right. Moreover, when sectors are aggregated to sensitivities (negatives) or coping-adaptive capacity

(positives), the complex nature of proxies becomes an issue. Increases in agricultural yields feeds more people, but if this development also displaces traditional farmers, creates new urban poverty, and depletes the land, a simple proxy cannot account for all these positive and negative changes. The aggregation issue becomes more serious at the highest level, when one number is calculated for vulnerability. The single number should always be understood as representing multiple complexities.

- Wealth is neither a necessary nor a sufficient determinant of vulnerability and resilience. Although country vulnerability-resilience indicators correlate with national GDP per capita, more than 20% of the countries studied show no significant correlation.
- Country-level results are useful for first-order comparisons, but subnational studies will be needed to craft meaningful national policies.
- Comparisons of scenario projections suggest that an emphasis on general development is an appropriate approach to building resilience to climate change.
- Scenario projections, based on the IPCC scenarios, seem optimistic when compared with case studies of the same areas, while linear extrapolations, either of improvement or degradation, are probably not realistic descriptions of the future either. This suggests that further scenario development is necessary.
- Our lack of knowledge about inequality in societies and potential inequality in the future hampers our ability to assess who in a society is vulnerable and to what.
- Many, perhaps all, proxies include both negative and positive implications. Vulnerability assessment needs to account for tradeoffs.

The next steps in development of the vulnerability indicators model include both analytic and technical/scientific tasks:

- Thoroughly review the set of proxies and sectors in light of the analyses detailed in this report. Add, delete, and modify as necessary. Consider especially overrepresentation of population data. Account for scale issues by using ratios/percentages wherever possible.
- Revise the model structure and mathematical processes to ensure that proxies are appropriately weighted in the indicators.
- Perform several case studies at a regional or local level (e.g., watershed, urban area, semi-arid plateau), developing specific indicators relevant to the case and using relevant data from the area.
- Involve local stakeholders (e.g., policymakers, business persons, workers, members of NGOs) in the determination of relevant proxies and weights.
- Use the model results in a larger framework of vulnerability assessment that employs qualitative as well as quantitative approaches.

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ACKNOWLEDGEMENTS

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DEFINITIONS

Adaptability/ adaptive capacity	"the degree to which adjustments are possible in practices, processes, or structures of systems to projected or actual changes of climate" as response to, or anticipatory of change" (Watson et al. 1996:Appendix B).
Climate	"average weather, described in terms of the mean and other statistical quantities that measure the variability over a period of time and possibly over a certain geographical region. Climate involves variations in which the atmosphere is influenced by and interacts with other parts of the climate system, and 'external' forcings" (Geer 1996).
Hazard	a possible source of danger. Climate-related hazards include wildfires, drought, and severe storms.
Leading proxy	a representative variable that tends to move ahead of and in the same direction as the whole.
Mitigation	"an anthropogenic intervention to reduce the emissions or enhance the sinks of greenhouse gases" (Watson et al. 1996:Appendix B).
Resilience	a tendency to maintain integrity when subject to disturbance.
Risk	the likelihood or probability of the occurrence of harmful events at a locality. Risks will change because of changes in climate and mitigation actions (Cutter 1996).
Sensitivity	"the degree to which a system will respond to a change in climatic conditions" (Watson et al. 1996:Appendix B).
Social indicator	a statistic of direct normative interest which facilitates concise, comprehensive and balanced judgments about the condition of major aspects of a society.
Vulnerability	"the extent to which climate change may damage or harm a system," depending "not only on a system's sensitivity but also on its ability to adapt to new climatic conditions" (Watson et al. 1996:Appendix B). (See discussion in "What is vulnerability to climate change?" below.)
Weather	"the state of the atmosphere at a definite time and place with respect to heat or cold, wetness or dryness, calm or storm, clearness or cloudiness: meteorological condition" (Bostrom et al. 1994: 964) or the state of the atmosphere, mainly with respect to its effects upon life and human activities; as distinguished from climate, weather consists of the short-term (minutes to months) variations of the atmosphere

BACKGROUND

Vulnerability analysis addresses two important challenges identified in the recent impact assessments of the Intergovernmental Panel on Climate Change (IPCC) (Watson et al. 1996, 1998, McCarthy et al. 2001).

The first of these is improving approaches for *comparing* and *aggregating* impacts across diverse sectors and populations. Much of what is now known about the potential impacts of climate change is detailed but fragmented information on the potential impacts of climate change derived from studies of what may happen in different sectors under different climate change scenarios. Changes in crop yields, water balances, incidence of vector-borne diseases, land cover, and other climate-sensitive processes/systems are modeled with increasing detail, but these results are difficult to use in summarizing the effects associated with different stabilization targets because they are impossible to aggregate. In contrast, results in economics are sometimes used as a potential metric for setting stabilization goals because they aggregate climate change impacts to a simple index, usually a percentage change in gross economic output (or other measures of economic welfare) driven by estimates of global mean temperature change. But even economists agree that economic metrics alone are not adequate for setting stabilization targets because they do not adequately incorporate important non-economic impacts to both ecosystems and societies. And because these measures average out differences across sectors and population groups, they need to be used in combination with other analytic approaches that preserve information about the diversity of effects and capacities for adaptation.

The second challenge identified in the IPCC reports is the need to model socioeconomic transformations as well as climate change in assessing the future significance of climate change. Most current climate change impact studies assume static social and economic structures in estimating the sensitivity of hydrological or terrestrial systems to projected climate regimes. Yet there will certainly be substantial changes in economies and societies over the coming decades, and these changes will influence profoundly the impact of climate change on society. Indeed, variations in current socioeconomic conditions across countries or regions lead to different levels of vulnerability to similar weather events (e.g., Hurricane Mitch produced catastrophic losses in Honduras while Hurricane Georges led to relatively light damage in Cuba).

It is important to recognize multiple dimensions of vulnerability and account for them in methodological frameworks to assess vulnerability.

One dimension, the physical-environmental, accounts for the harm caused by climate. It can usually be measured using relational data. This dimension typically includes changes in rainfall and water availability (including droughts and floods) severe enough to affect agricultural, forestry, and livestock productivity. Similarly, rise in sea level will adversely affect fisheries (including hatcheries), housing, and tourism. Health effects may also be estimated and quantified by reference to increases in vectors, and thus vector-borne diseases; statistics about deaths from extreme cold or heat; maladies associated with warmer or colder climates; and so on. Scale effects are important in measuring physical-environmental changes. A timescale of a century is appropriate for climate change, and most of the projected effects have been quantified at a global scale; these scales are all-but-irrelevant to decision-makers dealing with issues that are national or local and near-term.

A second dimension is more difficult to assess and quantify – a region's[2] capacity to recover from extreme events and adapt to change over the longer term. This dimension includes cultural aspects such as the strength of civil society (the network of overlapping informal and formal associations that link people to one another) and the societal view of nature (as unknowable and therefore unmanageable or as benevolent and responsive to management, for instance). This dimension also includes some measure of the region's wealth, along with its record of using that wealth to improve the welfare of its citizens. Another aspect of this dimension is the diversity of a region's natural resources and sources of income; a region dependent almost solely on tourism, for example, will be greatly vulnerable to loss of its scenic beaches. Finally, institutional development and capability will be an important factor in whether a region will be able to cope in the short term and adapt in the longer term. Political stability of the region will play a role in its vulnerability, for instance; a region torn by civil strife will be more vulnerable than a peaceful region.

A third dimension – harder still to measure quantitatively – is the degree to which a region may be assisted in its attempts to adapt to change, through its allies and trading partners, diasporic communities in other regions, and international arrangements to provide aid, perhaps through mechanisms established under the Framework Convention on Climate Change. For example, regions may be assisted by international relief agencies when stricken by drought or flooding or, in the longer term, by income from tradable permits related to emissions or financing of water management projects in the case of climate change.

Vulnerability analysis is therefore highly interdisciplinary work. The challenge is to develop, from a wide range of domain (disciplinary) knowledges, indicators that are truly representative of the important factors of each – and then to relate these indicators to each other in a way that makes sense in analyzing vulnerability in a particular region, for a particular society in a particular environment.

The PNNL Vulnerability Assessment Program explores approaches for assessing the significance of potential future changes in climate for natural resources and socioeconomic systems. Multifaceted, interdisciplinary approaches are essential for improving our understanding of the environmental, social, and economic effects of different stabilization targets for greenhouse gases. This will be key for identifying a quantitative stabilization objective within the context of the UN Framework Convention on Climate Change. Such an improved understanding is also important for the process of developing priorities for adaptation. Our research seeks to address both of these issues by developing quantitative and qualitative frameworks for assessing the interaction of socioeconomic conditions and environmental changes.

WHAT IS VULNERABILITY TO CLIMATE CHANGE?

Although most scholars agree on the broad definition of vulnerability as "the capacity to be harmed," the use of the term varies among disciplines and research areas. Downing (1999) separates hazard (as the potential threat to humans and their welfare) and vulnerability (as exposure and susceptibility to losses); together, hazard and vulnerability add up to risk (the probability to hazard occurrence), with disaster as the realization of a risk. The inclusion of "exposure" in the definition of vulnerability appears to be problematic, since exposure by itself does not necessarily contribute to negative outcomes. Vogel (1999) quotes Blaikie et al. (1994:9) who define *vulnerability* as "the characteristics of a person or group in terms of their capacity to

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[2] We use "region" throughout this paper, although we recognize that in many, perhaps most, cases "region" will be synonymous with "nation."

anticipate, *cope* with, *resist* and *recover* from the impacts of natural hazards" and states that "vulnerability can be viewed along a continuum from resilience to susceptibility." She also discusses Anderson and Woodrow's (1989) attempt to identify different dimensions of vulnerability such as the "physical and material, social and organizational, and motivational and attitudinal." Vogel points to the importance of the relationship between empowerment and vulnerability, e.g., "how do different social actors gain access to and control of various resources."

Cutter (1996) identifies three distinct clusters of definitions for vulnerability: as risk of exposure to hazards, as a capability for social response (what we call below coping or adaptive capacity), and as an attribute of places (e.g., vulnerability of coastlines to sea level rise). Cutter (1996:532) proposes a "hazards of place" model that bridges various definitions and states "Vulnerability is the likelihood that an individual or group will be exposed to and adversely affected by a hazard. It is the interaction of the hazards of place (risk and mitigation) with the social profile of communities." She ultimately argues (1996:536) that "it is place that forms the fundamental unit of analysis" for vulnerability.

Vulnerability assessment is described by Ribot (1996:15) as extending impact assessment by highlighting *who* (as in what geographic or socioeconomic groups) is susceptible, *how* susceptible they are, and *why*, while c*limate impact assessment* addresses the magnitude and distribution of the consequences of climate variability and change. Ribot (1996:16) states that "with an understanding of causality, appropriate policy responses can be developed to redress the causes of vulnerability, rather than just responding to its symptoms" and "policy analysts must go beyond identifying its proximate causes to evaluating the multiple causal structures and processes at the individual, household, national and international levels." Ribot (1996:29) considers vulnerability to be *specific* in that it is concerned with a particular consequence, such as famine, hunger or economic loss.

Reilly and Schimmelpfennig (1999:775) define vulnerability as "a probability weighted mean of damages and benefits" and give as examples "yield vulnerability," "farmer or farm sector vulnerability," "regional economic vulnerability," and "hunger vulnerability." They distinguish (1999:746) between famine and chronic hunger, the former being "a shortage of food so severe that many people starve," the latter "limiting mental and physical development of children and impairing function in adults." Causes of and remedies for famine and hunger differ. Blaikie et al. (1994) would blur this line, citing situations in which "normal" daily life is difficult to distinguish from disaster.

Resilience is in general defined as a tendency to maintain integrity when subject to disturbance (Holling 1973); a resilient system or population is one that can cope with the *hazards* to which it is exposed, either by short-term recovery efforts or long-term proactive adaptation. This concept is based on both biophysical attributes (e.g., climate or other environmental conditions) and social/economic factors that mitigate or amplify the consequences of environmental change. Ludwig et al. (1997) define resilience as "how fast a variable that has been displaced from equilibrium returns to it. Resilience could be estimated by a return time, the amount of time taken for the displacement to decay to some specified fraction of its initial value." The resilience of a system can, however, not only potentially be expressed in terms of time to recover, but also in terms of cost of recovery, while allowing for renewal. Folke et al. (1998) distinguish the *stability* of a system, that is, how *resistant* a system is to disturbance, and the *resilience* of a system.

Resiliency can thus be considered the opposite of vulnerability, manifesting itself as *adaptability* or in its short-term form as *coping capacity*, that is, as having the resources available for making (immediate) adjustments in response to climate change and/or variability. Ribot (1996:26) states that reducing vulnerability (to climate variability and climate change) can be achieved by increasing people's ability to *cope*, while *adaptation* (based on immediate observation of the surroundings) makes extreme events survivable, rather than catastrophic.

Coping is the capacity to bounce back. Stern and Easterling (1999:38) state: "Social systems currently *cope* with climate variability (1) in anticipation of climatic uncertainty and (2) with crisis response strategies." Folke et al. (1998:425-426) state "Coping strategies are differentiated from adaptive strategies on the basis of the time-scale of response, the level of vulnerability, and the type of risk faced by households and communities. Coping strategies tend to be short-term responses in abnormal periods of stress. (T)he continued availability of a range of coping strategies may be necessary for livelihood strategies to remain adaptive in the long term."

Downing et al. (1996, from Fankhauser and Tol 1997:392) state that occurrences of extreme events such as floods, droughts, heat waves, and storms, drive *adaptation*. Reilly and Schimmelpfennig (1999:767) characterize adaptation as including "the prevention of loss, tolerating loss, or relocating to avoid loss." Reilly and Schimmelpfennig (1999:746) distinguish between *adaptation* as response to climate change and *adjustment*. Adaptation in the case of agriculture can mean "finding ways to produce the same crops at no additional cost." It can also mean "relocating and finding employment outside of agriculture." And they state that "adjustment costs arise, and are greater, when the adaptation response must be made in a short time period." Janssen and de Vries (1998:47) combine response of agents in the form of *adaptation* to an evolving system (a world with surprises) in their modeling of climate change. They follow the results of Cultural Theory-based hierarchist, egalitarian, and individualist types of rule-based responses of the system to change; they conclude, not surprisingly, that adaptation based on observation and knowledge of changes reduces the risk of a path to catastrophe.

The concept of vulnerability is itself thus highly contested. Less industrialized nations have used the term in an interpretive sense to mean the inequitable harm to them caused by the pollution-producing activities of industrialized nations. Industrialized nations are apt to use vulnerability as one side of a cost-benefit equation in which the sum, the bottom-line number, is the most important. Where for a cost-benefit analysis, differential impacts and equity are secondary considerations, for less industrialized countries – even in a quantitative sense – vulnerability means measures of harm (financial costs, human lives, and societal disruptions such as loss of livelihood and force emigration) that they bear the brunt of with no benefit to them.

Vulnerability, in its simplest denotative sense, meaning the potential to be harmed, relates vulnerability to sustainability, which in many of its meanings denotes the capacity to persist, i.e., that a society has the ability to withstand harm, specifically the harm of depleted environmental resources (Brundtland Report). Sustainability is a broader, more ambiguous term that includes a kind of balance-sheet metaphor; when humans use Earth's resources, they should repair any harm to the environment, so that future generations will be as able to live on the Earth as the current generation. To bring the discussion back to vulnerability, a sustainable society may include some vulnerability but must also have the capacity to repair harm.

Both vulnerability and sustainability imply long-term risks that must be addressed. Societies have choices to make in the present and future, choices that can increase or decrease vulnerability, promote or inhibit sustainability. Resource-constrained societies can probably not protect themselves against all risks and so must choose some combination of high-probability and catastrophic risks, taking into account the costs of protection and the likely cost of remaining or becoming increasingly vulnerable.

PREVIOUS RESEARCH

The multidisciplinarity of vulnerability analysis is reflected in the number of literatures that are relevant:

- Vulnerability to climate change
- Adaptation to climate change
- Impacts of climate change
- Natural hazards and responses, especially related to drought, storms, and floods
- Social indicators
- Sustainability.

Findings from research in all these areas contributes to understanding the scope of the problem, the environmental factors that condition coping and adaptive capacity, the human factors that determine coping and adaptive capacity, and various candidate methods for measuring these factors.

Vulnerability, Adaptation, and Impact Research

Much of the literature on adaptation and vulnerability is in the form of case studies.[3] This literature provides richly detailed information on how societies adapt (or fail to adapt) to climatic change and events such as droughts and floods. Smith et al. (1996) focus on managing adaptive change, using theoretical frameworks and sectoral information. Ribot et al. (1996) provide detailed case studies of semi-arid tropical regions, while the case studies in Kasperson et al. (1995) analyze empirical data to determine whether regions such as Amazonia and the Aral Sea basin meet their definition of "critical environmental regions." Single case studies include the US drought of 1987-98 (Riebsame et al. 1991), destruction of mangroves in Vietnam (Kelly and Adger 1999), drought in China (Chen 1991), the urban heat island (Changnon 1981), sea level rise (Nicholls and Leatherman 1995), and many others. Collectively, the case studies provide a benchmark with which to corroborate quantitative assessments of adaptive capacity.

Chambers (1989), summarizing case studies in vulnerability, coping, and policy, asserts that vulnerability is increasing in less industrialized countries. Reasons for this increase include a decline in patron-client obligations (except South India), decline in the support of an extended family, the rising costs of social events such as weddings, and the localized sale of the means of livelihood. The main asset of most poor people is their bodies for physical labor, so health, especially of the breadwinner, is a crucial issue for all members of households. All of these socioeconomic factors reduce the ability of individuals and households to tap into multiple sources of mutual support, thus increasing their vulnerability to the vicissitudes of life.

Downing's work on vulnerability (e.g., Downing 1991, 1992) recognizes the multivariate nature of societal vulnerability as including social, economic, and political structures. Causes of vulnerability may be remote from the site where people are experiencing climate-related impacts (in contrast to Cutter's emphasis on place, discussed earlier). Bohle et al. (1994) frame a causal structure, including the human ecology of production, expanded entitlements in market

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[3] Other techniques used in vulnerability studies include historical narratives, contextual analyses, statistical analyses, and GIS and mapping techniques.

exchanges, and political economy. Poor people depend on others, e.g., informal markets, international aid. Alternative models of causality are the pressure and release (PAR) model, which focuses on the intersection between exposure and a hazard or disaster event, and the access to resources model, which locates root causes in political and economic forces (Blaikie et al. 1994). Meyer (2000) locates people's perceptions about the amenities or disamenities of the weather in their uses of it. For example, people don't notice fluctuations in precipitation until they use hydropower or grow crops that need rain at certain times.

The Intergovernmental Panel on Climate Change (IPCC) established a methodology for vulnerability assessment (IPCC 1991) that included response strategies, focusing on potential sea level rise (see also Bijlsma et al. 1996). Nicholls et al. (1995) assigned two sets of costs: for protection of important areas and for total protection.

The World Coast Conference aggregated case studies to measure vulnerability (WCC 1994), again primarily to assess vulnerability of countries to sea level rise. The results show a wide range of vulnerabilities among 30 countries and 8 localities in five categories (Rahman and Huq 1998, Nicholls 1995): people affected, people at risk, capital value at risk of loss, land at risk of loss, and wetlands at risk of loss. Thus Kiribati and the Marshall Islands are estimated to have 100% of their people affected, Uruguay less than 1%. In a subsequent study of 10 countries (Nicholls and Leatherman 1995), Bangladesh, Senegal, Nigeria, and Egypt appeared most vulnerable (see also Rahman and Huq 1998).

Yohe et al. (1998) outline another method to use existing case studies to analyze vulnerability. First, the analyst identifies existing studies that identify critical impact variables driving prospective change and defining the context of possible adaptive responses. The second step is to determine whether COSMIC (Country Specific Model for Intertemporal Change) reports the variables, or reasonable proxies; if not, the vulnerability analysis cannot be performed. If COSMIC reports the variables or proxies, the third step is to derive ranges of trajectories and perform adaptation analysis. For the final step, Yohe et al. then demonstrate how to plot sustainability areas (circles) and areas representing "not implausible" climatic conditions. The extent of overlap of the two circles will indicate the degree of vulnerability.

Particularly interesting for conceptual purposes are studies that consider ecosystems and human institutions together. Berkes and Folke (1997), for example, stress the importance of a systems approach and adaptive management, emphasizing institutions and property rights. They list socio-ecological practices and mechanisms for resilience and sustainability, including protection of species and habitat, restrictions on harvest, multiple species management, and nurture of sources of ecosystem renewal (Berkes and Folke 1997:418). Folke et al. (1998) locate resource management problems in a failure of fit between the temporal and spatial scales of the institutions that are responsible for management and the ecosystems to be managed; i.e., an institution that must try to manage part of a watershed and report yearly is too narrowly focused to provide long-term resilience in the whole watershed. Ribot et al. (1996) discuss the semiarid tropics as cases of social vulnerability, which is "configured by the mutually constituted triad of entitlements, empowerment and political economy" (Ribot 1996:3).

Natural Hazards and Responses

The literature on natural hazards exhibits a mix of focal points, very often emphasizing the environmental vulnerabilities of specific places as the starting place for discussing societal and governmental responses. Buckland (1997), for example, discusses rainfall in Zimbabwe and yields of agricultural crops (maize hybrids and sorghum). The study locates causes of drought impacts in highly variable yields, population pressures and consequent overfarming, and increased numbers of livestock. Rook (1997), on the other hand, details the relationship between foreknowledge of the 1991-1992 southern African drought and its consequences. In this case, early discussions with donors and timely deliveries prevented disaster.

Burton et al. (1993) characterize the responses to hazardous events as loss acceptance, loss reduction (either control of the event or reduction in vulnerability), changes in resource use, migration, or some combination. Poor societies may have a high capacity to adapt through traditional bearing or sharing of losses. Modern industrial countries share losses with the wider society through relief or insurance programs, and they develop technological fixes.

Much research, mostly using a case study approach, has been done on how the poor adapt to climate or weather hazards. Chen's (1991:108) narrative of a drought-affected village in India contains a good summary of the coping strategies of the poor: "growing a mix of crops and/or rearing a variety of livestock, entering the labour and tenancy (sharecropping) markets as needed, drawing down stored goods or fixed assets, adjusting consumption, borrowing, using common property resources, migrating (seasonal), and drawing upon traditional social security arrangements." One measure of vulnerability that can be used is the number of income- or food-generating strategies that are available to households in an affected society.

Work such as Chen's is rooted in Sen's (1981) analysis of poverty and famines and his theory of entitlements. Sen makes an important distinction between what exists and who can command what is there. The amount of food is unimportant compared to who has access to it. Blaikie et al. (1994) emphasize that demographic characteristics such as age and gender often determine who has access to resources.

Riebsame et al. (1991), in their study of the 1987-1989 drought in the United States, inventory some vulnerability-reducing strategies available to wealthy nations: building and enlarging reservoirs, improving water systems with public funds, changing farm policies, establishing new insurance and aid programs, and taking sensitive lands out of food production. Even so, there were hardships because accurate information was not available or not used, and emergency plans were lacking or out of date.

Research into societal responses to droughts, floods, and extreme weather events provides partial analogues to both capacity to deal with climate change and with its likely negative manifestations. It is well established that climate variability or change factors alone are insufficient to predict whether societies will decline or flourish (see, e.g., Glantz 1988, Meyer et al. 1998); rather, what societies do in response to change determines their well-being. Concluding that people died/fluoresced/migrated/intensified because climate changed simply affirms the consequent without establishing a necessary causal relationship between the events. More valid analysis would ask, for example, "It did get cold and they did die out—but why?" "Intervening between the physical events and the social consequences is the vulnerability of the society and its different groups, activities, and individual members" (Meyer et al. 1998:238).

Sustainability

Banuri et al. (1994:7) enlarge on the Brundtland definition of sustainability by adding the formation of social capital and equity: "Sustainable human development, therefore, can be defined as *the enlargement of people's choices and capabilities through the formation of social capital so as to meet as equitably as possible the needs of current generations without compromising the needs of future ones*." Such a definition has clear implications for vulnerability, in that social capital is key to building resilience. Sustainable development projects, in this view, will be effective only if they are locally designed and controlled, open and participatory, inspirational, and catalytic. Musters et al. (1998) characterize sustainable development as entailing "a permanent political discussion" in which people must choose carefully what to control and how to control. Describing all the valuable features of a socio-environmental system requires detailing both structures and functions, i.e., tables and maps.

The literature on sustainability is broad and deep. The concept can be applied to ecological systems, industrial systems, agriculture, urban areas, and so on; and to geographical and political regions, such as watersheds and countries. Munasinghe and Swart (2000) provide good summaries of the sustainability literature as it relates to climate change.

Environmental and Social Indicators

Considerable attention has recently been devoted to development of indicators of sustainable development, building on earlier work on social and ecological indicators. This work has been conducted in both political and research contexts and was motivated by the conclusion that "commonly used indicators such as GNP and measurement of individual source or pollution flows do not provide adequate indications of sustainability" (Chapter 40 of Agenda 21). The United Nations Commission on Sustainable Development (UNCSD) sought to coordinate a process that reached consensus on a set of indicators that reflected the many concerns encompassed by sustainable development and that could be used and incorporated in internationally comparable reports and databases. The process led to development of a number of different analytical frameworks for indicators of sustainable development. These include approaches that focus on environmental media (e.g., air, water, land, living resources); "goals" (indicators selected according to legal and administrative mandates); "sectors" (indicators of environmental impact from the perspective of economic sectors – transportation, industry, agriculture, etc.); and "thresholds" (warning or "precautionary" indicators which warn when a critical threshold is exceeded).

Across these approaches, a "Driving Force-State-Response" (DSR) model was adopted by the UNCSD that considers the state of components of the human system, the state of the environment, and potential policy or societal responses to reduce forcing of undesirable environmental change (Mortensen 1997). These indicators do not consider the effects of environmental change on human activities. The DSR model tends to encourage static, linear analyses that measure levels and trends, not rates of change, and does not distinguish well between stocks and flows.

WHY VULNERABILITY INDICATORS?

Although "coping and adaptive capacity," and "vulnerability and resilience" are useful integrative and multidimensional concepts for evaluation of the potential effects of climate change, they are also complex concepts that cannot be directly measured or observed. As a result, it is necessary to identify proxy variables or indicators for use in modeling or observation. Desirable indicators are variables that summarize or otherwise simplify relevant information; make visible or perceptible phenomena of interest; and quantify, measure, and communicate relevant information. They should simplify or summarize a number of important properties rather than focus on isolated characteristics of a system. Indicators must be measurable or at least observable, and the methodology used to construct them should be transparent and understandable (Gallopin 1997).

Development of indicators of vulnerability is less advanced but increasingly discussed in both decision-making and research contexts. Within the UNFCCC, indicators of vulnerability have been proposed not only to assist in determining what levels of climate change might be "dangerous" but also to identify countries or groups that are especially vulnerable for the purposes of allocating the proceeds of the clean development mechanism (Kyoto Protocol Art. 12). Vulnerability indicators have been developed for assessing the significance of increased sea level (Nicholls 1995; Nicholls and Leatherman 1995) and changes in agricultural output (Schimmelpfennig and Yohe 1998). Schimmelpfennig and Yohe measure vulnerability in agricultural systems as the probability of crossing a threshold—a 10% reduction below trend in the yields of six major cereal crops.[4] The objective of the indicator is to help farmers evaluate the need for new technologies by indicating vulnerability of their current crops absent adaptation. A high vulnerability index indicates a greater susceptibility to the extreme weather events in the tails of the weather distribution. Their indicator is not intended as a comprehensive analysis of vulnerable systems, but a simple approach to support planning processes and help identify systems where more complete data sets/more comprehensive analytical tools will yield insights.

In addition to these efforts, wealth (typically measured in GDP) has often been used as an indicator of a society's resilience or ability to adapt to climate variability or change. In a recent report on the effects of climate variability, the NRC Committee on the Human Dimensions of Global Change asserted that "Coping strategies are not equally available to all affected actors, and the availability of robust coping strategies is likely to be a function of wealth" (Stern and Easterling 1999). This is a testable hypothesis, not necessarily true or not necessarily true in all circumstances. Certain strategies require institutional infrastructures (e.g., agriculture extension services, insurance markets); others require public expenditures (e.g., flood control, disaster relief, subsidized disaster insurance); others (e.g., informal income support) benefit from the presence of tightly knit communities, which are arguably undermined by government assistance programs. These attributes are not necessarily associated with wealth alone, however, and thus one needs to look at the required resources for implementation of different strategies to assess whether they are viable in different circumstances. Small and subsistence farmers have little financial flexibility in responding to climate variability (and ENSO forecasts), but they are by definition survivors, able to cope with existing weather patterns and uncertainties. They may, for example, have the ability to use strategies that rely on planting a mix of crops that respond to varied climate conditions, and thus reduce the risks posed by large-scale commercial mono-cropping (see, for example, Ribot et al. 1996).

Many have harshly critiqued the notion that wealth is an adequate proxy of adaptive capacity. For example, Stockhammer et al. (1997:19), in proposing an index of sustainable economic welfare, noted that "[h]ardly anyone would argue explicitly that GDP measures economic welfare, but everyone is using it in a way as if it did." Other measures of human welfare, including the human development index (HDI) (UNDP 1990) and Putnam's (1993) measurements of institutional performance, have been designed to ameliorate the shortcomings of both the notion that wealth automatically yields the ability to provide the good life for all citizens and the assumption that GDP measures well-being; these are also potentially relevant to analysis of adaptive capacity. Social welfare indicators display a wide range of measurements and factors to be measured. Included in the Human Development Index, for example, are average life expectancy, proportion of people with access to health services, adult literacy rates, income per

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[4] The question of thresholds is not an easy one to answer. A percentage reduction in yield could be a threshold; so too could a number of years of crop failure, either in succession or in a given timespan (e.g., 2 in 5 years). Furthermore, we have no good way of estimating the probability that a threshold will be crossed.

capita, childhood mortality rates, immunization rates, school enrollment for girls, and the proportion of people in urban and rural areas. Other indicators have been devised to measure the degree of democracy in a country, the degree of individual freedom, civil society, and so on. El Sarafy (1997) has devised a system of integrated environmental and economic accounting (SEEE) that includes income depletion using a method that converts revenue from extraction into an income stream and corrects for pollution effects. The "Genuine Progress Indicator" (Cobb et al. 1995) contains negative adjustments to GDP to account for harms to society, for example, the depreciation of environmental assets and natural resources.

Other measurement methods that have been attempted for vulnerability analysis include household models, income estimation, and domestic resource capacity (Vogel 1997). Household models can describe in detail the strategies of a typical household, but there is difficulty in aggregating such a micro scale analysis. Income estimation has all the disadvantages of a single measure and must be supplemented with anecdotes or case studies. Domestic resource capacity resembles, in Vogel's account, a cost-benefit analysis that elides consideration of differential impacts. This may be an issue in using any aggregated measure, including indicators. However, constructing a transparent process for developing indicators and making the contributing data available for inspection can address this issue.

The initial investigations into anthropogenic climate change focused on environmental processes; later research into economic and social/institutional issues largely ran on a separate track as part of human dimensions programs. Integration of these perspectives has been difficult. Physical scientists have attempted various methods to solve the integration problems inherent in computer-based and quantitative models with different foci and at different scales (e.g., agriculture, carbon cycle, climate, hydrology, pollution). Social science research has tended to be located in governance issues at the national and international level.

Integrated assessment approaches the issue of representing environmental and social perspectives by using the common factor of economic measures, typically environmental and health damages denominated in dollars. The very aggregated "bottom line" approach of integrated assessment, while helpful in scoping the overall magnitude of climate change effects, has proven insufficient to guide policy that must take into account the differential contributions to and impacts from climate change in different countries and regions of the world.

Developing proxy variables and indicators for use in modeling or observation enables sophisticated vulnerability analyses that integrate environmental and social perspectives. In short, the "quest is for a *limited* yet *comprehensive* set of *coherent* and *significant* indicators, which can be *monitored* over time, and which can be *disaggregated* to the level of the relevant social unit" (Andrews and Withey 1976:4).

VULNERABILITY INDICATORS: PROTOTYPE DEVELOPMENT

We identified proxies for five sectors of climate sensitivities: settlement sensitivity, food security, human health sensitivity, ecosystem sensitivity and water availability; and for three sectors for coping and adaptive capacity: economic capacity, human resources and environmental or natural resources capacity. Tables 1 and 2 list the proxy variables and key hypothesized relationships that were used in constructing the subcomponents of the vulnerability-resilience 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. Figure 1 depicts the hierarchical framework we used in aggregating the proxies into sectoral indicators, sensitivity and coping/adaptive capacity indicators and vulnerability-resilience indicators. This framework emerged from an iterative process of identifying sectoral climate sensitivities and coping and adaptive mechanisms and the relevant proxies, finding the necessary baseline data (USA and world), and identifying relevant outputs from integrated assessment models that could be used in projections of vulnerability to socioeconomic and climate change.

An overview of the indicators and procedures is presented below.

Table 1 Indicators, sectors, proxies and sources

Indicator	Sector	Proxy	Source
Sensitivity	Settlement/ Infrastructure	Sea level rise resulting in number of people at risk	Delft Hydraulics 1993
		% Population with access to safe water	World Bank 1998
		% Population with access to sanitation	World Bank 1998
	Food Security	Cereal production/ agricultural land	World Bank 1998 & FAOSTAT98
		Animal protein demand per capita	World Bank 1998 & FAOSTAT98
	Human Health	Birth rate	World Bank 1998
		Life expectancy	World Bank 1998
	Ecosystems	% Managed land	FAOSTAT98
		Fertilizer use/area cropland	World Bank 1998
	Water Resources	Water sensitivity, based on availability and consumption	World Resources 1994-95
Coping-Adaptive Capacity	Economic Capacity	GDP per capita	World Bank 1998
		Income distribution equity	World Bank 1998, Deininger and Squire 1996, 1998 & www.worldbank.org/research/growth/dddeisqu.htm
	Human and Civic Resources	% Population in the workforce	World Bank 1998
		Illiteracy	World Bank 1998
	Environmental Capacity	% Non-managed land	FAOSTAT98
		SO_2 emissions	GEIA, Benkovitz et al. 1991
		Population density	World Bank 1998

PNNL's MiniCAM integrated assessment model (Edmonds et al. 1997) and post-processor Sustain (Pitcher 1997) outputs were used for our projections (see also Table 9). 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, sea level change, and several socioeconomic variables. A post processor was used to calculate changes in some socioeconomic variables that are not part of the standard model outputs, but for which relationships with model outputs are postulated in the literature. The socioeconomic scenarios were developed based on the IPCC scenarios described in its Third Assessment Report (Nakicenovic et al. 2000). To test whether the projections developed were plausible, we used, in some cases for some countries, 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.

Table 2 Proxy explanations

Proxy	**Proxy for** (from Moss et al. 2000)
Sea level rise resulting in number of people at risk	Potential extent of disruption from sea level rise and surges
% Population with access to safe water % Population with access to sanitation	Access of population to basic services to buffer against climate variability and change
Cereal production/ agricultural land	Degree of modernization in the agriculture sector; access of farmers to inputs to buffer against climate variability and change
Animal protein demand per capita	Access of a population to markets and other mechanisms (e.g., consumption shift) for compensating for shortfalls in production
Birth rate Life expectancy	Composite of conditions that affect human health including nutrition, exposure to disease risks, and access to health services
% Managed land	Degree of human intrusion into the natural landscape and land fragmentation
Fertilizer use/area cropland	Nitrogen/phosphorus loading of ecosystems and stresses from pollution
Water sensitivity, based on availability and consumption	Supply of water from internal renewable resources and inflow from rivers. Withdrawals to meet current or projected needs
GDP per capita Income distribution equity	Distribution of access to markets, technology, and other resources useful for adaptation
% Population in the workforce	Social and economic resources available for adaptation after meeting other present needs
Illiteracy	Human capital and adaptability of labor force
% Non-managed land	Landscape fragmentation and ease of ecosystem migration
SO_2 emissions	Air quality and other stresses on ecosystems
Population density	Population pressure and stresses on ecosystems

Sensitivity Indicators

Settlements/infrastructure sensitivity

Settlement sensitivity 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 et al. 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, land slides, 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).

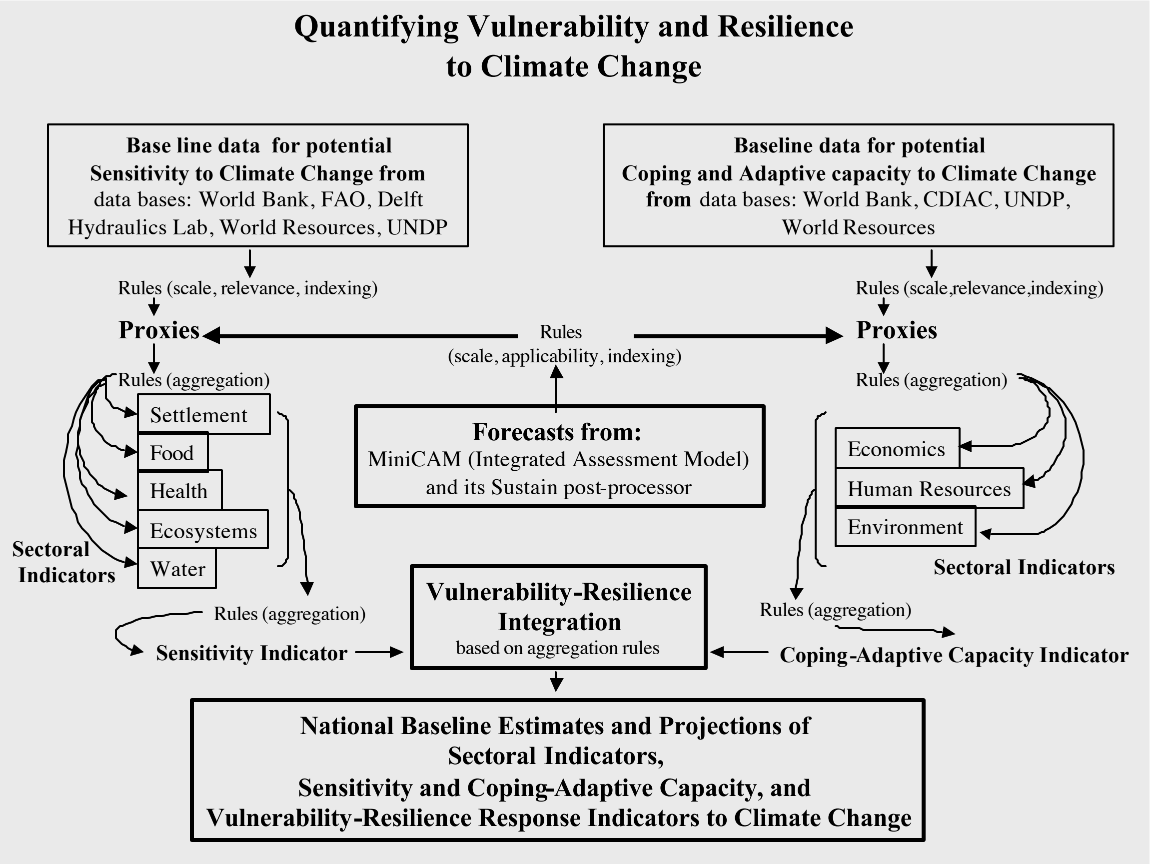

Figure 1 The basic framework of the vulnerability-resilience indicator prototype (VRIP) calculations

Three 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 populations 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 populations in a country without access to safe water and sanitation are obtained from historical data; projections are derived by scaling these observations using MiniCAM's outputs of regional GDP per capita, and then indexing this to the USA and world baseline value for 1990. The settlement sensitivity indicator 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 safe water and sanitation.

Food sensitivity

Sensitivity to food security 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 socioeconomic 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 high 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 indicator 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 indicator are calculated for 1990 using data from FAO (FAOSTAT98 and World Bank 1998). Future projections of cereal production per unit area are calculated from the MiniCAM projected crop production/region and area of country, which are then scaled to the USA and to the world baseline value for 1990. The animal protein consumption per capita projections are calculated from MiniCAM outputs of animal demand/region and assumed population growth/region, which are then scaled to the USA and to the world baseline value for 1990.

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 transitional 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 the World Bank (1998). 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 and to the world baseline value for 1990. Future life expectancy and birth rates from the Sustain outputs for the region are used in the projections. The health sensitivity indicator is calculated as the geometric mean of the scaled proxies for the fertility rate and life expectancy.

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 ecosystem sensitivity indicator is calculated as the geometric mean of the scaled proxies for land use (100% minus the % unmanaged land and old forest) and fertilizer.

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 outputs, and the recalculated percentage of managed land/country is scaled to the USA and to the world baseline value for 1990.

Fertilizer use per 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 nonlinear. 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 600 kg/ha, sensitivity increases, due to increasing loads of pollutant runoff. Projected changes, calculated as percent change from 1990 values by MiniCAM outputs of cereal production per projected cropland area, are used to calculate changes in projected fertilizer use/unit area. When projected fertilizer use exceeded 600 kg/ha, MiniCAM's projected increase in crop production was assumed to result from other agricultural management changes than fertilizer use, given that at present fertilizer use above a 600 kg/ha does not increase crop yield in general. The projected values are scaled against the USA and the world baseline values for 1990.

Water availability

Climate variability already has a large impact on the general hydrology of a landscape and on the availability of water at the local and national scale, and climate change can be expected to have as large or larger an impact. Presently, 19 countries around the world are classified as water-stressed (Watson et al. 1998). This number can be expected to change due to population growth, changes in land use, precipitation, and evapotranspiration (linked to temperature increase). Moreover, not only will socio-economic aspects of society be affected through changes in water availability, but also government policies can be expected to respond.

Presently, we have defined the sensitivity to water availability through one proxy, composed of withdrawals to meet current or projected needs and (divided by the sum of) the supply of water from internal renewable resources and inflow from rivers. Future projections of national water availability are scaled by means of the MiniCAM projected crop production/region, using the same indexing and scaling procedures as for the other sensitivity indicators. Actual changes in climate affecting precipitation and temperature (e.g., GCM outputs), and changes in land use, besides changes in agricultural land use, have not yet been incorporated in the forecasts. Moreover, the proxy projections do not account for the direct effects of population growth and the present or future intensity (level) of regional or national water management.

Coping-Adaptive 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[5]) per capita as one of the proxies for economic capacity. The 1990 GDP per capita (World Bank 1998) for a country is used as a starting point. Projections are calculated using MiniCAM outputs of GDP and assumed population growth in the region in which the country is located; the GDP per capita for each country is then scaled to the USA and to the world baseline value for 1990. However, in societies where the distribution of wealth or income is very unequal, coping capacity will also be unequally distributed. Thus we attempted to include unequal distribution of income within a society as a component of our indicator of coping-adaptive capacity. Neither historical data nor projections are readily available for income inequality. We identified 1990 values for our sample countries (Deininger and Squire 1996, 1998;www.worldbank.org/research/growth/dddeisqu.htm), and then scaled these to the USA and to the world baseline for 1990. We held these values constant during our projections on the assumption that changes in the distribution of income 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 per capita. The economic coping-adaptive capacity indicator is calculated as the geometric mean of the scaled proxies for GDP per capita and the index of income inequality.

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[5] We did not use purchasing power parity (PPP) adjusted GDP per capita because over the course of the century for which we make projections. PPP will clearly change as countries develop. Using a fixed PPP adjustment wildly inflates that level of wealth in countries that are currently poor to the point that their GDP per capita dwarfs that of those countries that are currently economically developed.

Human resources

Human and civic resources are another critical component of the coping and adaptive 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 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 outputs from the Sustain model for the region in which the country is located. The dependency ratio is scaled to the USA and to the world baseline value for 1990, with the result that an increase in the dependency ratio decreases coping-adaptive capacity.

The literacy rate (World Bank 1998) was also included as a measure of the skills that individuals would have to have in order to adapt. Development of historical data on illiteracy/literacy at a country level requires interpolation from available information. Illiteracy data were recalculated as percentages of a population which are literate and scaled to the USA and to the world baseline value for 1990, so that higher literacy rates imply better coping capacity. The human and civic resources coping capacity indicator is calculated as the geometric mean of the scaled proxies for age dependency and literacy and projected by means of Sustain output.

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.

Environmental Coping and Adaptive Capacity

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 on 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 and adaptive 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, 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 and to the world baseline value for 1990. Baseline SO_2 emissions by country per unit area are developed using 1985 data from the Carbon Dioxide Information Analysis Center (CDIAC) and GEIA. Projections are based on the percentage change in emissions in a region as projected by MiniCAM, and then scaled to the USA and to the world baseline value for 1990 for purposes of standardization. Baseline population density for each country is calculated from 1990 data from the World Bank (1998). Projections are developed by scaling national baselines using MiniCAM scenario assumptions for the region in which the country is located, scaled to the US and world 1990 baseline. The environmental coping and adaptive capacity indicator 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).

Additional considerations: Time - and Spatial Scales

With an acknowledgement that "the world is not a set of Chinese boxes" (Folke et al. http://www.uni.bonn.de/ihdp/wp02main.htm) scale is all-important in evaluating and comparing vulnerability of specific units to potential changes in climate. For the initial development of vulnerability-resilience indicators we chose to calculate at the national level. This choice was primarily driven by data availability. In principle, an integration of sensitivity-relevant spatial units and response-time-determined temporal scales can deliver more insightful results.

With regard to the temporal scale, Rothman (1998:180) states that rapid turnover attributable to rapid growth implies quicker replacement of older, dirtier technology. Reilly and Schimmelpfennig (1999:772) present a table of adjustment times for various adaptation measures applicable in agriculture: fertilizer adoption, 10 years; transportation systems, 3-5 years; irrigation equipment, 20-25 years; opening up of new land, 3-10 years; new crop adoption, 15-30 years; change in tillage, 10-12 years; development of crop varieties 8-15 years; dams and irrigation, 50-100 years. Watson et al. (1998:23) list some time scales relevant to processes influencing the climate system: restoration/rehabilitation of damaged or disturbed ecological systems, decades to centuries; equilibration of sea level given a stable climate, centuries; equilibration of climate given a stable level of greenhouse gas concentrations, decades to centuries; stabilization of atmospheric concentrations of long-lived greenhouse gases given a stable level of emissions, decades to millennia; turnover of capital stock responsible for emissions of greenhouse gases, years to decades.

With regard to the spatial scale of sensitivities, the national scale is a poor one for biophysical reasons. Watersheds, elevation levels, latitudinal belts, flood plains, wetlands, coastal zones, type and extent of agricultural and physiographic zones, etc. are much more relevant. Countries can also be dissected, for example, based on type or intensity of economic activity, or on being rural versus urban. Given, however, that response to impact will be decided often at the national level, the national scale remains relevant. The economic unit of interest, the whole nation, will often determine the policy response and resource allocation to subnational units.

BASELINE CALCULATIONS OF NATIONAL VULNERABILITY AND RESILIENCE

Methods

For step one in our calculations, data were collected for the proxies (Table 1) for the year 1990, representing the baseline year for the calculations for 38 countries and the world (see also Table 5). When data were not available for a year, linear interpolations between available data from close-by years were performed to obtain the 1990 values. In a couple of instances, when not all data were available for a specific country, data were scaled from an economically analogous country, i.e., North Korea data from China, Ukraine data from the Former Soviet Union. When world data were not available, available national data for that proxy were population-weighted to obtain world values.

For step two, we indexed (scaled) the proxies against (a) the 1990 world data, which were set to 100, and (b) as an alternative, against the 1990 USA data, set to 100. Through these procedures we obtained two sets of indexed proxies.

Step three consisted of calculating the sectoral indicators, sensitivity and adaptative capacity indicators and the overall national vulnerability-resilience (VR) indicators. This was performed by aggregating the information hierarchically: the geometric means of the indexed proxies determine the value of a sectoral indicator and the geometric means of the sectoral indicators become indicators for sensitivity (S) to climate impact or coping and adaptive (CA) capacity. A simple difference between the coping-adaptive capacity as a positive value and sensitivity as a negative value becomes the value of the vulnerability-resilience indicator (see Table 1 and Figure 1). The relative value of the vulnerability-resilience indicator indicates where a country stands relative to other countries in its sensitivity and capacity to cope and or adapt to climate impacts. The vulnerability-resilience indicators can easily be decomposed into all their contributing aspects and remain therefore transparent. Analyzing the overall VR indicator for its sensitivity and coping and adaptive capacity and contributing sectors and/or proxies is informative for the further development of the prototype.

Results

Overall national baseline vulnerability and resilience of 38 countries and a first decomposition in sensitivity and coping-adaptive capacity

An important question in constructing indicators, for indicator comparison potential, is what they will be indexed to: average world values or US values? We performed side-by-side and statistical analyses of results for each method. We decided on world baseline values because theory indicates that country-to-country comparisons will be thereby facilitated. Differences between the two sets of values are discussed below.

Vulnerability-resilience indicators range widely when we index the proxy data against world based data (Figure 2) and we find both developing and developed countries to be variably vulnerable to socioeconomic change and climate impacts. Neither the sensitivity nor the coping-adaptive capacity determines the level of vulnerability exclusively (Figure 3). This is confirmed through a simple correlation analysis. The squared Pearson correlation coefficient between the sensitivity and vulnerability-resilience indicator for the 39 observations is 0.62, while it equals 0.52 between coping and vulnerability-resilience.

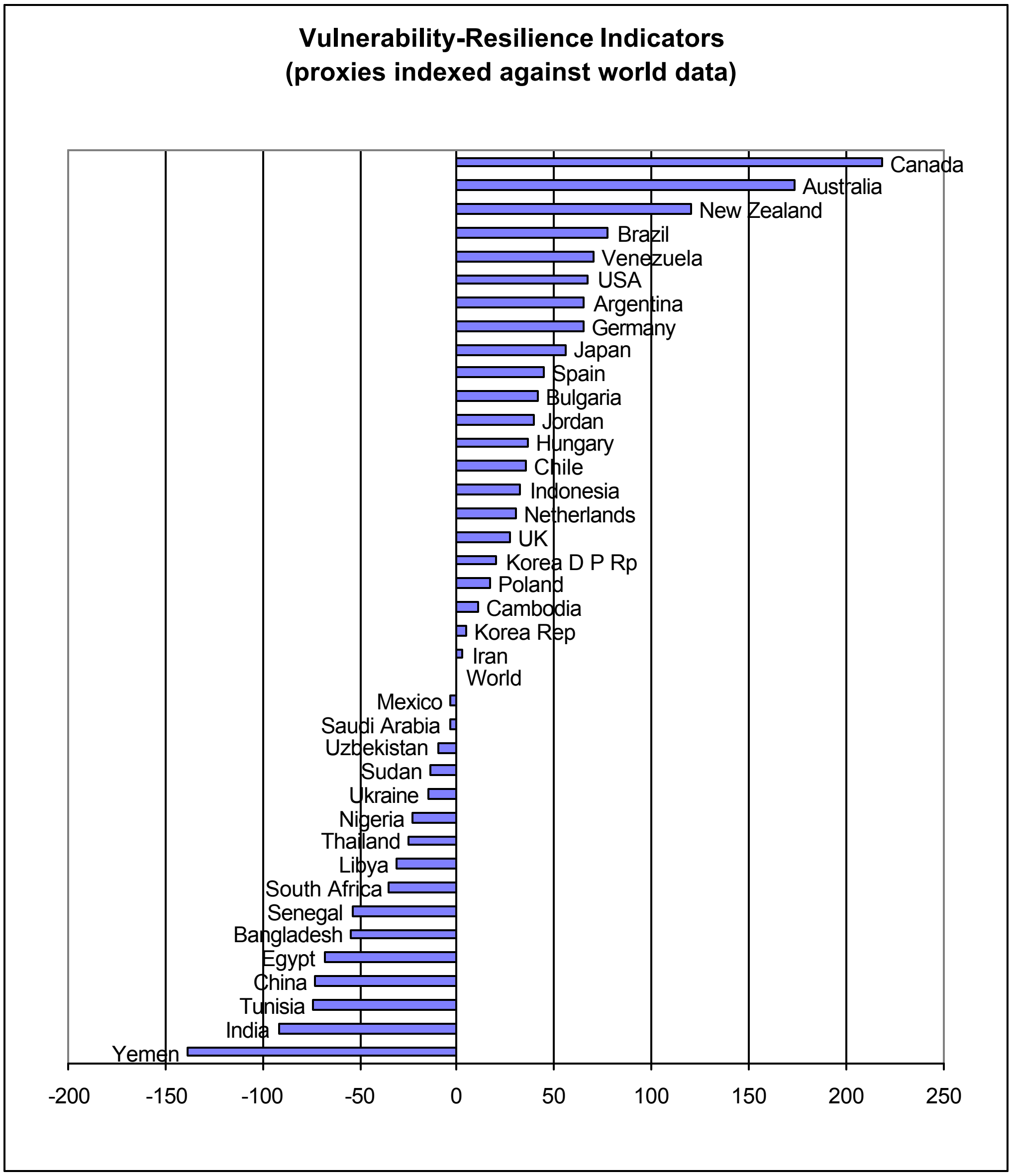

Figure 2 Baseline vulnerability-resilience indicators (proxies indexed against world baseline data)

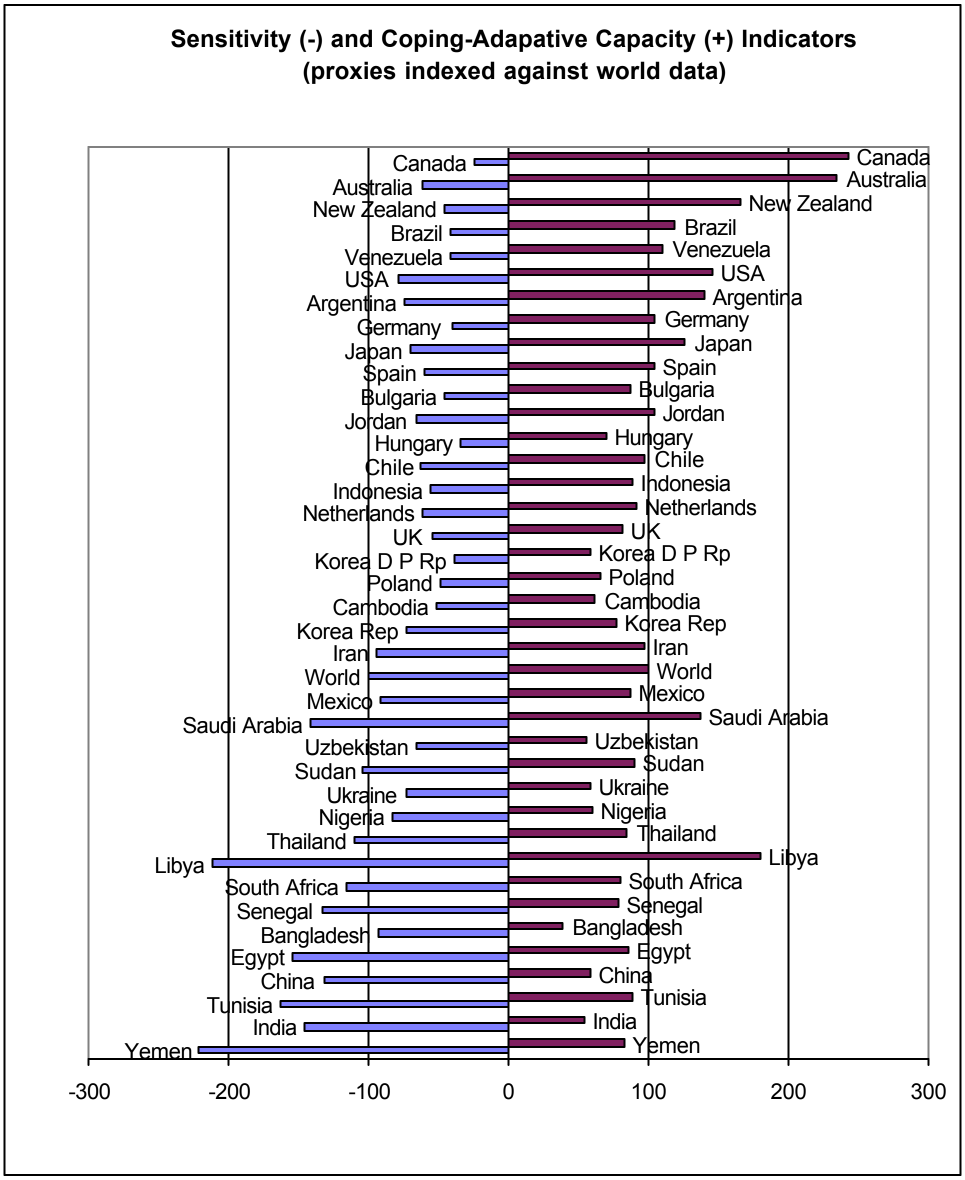

Figure 3 Baseline sensitivity and coping-adaptive capacity indicators (proxies indexed against world baseline data)

When we index the proxies against USA baseline data, all countries show increased vulnerability (Figure 4). Sensitivity, in general, shows an increase with this increased vulnerability, while coping-adaptive capacity is more varied (Figures 4 and 5). This, again, can be quantified through a simple correlation analysis. The squared Pearson correlation coefficient between the sensitivity and vulnerability-resilience indicator is 0.83, confirming the systematic increase in both the sensitivity and vulnerability of countries when indexing is based on USA baseline data compared to world baseline data. The correlation between the coping-adaptive capacity and vulnerability drops from 0.52 to 0.28, illustrating the more varied change in the overall coping and adaptive capacities of the countries when indexing would be USA-based.

Not only do the correlations among aggregates change when we index against USA baseline values instead of to world baseline values, the countries shift in their relative locations to each other. For example, Libya's vulnerability increases to the 4th lowest when indexed against USA baseline data (Figure 4) from 9th lowest when indexed against world baseline data (Figure 2), and Hungary shifts from 13th in resilience when indexed against world baseline data (Figure 2) to 7th when indexed against USA baseline data (Figure 4). The shifts result from different balances between sensitivity and coping values because of different weights of the indexed proxies.

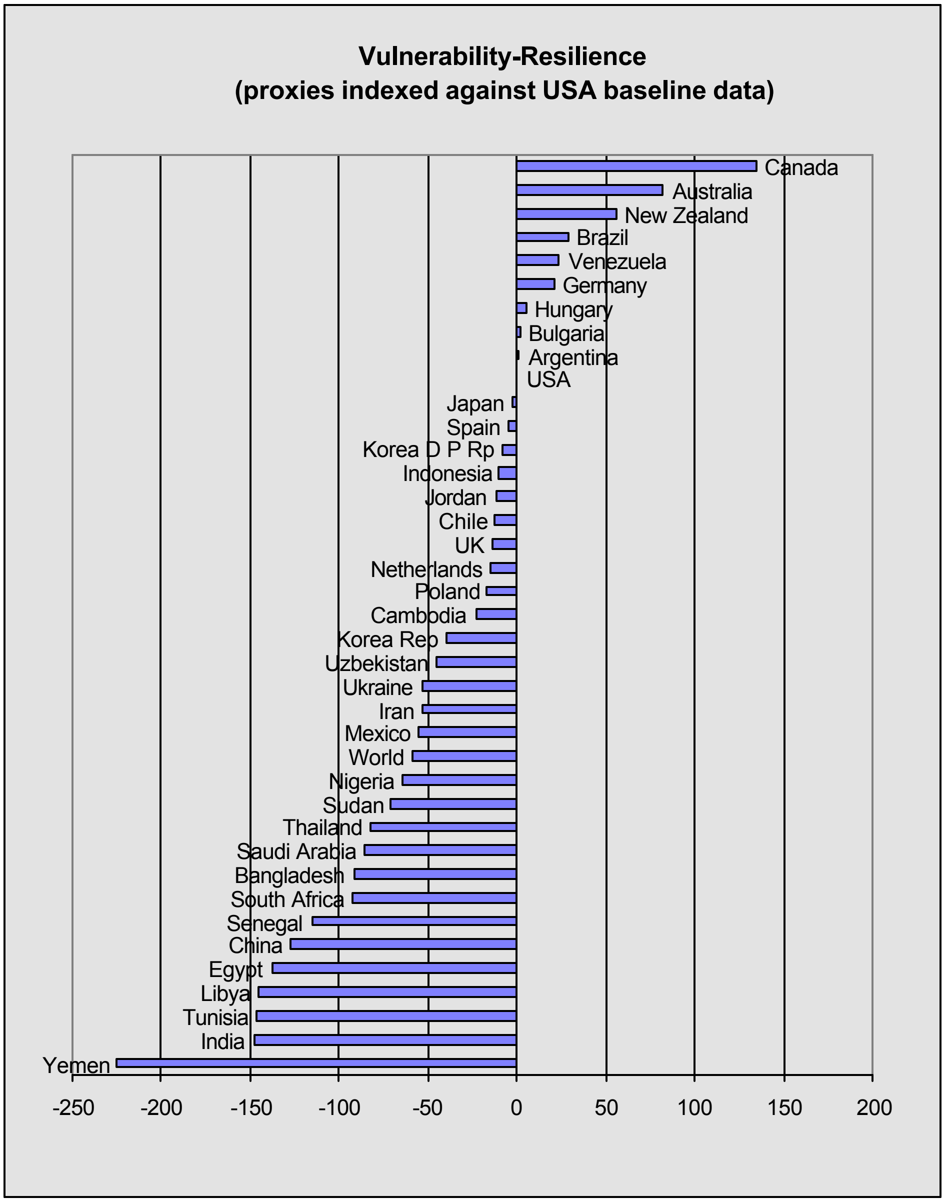

Figure 4 Baseline vulnerability-resilience indicators (proxies indexed against USA baseline data). Compared with Figure 2 (proxies indexed against world baseline data), vulnerability is increased and the relative positions of countries are somewhat altered

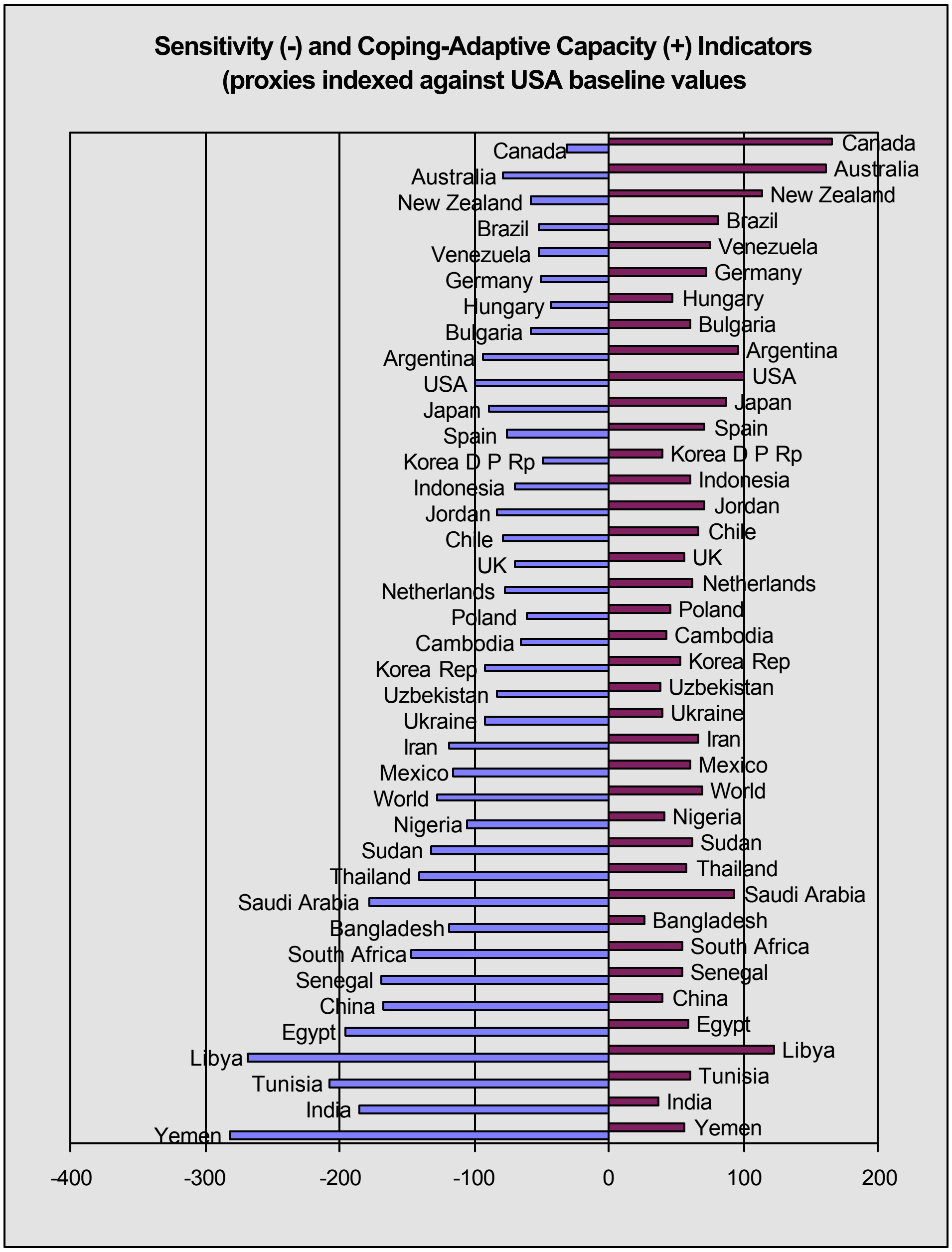

Figure 5 Baseline sensitivity and coping-adaptive capacity indicators (proxies indexed against USA baseline data). Compared with Figure 3 (proxies indexed against world baseline data), sensitivity in general increases and coping and adaptive capacity is more varied

Decomposition of baseline vulnerability-resilience to the indexed proxy level

Individual indexed proxy values shift systematically when indexed against world versus USA baseline values. A similar but more complex shift occurs at the model level when the vulnerability-resilience indicator is calculated from the sensitivity and coping-adaptive capacity aggregates. The model structure for calculating the vulnerability-resilience indicator (the hierarchical combination of proxies into sectoral indicators and sectoral indicators into sensitivity and coping-adaptive capacity from which the arithmetic difference becomes the vulnerability-resilience indicator value) keeps the values of country-level vulnerabilities dependent on the relative weight of the values of the proxies. The vulnerability-resilience indicator values are thus not uniformly shifted but are dependent on the baseline values to which they are indexed. Figure 6 illustrates the non-uniform shift in the national vulnerability-resilience indicators. Libya (triangle), Saudi Arabia (larger triangle), and Yemen (still larger triangle)'s overall vulnerability-resilience indicators shift due to the different weight of the water sensitivity because of the indexing against either world or USA baseline data. For Australia (square) and Canada (larger square) major shifts in population density and sulfur emissions tend to compensate for each other but still produce more than an average shift. And for Germany and Japan, shifts in the indexed GDP per capita are major contributors but are compensated for in shifts in other indexed proxies, resulting in an average shift in vulnerability-resilience for those countries.

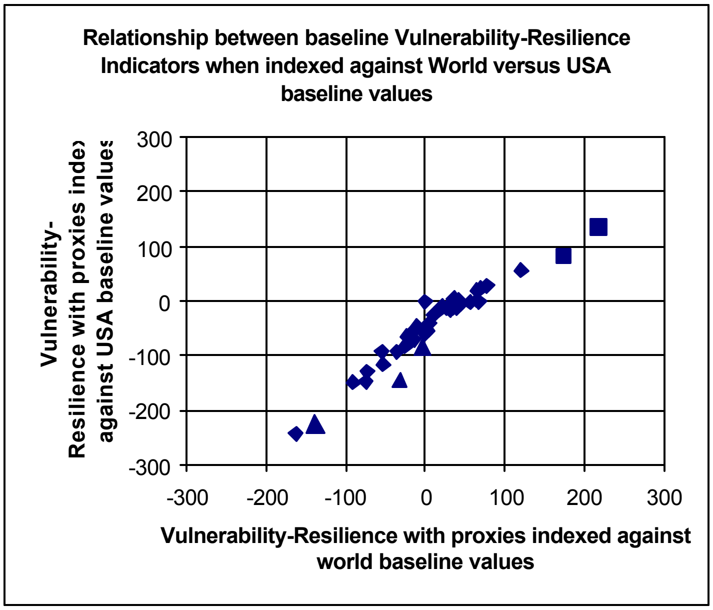

Figure 6 The effect of indexing procedures on the vulnerability-resilience indicator

Using the model, we examined the role of the GDP per capita proxy in vulnerability. The literature strongly suggests that wealth or income is a key determinant of vulnerability-resilience, but our analyses do not confirm that wealth is a necessary or a sufficient condition to establish a level of vulnerability-resilience.

When the indexed GDP per capita data (Figure 7: x-axis) for all analyzed countries are plotted against their calculated vulnerability-resilience indicator values (Figure 7: y axis), we find that only Japan and Germany claim higher GDPs per capita than the USA (the USA value is the enlarged diamond; Germany and Japan are on the right of the USA value when following the x-axis). These figures also show that high GDPs per capita for countries are not necessarily linked to higher resilience (Low GDP countries show a wide variety of VR indicator values; see the y-axis).[6] The global baseline vulnerability-resilience indicator of zero (enlarged square) has as equivalent $3,400 US-1987 as actual GDP per capita; the USA's baseline vulnerability-resilience indicator (enlarged diamond) of 68 has as equivalent $19,655 US-1987 as actual GDP per capita.

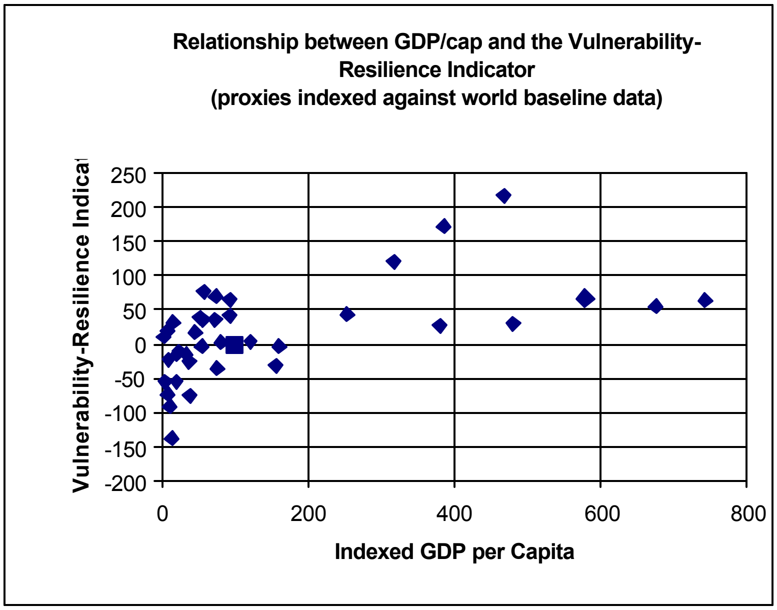

Figure 7 Relationship between the vulnerability-resilience indicator and the GDP per capita indexed against the world baseline data

When we analyze the USA vulnerability-resilience indicator (of 68) for its underlying proxy values, we find GDP per capita as major contributor (Figure 8). We show sensitivities as positive values in the radar graphs. Sensitivities are located on the right in the radar graphs, coping and adaptive capacities on the left. Figure 9 shows the sectoral indicators of the USA vulnerability-resilience indicator. Figure 9 indicates that sensitivity to water availability might well be compensated for by the economic coping capacity, while human resources add some to the resilience side of the overall vulnerability-resilience indicator. We also sense that the ecosystem sensitivity can be compensated for by the environmental coping-adaptive capacity in an equal measure.

This type of analysis raises more general questions about the interactions among proxies and among sectors. First, what compensatory proxy and/or sectoral indicator values determine the overall vulnerability-resilience indicator value? Second, how should proxies be combined into indicators? Finally, how can we account for diverse conditions?

An example that addresses the last question relates to the proxies for environmental coping-adaptive capacity: sulfur emissions, population density and percentage unmanaged land. These

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[6] Reilly and Schimmelpfennig (1999: 753) consider both "the nature of economic growth and the distribution of its benefits important in determining future vulnerability to climate change" and point out that there are "countries that have achieved high levels of human development in terms of life expectancy, infant mortality, and educational attainment with relatively low per capita income, while others have achieved relatively high average per capita income with little improvement in the welfare of large segments of the population."

proxies can be expected to vary greatly depending on regions within countries. National-scale analyses will not reflect local population densities and pollution, and local settlement sensitivities. The scale questions, addressed briefly above, should be, therefore, kept in mind. In order to capture the diversity at smaller scales, subnational regions would need to be defined and assessed separately. These smaller regions could be principal agricultural regions, cities, coastal areas, and so on.

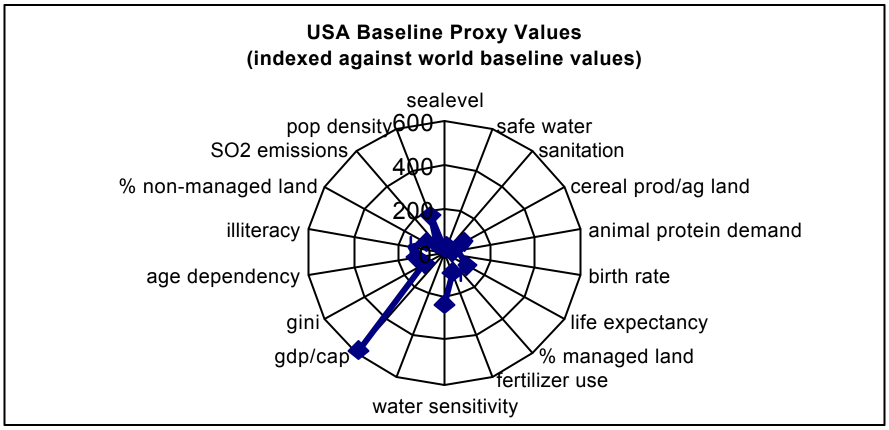

Figure 8 USA's vulnerability decomposition into 17 proxies

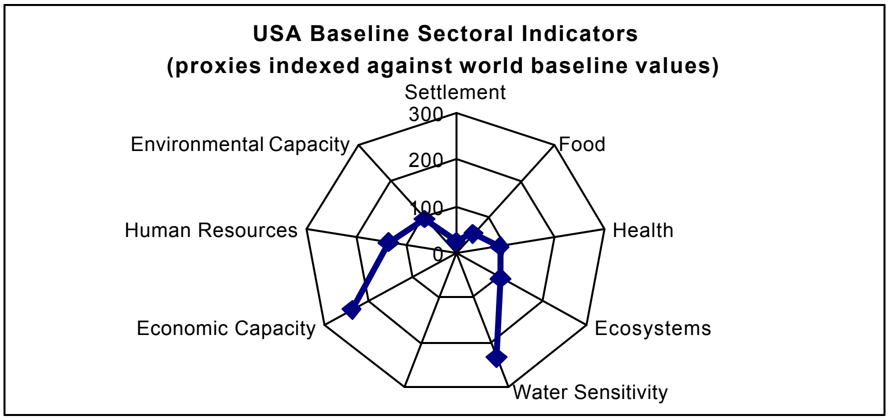

Figure 9 USA's vulnerability decomposed into 8 sectors

Looking at another proxy, we expected present sea level surges and percent population potentially affected to be an important aspect of settlement sensitivity even in 1990 for some countries. In the present way of combining proxies into sectors this aspect of settlement sensitivity may be lost.

We therefore calculated the VR indicator when settlement sensitivity did not include the proxies for infrastructure development, that is, access to clean water and sanitation—but purely based on the percent population at risk due to sea level surges (Table 3). Values of settlement sensitivity then increase or decrease dependent only on how the quality of the infrastructure for a country weighs against the risk of the population exposed to sea level surges. When proxies for the quality of infrastructure are omitted in our calculations, the sea level effect proxy does contribute to overall vulnerability to a large degree for the Netherlands, Senegal and Bangladesh, for example (Figure 10). This manifests itself clearly in the shift in the overall vulnerability-resilience indicator. We also find that not all shifts are in the direction of increased vulnerability (see, for example, Australia, the Sudan, Saudi Arabia and Iran). And we find that the shift for the Netherlands is larger than for Senegal and Bangladesh. For Senegal and Bangladesh the impact of the access to clean water and sanitation on the settlement sensitivity indicator is less than for the Netherlands given that the settlement sensitivity is high in either case (with or without access), while for the Netherlands access to clean water and sanitation compensates for its sensitivity to the sea level rise proxy when those proxies are included. Due to averaging sectoral indicators through geometric means, the higher settlement sensitivity indicator values for Senegal and Bangladesh when access to clean water and sanitation are not included do not affect the final sensitivity indicator and the overall VR indicator as much as expected.

This analysis shows that access to clean water and sanitation, initially conceived as a sensitivity measure, also functions as a compensatory (coping-adaptive capacity) measure within the settlement sector because when infrastructure of a country is good, sea level surges and sea level rise will have diminished impact compared to when infrastructure is not as good.

This exercise demonstrates that our method for calculating vulnerability-resilience indicators reflects both the individual proxies (so selection of proxies is very important) and the interactions among proxies (so the composition of the set of proxies is also very important). Moreover, the "backward" analysis of how proxies and indicators vary can yield more insight about the study region than a simply calculation of results.

Table 3 Shift in the vulnerability-resilience indicators due to eliminating the proxies for the quality of the infrastructure

	Vulnerability-Resilience indicator	without access	Settlement Sensitivity indicator	without access	Overall Sensitivity indicator	without access	Coping-Adaptive Capacity indicator
Canada	218	215	2	4	25	28	243
Australia	173	178	11	7	62	57	235
New Zealand	120	122	16	14	46	44	166
Brazil	78	88	16	4	41	31	119
Venezuela	70	80	16	4	41	30	111
USA	68	70	25	21	79	76	146
Argentina	65	72	53	33	74	67	139
Germany	65	34	0	7	40	71	105
Japan	56	60	16	12	70	66	126
Spain	44	16	2	11	60	89	104
Bulgaria	42	44	2	2	46	43	87
Jordan	39	66	1	0	65	38	104
Hungary	36	48	1	0	34	21	70
Chile	35	42	25	14	63	56	98
Indonesia	33	44	39	12	55	44	88
Netherlands	30	-65	3	305	61	156	91
UK	27	-4	4	34	55	85	81
Korea D P Rep	20	-3	0	3	38	61	59
Poland	17	13	1	2	48	53	65
Cambodia	10	19	87	36	51	43	62
Korea Rep	5	-18	3	12	73	95	77
Iran	3	35	8	1	94	62	97
World	0	0	100	100	100	100	100
Mexico	-3	14	24	8	91	74	87
Saudi Arabia	-4	31	8	2	141	106	137
Uzbekistan	-10	19	2	0	66	37	56
Sudan	-14	28	12	1	104	62	90
Ukraine	-15	6	5	1	73	52	58
Nigeria	-23	-5	39	11	82	64	60
Thailand	-26	-25	60	58	110	109	85
Libya	-31	-52	37	59	211	231	180
South Africa	-36	-12	32	10	115	92	79
Senegal	-54	-78	264	605	133	157	79
Bangladesh	-54	-76	291	838	93	115	39
Egypt	-69	-81	146	215	154	167	86
China	-73	-84	103	154	132	143	59
Tunisia	-74	-69	44	37	163	158	89
India	-92	-91	119	118	145	145	54
Yemen	-139	-115	67	38	221	197	82

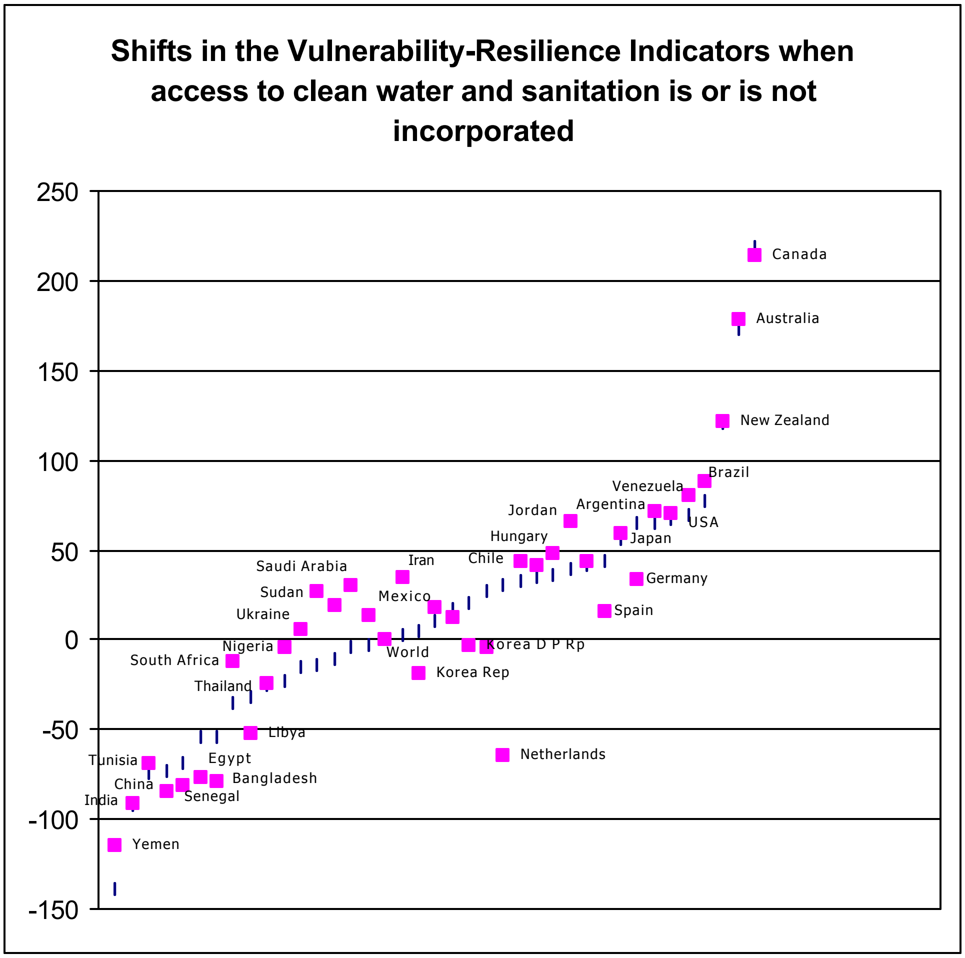

Figure 10 Shifts in national vulnerability-resilience indicators due to eliminating the proxies for the quality of infrastructure, that is, access to clean water and sanitation (vertical bars=when access is included; squares=when access is not included in the indicator), sorted by, when access is included.

Observations

Indexing proxies against either world or USA baseline data results in differences in proxy weights, which result in differential weighting within and among sectors and consequently in potential different countries' vulnerability-resilience rankings as was shown in Figures 2 through 5. Addition or elimination of proxies and or sectors also results in potential differences in national vulnerability-resilience indicators. Thus, at what level potential compensatory mechanisms ought to be weighed against each other when building the hierarchy of indexing proxies, combining proxies into sectoral indicators, and aggregating sectoral indicators becomes a crucial question. And, when proxy values are derived from different types of units, what are the consequences?

We presently evaluate the arithmetic difference of the sectoral aggregates of sensitivity and coping as vulnerability-resilience indicator. Alternatively, we could look at a national vulnerability as a summation of sectoral vulnerabilities. Sectoral vulnerabilities could be built as arithmetic differences in sensitivity and coping at the sectoral level. For example, settlement vulnerability could be composed of the sensitivity of sea level change and proneness to floods and mudslides, and coping with sea level change, floods, and mudslides based on wealth, a measure of the infrastructure and a measure of information technology. Similarly, food vulnerability could depend on local sensitivity of production, the available supply from the outside, the balance of local production and outside sources, etc. Keeping vulnerability *specific* with regard to a particular consequence would be in line with Ribot's (1996) discussion on vulnerability. Aggregation into sectoral vulnerabilities might add transparency, avoiding the current problem of sectors that cannot in reality compensate for each other but do, in our present calculation methodology, reduce the overall national vulnerability indicator.

Moreover, the conceptual framework could be set up such that sub-national specific (sectoral) vulnerabilities have a local sensitivity and coping aspect, a national response mechanism and an international response mechanism in the form of hierarchically recalculated vulnerabilities from local to national to international levels through feedback responses, and from a range of immediate to longer term responses. This may be a promising direction for a next phase of the model. The starting point in the model's hierarchy would be where climate change is assumed/expected to have impact;[7] who and what are affected; and how the compensatory mechanisms, in ever widening circles—social, economic and political—might play their roles.

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[7] Cutter argues (1996:536) that "it is place that forms the fundamental unit of analysis" for vulnerability.

VULNERABILITY AND RESILIENCE TO POTENTIAL CLIMATE CHANGE

Methods, MiniCAM and Sustain model outputs, and climate change scenarios

Step four in developing the prototype calculations of national vulnerability-resilience indicators involved identifying relevant outputs by integrated assessment models that could be used in the calculations of potential vulnerabilities to socioeconomic and climate change. We used the PNNL model MiniCAM and its post-processor Sustain to produce our projections. Table 4 lists the parameters. They include land use change, changes in the economy, demographics, food security, and the environment. MiniCAM's and Sustain's projections are regional. Table 5 provides a list of the regions in which the countries studied so far are located.

Table 4 MiniCAM and Sustain outputs used as inputs for projections

Projected changes in
Forest land
Unmanaged land
Cropland
GDP
Population number in the workforce
Literacy level
Gini coefficient was not projected
Population
Demand for animal protein
Agricultural production
Birth rate
Life expectancy
Sulfur emissions
Sea level rise

Table 5 Countries for which the vulnerability-resilience indicators are calculated

MiniCAM Region	Country
1	USA
2	Canada
3	Germany, the Netherlands, Spain, United Kingdom
4	Japan
5	Australia, New Zealand
6	Bulgaria, Hungary, Poland, Ukraine, Uzbekistan
7	China, Korea D. P. Republic
8	Iran, Jordan, Saudi Arabia, Yemen
9	Egypt, Libya, Nigeria, Senegal, South Africa, Sudan, Tunisia
10	Argentina, Brazil, Chile, Mexico, Venezuela
11	Bangladesh, Cambodia, India, Indonesia, Korea Rep., Thailand
12	World

As part of the IPCC effort, PNNL researchers developed a number of different socioeconomic scenarios. These scenarios primarily focus on emissions mitigation but can be used in the calculation of vulnerability. We used MiniCAM and Sustain outputs for three different scenarios. The scenarios are quantitative representations of different futures in which economic growth, demographic trends, technology development, and other factors (e.g., human preferences) lead to different emissions trajectories, levels of climate change, sensitivities, and capacities for adaptation and coping (Nakicenovic et al. 2000).

The scenarios are based on "business as usual"; that is, the scenarios incorporate neither additional climate mitigation options nor adaptation to projected climate change. Using this category of socioeconomic projections allows for a "clean" evaluation of national capacities for coping, adaptation, and resilience.

In the "rapid growth" scenario (A1v2) economic development is robust and population growth moderate. Population peaks around the year 2065 (Table 6). Over time, current distinctions between "poor" and "rich" countries decrease. There is great improvement in the health and social conditions of most. With increases in income, dietary patterns shift towards increased consumption of meat and dairy products. Land use shifts to sprawling urbanization and intensification of agriculture. In the scenario used here, annual CO_2 emissions are 17.5 Gt C in 2095, and average temperature increases 2.47°C.

In the "local sustainability" scenario (B2h) there is increased concern for environmental and social sustainability. Global average income per capita grows at a moderate rate to reach about US$10,000 by 2050, compared to about US$14,000 in the rapid growth scenario. 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. Another way of capturing this scenario would be by calling it the "coal-use" scenario. This scenario results in annual CO_2 emissions of about 22.1 Gt C by 2095, corresponding to a mean temperature change of 2.47°C, which results from higher sulfur emissions offsetting the higher carbon emissions. 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 the A2 scenario and is called "delayed development" (A2 to A1). In this scenario, economic development in Africa and parts of Asia and Latin America is less vigorous because of continuing institutional setbacks. 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 close to 12 billion by 2100 with low global income per capita of around US$6,000 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). Total carbon emissions amount to 21.4 Gt C/yr in 2095. 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.

Tables 6 and 7 and Figures 11, 12 and 13 illustrate the most relevant differences among the scenarios in assumed changes in world population, gross domestic product per capita, projected changes in land use and carbon emissions. Table 8 illustrates the differences in the scenarios by the year 2095 with regard to temperature increase, atmospheric CO_2 concentration, projected CO_2 emissions, SO_2 emissions and sea level rise. The latter values are the cumulative results of scenario-specific pathways of combinations of changes in carbon dioxide emissions, sulfur emissions, etc.

Table 6 Assumed changes in world population and GDP per capita in three socioeconomic scenarios

	World Population in billions				**World GDP per Capita in 1000 $US87**		
	A1v2	**B2h**	**A2A1**		**A1v2**	**B2h**	**A2A1**
1990	5.3	5.3	5.3		4	4	4
2005	6.3	6.6	6.4		5	5	5
2020	7.2	7.9	7.6		7	6	5
2035	8.0	9.0	8.7		10	8	5
2050	8.4	9.9	9.7		14	10	6
2065	8.4	10.4	10.5		21	13	8
2080	8.2	10.6	11.2		29	17	11
2095	7.9	10.5	11.8		39	22	15

Table 7 Global land use in three socioeconomic scenarios used in the MiniCAM model

	Old forest	**Unmanaged land**	**Crop land**	**Old forest**	**Unmanaged land**	**Crop land**	**Old forest**	**Unmanaged land**	**Crop land**
	A1v2			**B2h**			**A2A1**		
1990	41%	44%	15%	41%	44%	15%	41%	44%	15%
2005	42%	41%	15%	42%	41%	15%	42%	41%	15%
2020	39%	38%	15%	39%	39%	15%	39%	42%	15%
2035	34%	38%	15%	35%	38%	15%	41%	41%	14%
2050	31%	38%	14%	34%	37%	14%	44%	39%	13%
2065	36%	38%	12%	38%	36%	12%	46%	38%	12%
2080	42%	39%	10%	41%	37%	11%	40%	40%	12%
2095	44%	41%	8%	40%	38%	9%	38%	41%	11%

Table 8 Projected changes in temperature, carbon dioxide and sulfur emissions and sea level rise in three socioeconomic scenarios calculated in the MAGICC regional module of the MiniCAM model

By the year 2095	**A1v2**	**B2h**	**A2A1**
Temperature increase (degrees C total)	2.5	2.5	1.8
CO_2 concentration (ppm)	667	723	634
CO_2 emissions (Gt/yr)	18	22	21
SO_2 emissions (million tons/yr)	29	45	84
Sea level rise (cm total)	52	49	41

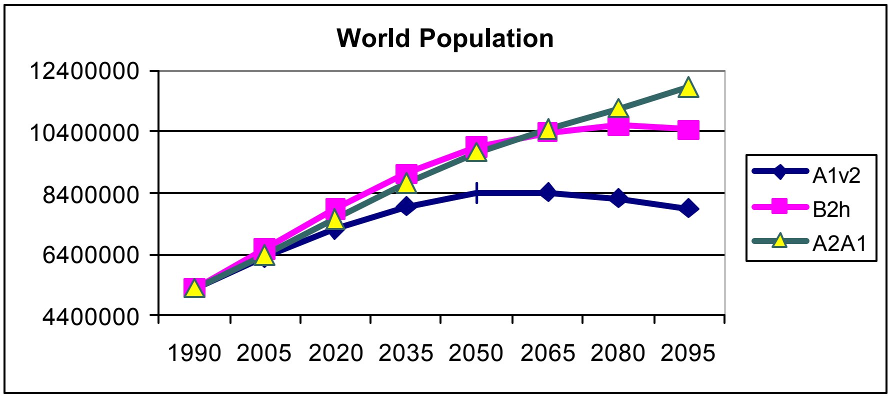

Figure 11 Changes in world population in three climate change scenarios

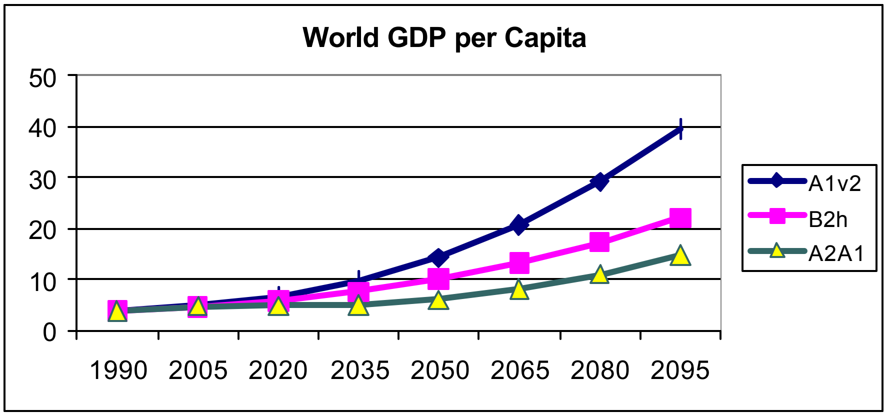

Figure 12 Changes in GDP per capita in three climate change scenarios

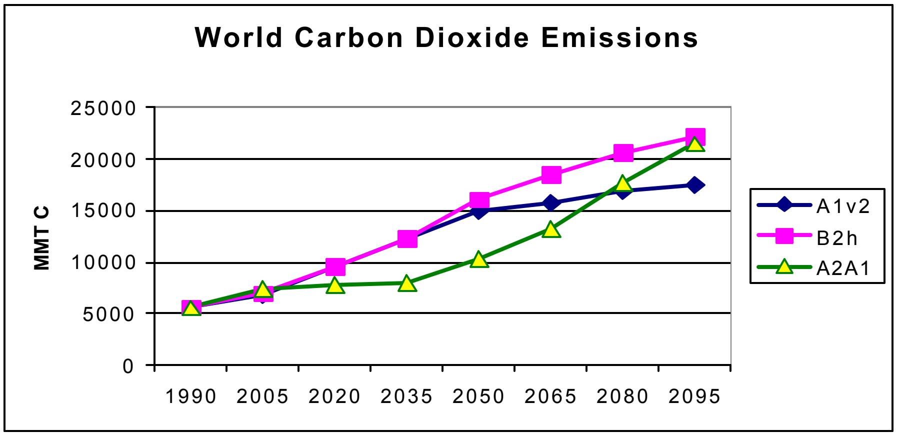

Figure 13 Carbon Dioxide emissions for three climate change scenarios

Step five in the calculations of the vulnerability-resilience indicators consisted of calculating from the MiniCAM and Sustain outputs (Table 4) the values of the variables for projecting the indexed proxies. We calculated the percentage changes from 1990 to 2095 from the outputs for every 15 years up to the year 2095 (Table 9). From these, we calculated the new proxy values, sectoral indicators, sensitivity and coping-adaptive capacity indicators and overall vulnerability indicators as in the baseline case for each of the scenarios (see also Figure 1).

Table 9 Relationship between proxies and MiniCAM's and Sustain's outputs

Proxy (third column Table 1)	Projected through changes in
Sea level rise resulting in number of people at risk	Sea level rise and population
% Population with access to safe water	GDP per capita
% Population with access to sanitation	GDP per capita
Cereal production/agricultural land	Agricultural production/cropland
Animal protein demand per capita	Demand for animal protein per capita
Birth rate	Birth rate
Life expectancy	Life expectancy
% Managed land	(100-% Unmanaged land)
Fertilizer use/area cropland	Agricultural production/cropland
Water sensitivity, based on availability and consumption	% change in precipitation
GDP per capita	GDP per capita
Income distribution equity (Gini coefficient)	not changed
% Population in the workforce (age dependency)	% Population in the workforce
Illiteracy	(100-% Literate)
% Non-managed land	% Non-managed land
SO_2 emissions	Sulfur emissions
Population density	Population

Results

Global and national vulnerabilities over time

The results for global vulnerability and resilience to socioeconomic and climate change are depicted in Figure 14. From now on, we will only show the results when indexing was performed against world baseline data. Over time the global sensitivities remain relatively stable while coping and/or adaptive capacities increase, resulting in an overall decrease in vulnerabilities (increase in resilience) over time. This is an optimistic result, counter to many case studies that predict worsening conditions in the future. Between the years 1990 and 2020 in the delayed development scenarios (A2A1) the combination of sensitivity and coping decreases the overall vulnerability (increased resilience), followed by an increase in vulnerability for about 30 years. Figure 14 also shows that changes in coping and adaptive capacities are larger than changes in sensitivities in all scenarios. Table 10 lists the calculated percentage changes between the years 1990 and 2095 for all three scenarios, illustrating the large increases in coping and adaptive capacity, especially in the rapid growth scenario (A1v2), while sensitivities actually decrease in that scenario. Sensitivities increase only slightly in the local sustainability scenario (B2h), increase more in the delayed development scenario (A2A1), and actually decrease in the rapid growth scenario.

Table 10 Percentage changes in global indicator values from year 1990 to 2095

Global indicator values	Scenarios		
	A1v2	B2h	A2A1
Coping-Adaptive Capacity	61%	33%	13%
Vulnerability-Resilience	68%	30%	3%
Sensitivity	-8%	3%	10%

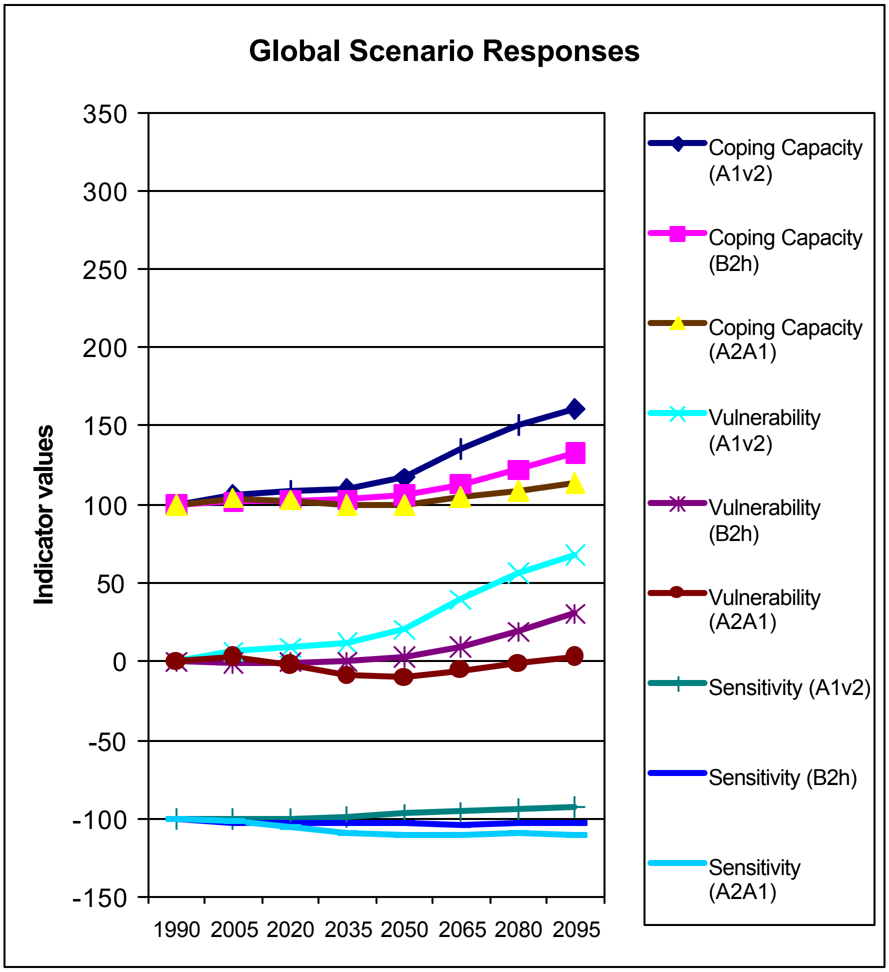

Figure 14 Global indicator values: A1v2 = the rapid growth scenario; B2h = the local sustainability scenario; A2A1 = the delayed development scenario

For some representative countries from each of the 11 regions for which MiniCAM and its post-processor provide outputs, we produced graphs similar to Figure 14 (Figures 15, 16 and 17 and in the Appendix, Figures A1-A12) . All axes are scaled identically for comparison purposes.

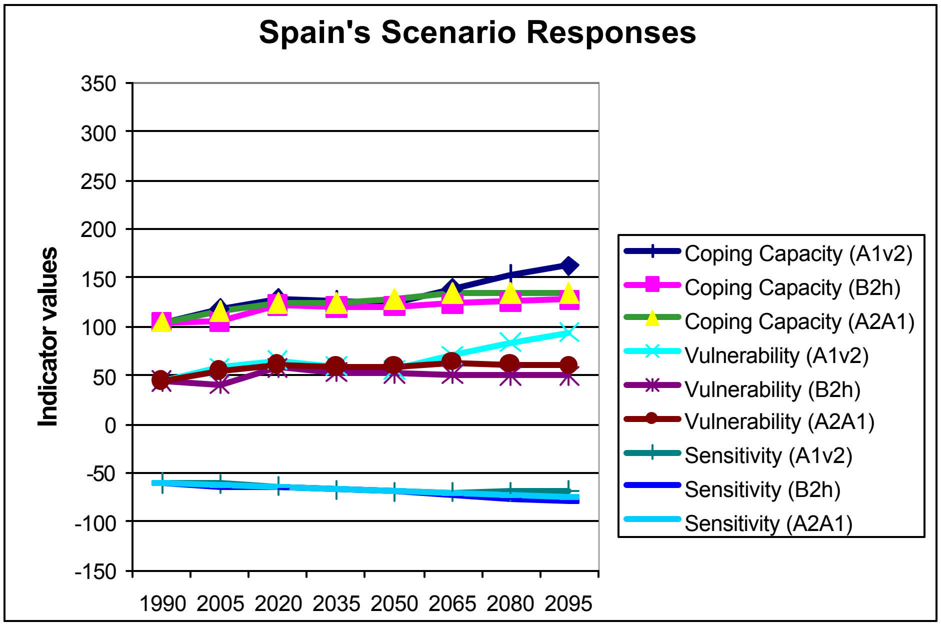

Figure 15 Spain's indicator values over time (MiniCAM region 3)

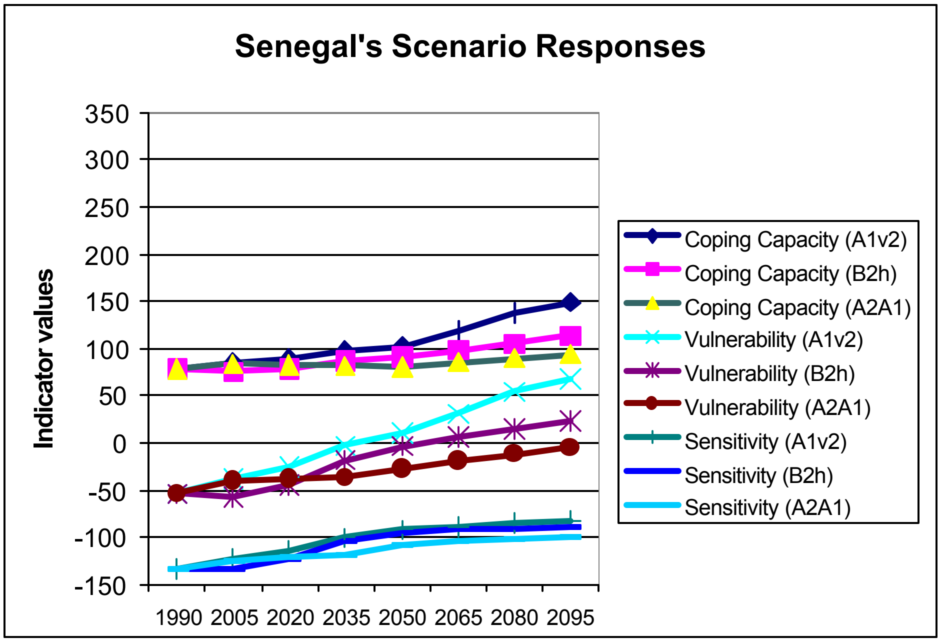

Figure 16 Senegal's indicator values over time (MiniCAM region 9)

Different countries in the same MiniCAM region show different sensitivities, coping and adaptive capacities and vulnerability and resilience indicator values. This is due to their different 1990 baseline proxy values. And, as was explained above, the relative weights of the proxies, resulting from the baseline data values and the indexing scheme, determine, in combination with the hierarchical combination of the proxies, the values of the sensitivities and coping and adaptive capacities. Although the percentage changes over time in each of the proxies are the same for any of the MiniCAM region, the proxy values will weigh differently against each other over time, resulting in country-specific pathways of the indicator values. After the sorting for percentage change in the sensitivity or coping-adaptive capacity in the rapid growth scenario, we do not find clustering of countries by MiniCAM regions in Table 11. Nor do we find clustering by MiniCAM region in Table 12, which was sorted for the absolute change in the VR indicator value between 1990 and 2095 in the rapid growth scenario.

The percentage changes in the sensitivity indicators for Thailand differ from those for India's and Bangladesh's, while India's and Bangladesh's are similar (see Table 11). For the coping and adaptive capacity the three countries differ in the rapid growth scenario (A1v2), while India and Bangladesh show similar changes in the other two scenarios (see also Figures A10, A11, A12). Examples of two other countries within a MiniCAM region, Brazil (Figure 17) and Mexico (Figure A9), illustrate not only the difference in balance between sensitivity and coping-adaptive capacity with regard to climate impact at the baseline year of 1990, but also that these balances roughly maintain themselves. For Brazil and Mexico percentage changes in sensitivity are very similar (Table 11), but changes in the coping and adaptive capacities differ.

The values of the baseline proxies ultimately determine the country-specific indicator values. Projected indicator values are similarly fully dependent on those baseline data. The world 1990 baseline data values are also of utmost importance, given that we index against those global proxy values. If any of the baseline data for, in our case, 1990 are accidentally high or low there will be consequences for the projected values.

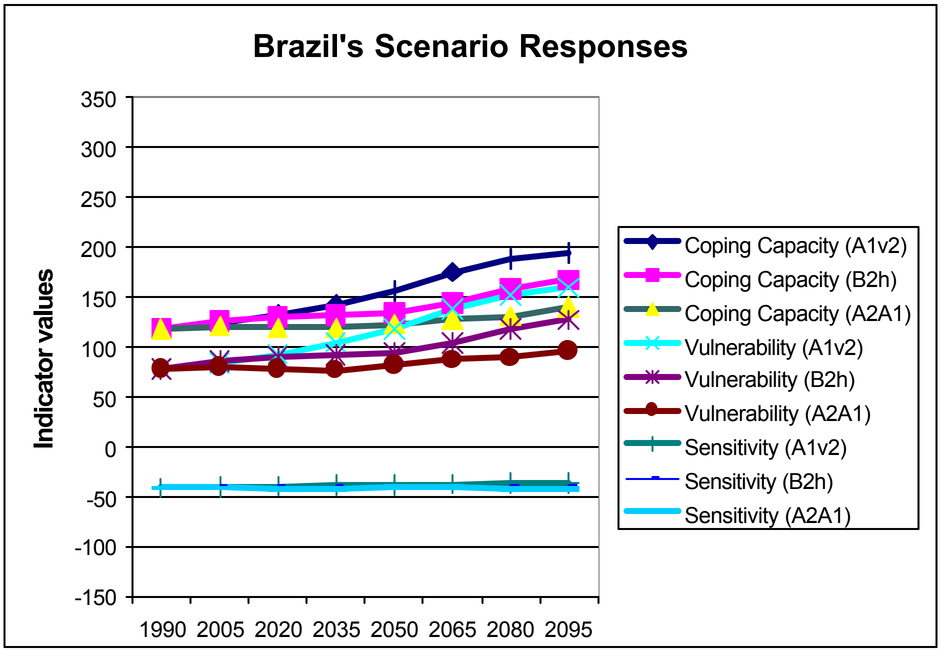

Figure 17 Brazil's indicator values over time (MiniCAM region 10)

From the individual country figures (Figures 15-17, A1-A12, and 2-3) one may conclude that sensitivities are higher in 1990 in the developing countries compared to the developed countries. Sensitivities are projected as decreasing over time in the developing countries. Developed countries, in contrast, show increasing sensitivities over time, especially in the delayed development scenario and, for example, for the USA and Spain for the sustainable development scenario. Part of this may be attributable to the projected rates of change in such proxies as % population with access to safe drinking water and sanitation; the rates of increase in developing countries will be higher because, in general, these countries are starting with much lower percentages than developed countries.

Tables 11 and 12 show more clearly than the individual country graphs the final outcome (in year 2095) of the trajectories of the projected sensitivities and coping-adaptive capacities and the vulnerability-resilience between developed and developing countries. Sensitivities are decreasing over time in the developing countries, but in developed countries they may increase. Coping and adaptation capacity are projected as increasing significantly over time in the developing countries. This change is much larger than in the developed countries; however, the latter's base year values show they are already well able to cope and have good adaptive capacity. For the countries graphed in the Appendix, we find for China a great increase in the coping-adaptive capacity, followed by India, Senegal and Poland, especially for the rapid growth scenario. The reasonableness of the great increase in Senegal's coping and adaptive capacity can be questioned; the rapid rates of socioeconomic development in Senegal and other developing countries may be characterized as optimistic, perhaps unrealistic.

Table 11 Changes (as percentages decrease or increase) from 1990 to 2095 in the sensitivities and coping-adaptive capacities sorted by the changes in the rapid growth scenario

	% Change in sensitivity from 1990 to 2095				**% Change in coping-adaptive capacity from 1990 to 2095**		
	A1v2	**B2h**	**A2A1**		**A1v2**	**B2h**	**A2A1**
Cambodia	-44%	-39%	-31%	Tunisia	148%	92%	72%
Nigeria	-43%	-40%	-32%	Nigeria	146%	89%	69%
Korea Rep	-43%	-35%	-25%	Argentina	118%	60%	31%
Sudan	-38%	-34%	-24%	China	113%	64%	34%
Korea D R Rep	-36%	-28%	-23%	Indonesia	111%	65%	35%
Indonesia	-35%	-27%	-18%	India	110%	66%	35%
Senegal	-35%	-29%	-19%	Libya	98%	65%	35%
China	-33%	-25%	-20%	Bangladesh	98%	66%	35%
India	-33%	-28%	-19%	Korea Rep	92%	45%	20%
Bangladesh	-32%	-28%	-19%	Cambodia	92%	45%	20%
Egypt	-30%	-22%	-10%	Senegal	92%	44%	19%
Tunisia	-25%	-25%	-8%	Korea D R Rep	91%	43%	18%
Saudi Arabia	-24%	-17%	-13%	Sudan	91%	43%	18%
Thailand	-24%	-21%	-10%	Japan	90%	65%	25%
Libya	-21%	-11%	0%	Ukraine	90%	66%	26%
Jordan	-20%	-12%	-8%	Bulgaria	90%	66%	26%
South Africa	-20%	-14%	-6%	South Africa	90%	66%	27%
Argentina	-18%	-14%	-7%	Germany	90%	67%	28%
Yemen	-15%	-7%	0%	Saudi Arabia	89%	37%	14%
Venezuela	-15%	-5%	3%	Thailand	89%	36%	14%
Brazil	-13%	-3%	5%	Mexico	63%	33%	14%
Mexico	-12%	-3%	5%	Chile	62%	41%	15%
Iran	-12%	-3%	4%	Yemen	62%	41%	15%

Chile	-10%	-1%	7%	World	62%	40%	13%
World	-6%	3%	12%	UK	58%	21%	23%
Japan	-6%	6%	-3%	Uzbekistan	56%	22%	25%
Hungary	-1%	6%	19%	Poland	56%	22%	25%
Ukraine	-1%	6%	19%	Netherlands	56%	23%	25%
Netherlands	0%	9%	8%	Venezuela	54%	38%	15%
Bulgaria	0%	8%	21%	Iran	52%	33%	12%
Uzbekistan	0%	10%	25%	Hungary	52%	32%	12%
Poland	3%	11%	25%	Egypt	51%	31%	11%
Germany	4%	18%	14%	Jordan	49%	29%	12%
UK	4%	14%	12%	Brazil	44%	26%	12%
Spain	15%	30%	26%	USA	38%	24%	23%
USA	17%	28%	27%	Canada	24%	19%	6%
Canada	20%	26%	26%	Spain	19%	10%	10%
New Zealand	22%	20%	31%	New Zealand	16%	20%	4%
Australia	23%	19%	29%	Australia	9%	15%	-2%

We find vulnerability decreasing (resilience increasing) over time under all scenarios for all countries but for New Zealand and Australia in the delayed development scenario (Table 12). The decrease in vulnerability, or increase in resilience, is most apparent for developing countries in the rapid growth scenarios. For the developed world vulnerability does not decrease much in the local sustainability scenario. For Canada (Figure A-2 in the Appendix) the local sustainability and delayed development scenarios produce similar increases in resilience. For Australia (Figure A-4), the local sustainability scenario proves rather advantageous with regard to resilience building. For all other countries the rapid growth scenario is most advantageous for decreases in vulnerability, followed, sequentially, by the local sustainability scenario and the delayed development scenario. This result accords with the priority given to development objectives over strategies for addressing climate change.

Table 12 Changes in the vulnerability-resilience indicators by year 2095 sorted by the change in the rapid growth scenario

	Actual changes in vulnerability-resilience indicator values 1990-2095		
	A1v2	**B2h**	**A2A1**
Libya	209	105	35
China	129	86	67
Egypt	125	72	32
Tunisia	123	78	30
Sudan	121	74	42
Thailand	120	78	41
Senegal	118	73	40
India	108	75	46
Korea Rep	107	68	40
Indonesia	105	73	41
Saudi Arabia	104	66	33

Korea D R Rep	94	60	47
South Africa	94	46	18
Nigeria	89	55	35
Cambodia	83	60	37
Argentina	82	50	21
Bulgaria	79	54	13
Bangladesh	76	50	30
Venezuela	74	47	15
Brazil	70	46	15
Yemen	69	37	9
World	69	30	2
Jordan	68	42	18
Chile	67	41	10
Mexico	65	37	7
Hungary	63	43	11
Iran	61	34	7
Poland	58	39	9
Germany	58	20	23
Ukraine	53	34	1
Spain	52	10	15
Netherlands	51	17	20
Uzbekistan	49	31	-1
UK	45	11	14
Canada	43	19	19
USA	42	13	13
Japan	35	20	9
New Zealand	17	24	-8
Australia	7	23	-21

Table 13 Vulnerability-resilience indicator ranges over 38 countries and the world for the three MiniCAM scenarios in 1990 and 2095

Minimum, maximum and range of vulnerability-resilience indicator values from 38 countries and the world				
	Base year-1990	**A1v2-2095**	**B2h-2095**	**A2A1-2095**
Minimum	-139	-67	-102	-135
Maximum	223	277	258	249
Range	362	344	360	384

The ranges of the vulnerability-resilience indicators for the world and all 38 countries, for which we calculated the indicators so far, may indicate the level of inequity in the world (Table 13, bottom row). Changes are not large between the years 1990 and 2095 (less than 10%). This implies that differences in ranges in the vulnerability-resilience indicators among the three scenarios by the year 2095 are not large (12-14%). In the rapid growth scenario (A1v2) the vulnerability range is reduced by the year 2095, while in the delayed development scenario (A2A1) the range is increased, and it remains similar for the local sustainability scenario.

Although in the local sustainability scenario (B2h) the vulnerability-resilience range (discrepancy) remains close to the same over time, the resilience increases. For the delayed development scenario (A2A1) the resilience of the most vulnerable countries stays about the same; only the countries already resilient improve, and the discrepancy increases between countries (see also Figures 18 and 19). The decrease in discrepancy in the rapid development scenario (A1v2) seems mostly attributable to improvements in the most vulnerable countries. The current distinctions between "poor" and "rich" countries were assumed to decrease in the rapid growth scenario (see the climate change scenario descriptions).

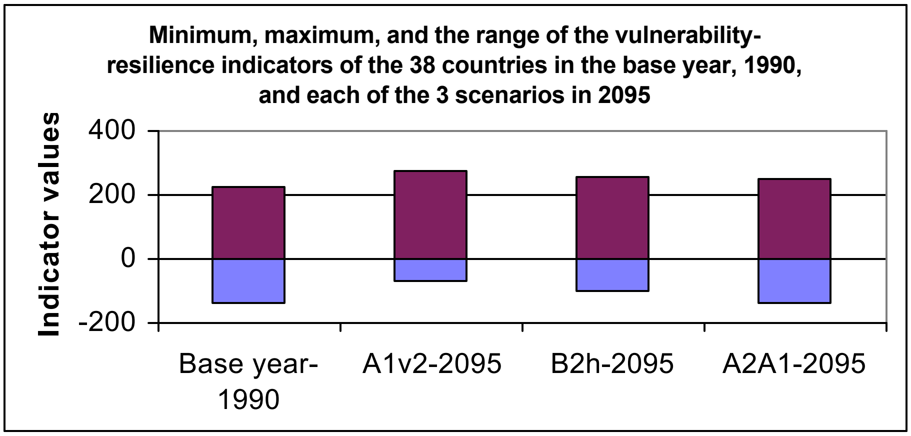

Figure 18 Scenario-dependent minimum and maximum vulnerability-resilience indicators over the 38 countries in 1990 and 2095

Figure 19 illustrates once more the difference among countries and between scenarios in projected response to socioeconomic and climate change impact. While in 1990 (Figure 2) 16 countries out of the 38 are considered more vulnerable to climate impact than the world as a whole, by the year 2095 it is projected that only one country remains vulnerable in the rapid growth scenario, three countries in the local sustainability scenario and nine countries in the delayed development scenario. The world or global VR indicator is located 17th from the bottom in 1990 (in Figure 2 the world VR indicator value is almost center), while in 2095 (Figure 19) it is ranked 14th from the bottom in the rapid growth scenario and 11th from the bottom in both the local sustainability and delayed development scenarios. Ranking of the individual countries also changed by the year 2095 and is scenario-dependent e.g., Libya ranks 9th from the bottom in 1990, but is projected as very resilient by the year 2095, especially in the rapid growth scenario (third from the top). Libya ranks 16th from the top (23rd from the bottom) in the local sustainability scenario and 13th from the bottom in the delayed development scenario. Previously, we noted for Senegal its significant increase in coping and adaptive capacity over time (Figure 16), resulting in a significant increase in resilience (decrease in vulnerability) in the rapid growth scenario.

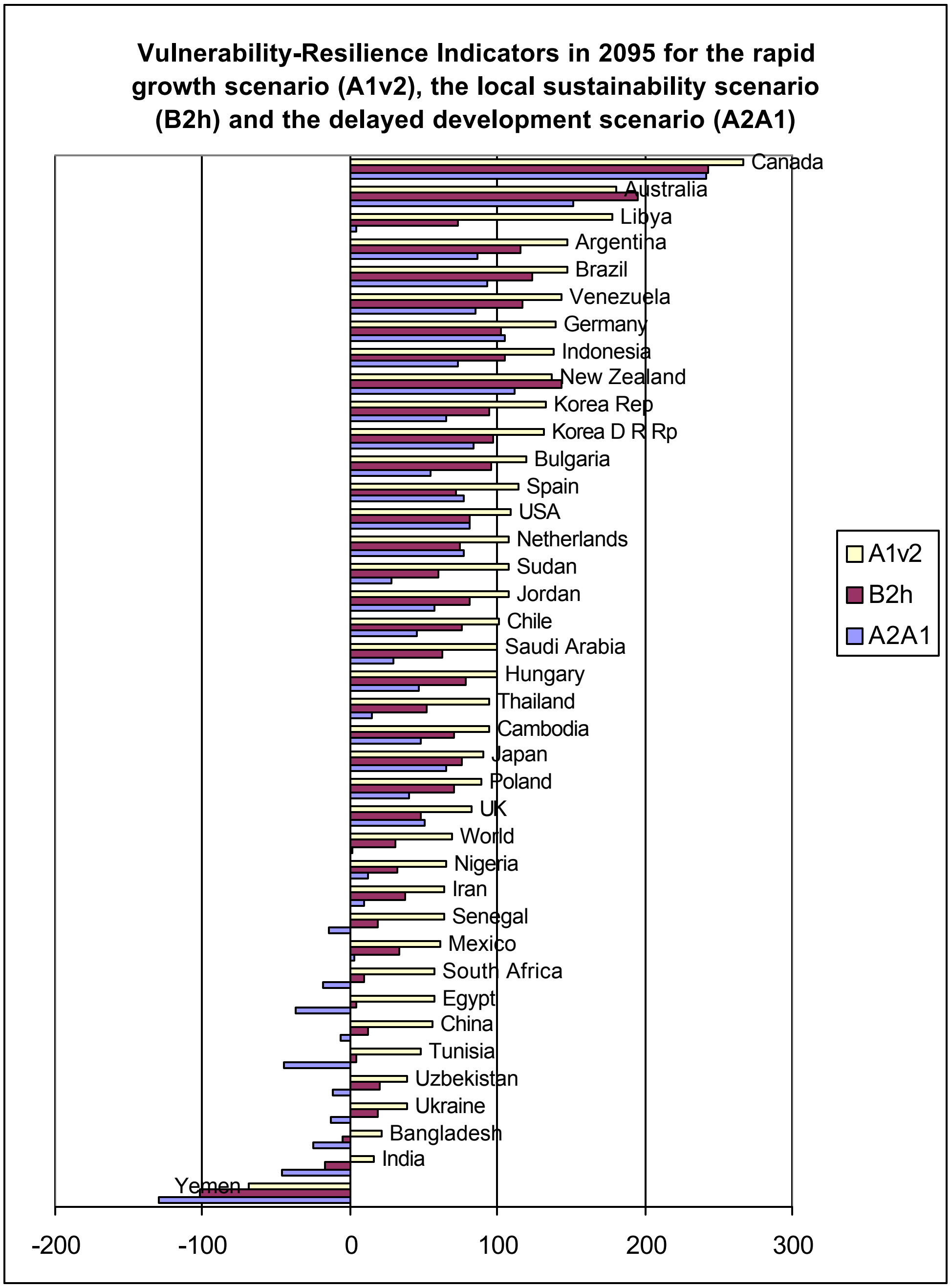

Figure 19 National vulnerability-resilience indicators in the year 2095 for all three scenarios. Proxies indexed against world baseline data

Vulnerability decomposed into sectors

As part of the explanation of changes over time in the vulnerability-resilience indicators, we analyzed the sectoral contributions to those indicators. Figure 20 and Figures A13-A29 in the Appendix show radar plots of sectoral indicator values contributing to the global vulnerability-resilience indicators in all three scenarios and the country-specific vulnerability-resilience indicators of the countries previously graphed (Figures 15-17, A1-A12) in the local sustainability scenario. Center-points have values of –200 for clearer visualization of the changes over time. Sensitivities are depicted as positive instead of negative values.

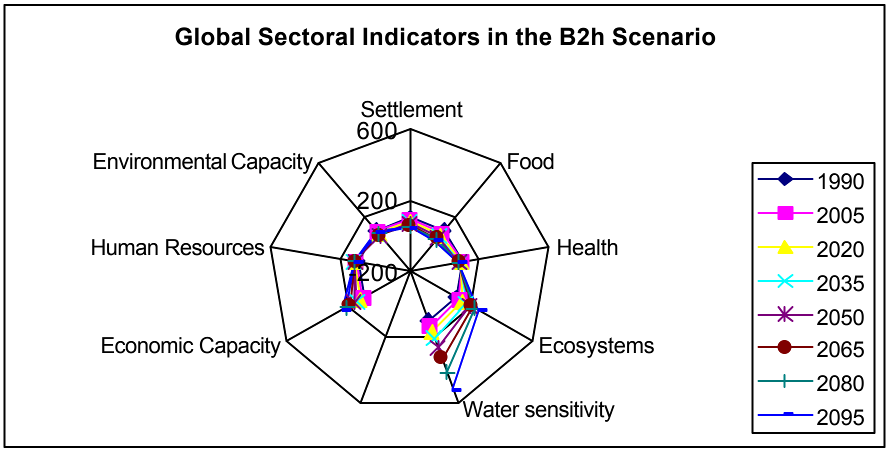

Figure 20 Global sectoral indicators in the local sustainability scenario

Table 14 shows how much the global sectoral indicators themselves change between 1990 and 2095 and how much those changes differ among the scenarios. Water sensitivity shows the largest change over time with barely any difference among the scenarios (changes from 1990 to 2095 amount to 418%, 414%, and 408%). Scenarios differ, although not greatly, in environmental coping capacity; the delayed development scenario (A2A1) shows degradation, the local sustainability scenario shows less degradation, and the rapid growth scenario (A1v2) shows some improvement. Ecosystem sensitivity more than doubles in all three scenarios. The scenarios differ most by 2095 in the projected change over time in the economic coping-adaptive capacity (218% versus 94%) with the greatest economic increase occurring in the rapid growth (A1v2) scenario.

Table 14 Percentage increases or decreases in the global sectoral indicators from global baseline sectoral indicator values by the year 2095

	Settlement	Food	Health	Ecosystems	Water Sensitivity	Economics	Human Resources	Environmental Capacity
A1v2	-65%	-79%	-23%	128%	418%	218%	12%	17%
B2h	-53%	-75%	-22%	146%	414%	138%	14%	-13%
A2A1	-43%	-74%	-11%	145%	408%	94%	11%	-33%

The dominance of the water sensitivity indicator, globally, and in eleven out of the sixteen countries (Figures 15-17, A1-A12) brings to the foreground the importance of the methods and data used for building an indicator. Indicators should represent relevant information adequately, be well balanced and be able to fully respond to or reflect changing conditions. If water sensitivity would distinguish among electricity-generating-hydropower (e.g., very important in Brazil), industrial water use, agricultural water use and household water use, besides the general ratio general water use versus available river water, and if we would use different sets of projectors besides agricultural water use, a different water sensitivity might emerge.

When water sensitivity is not the dominating sectoral indicator, environmental capacity, especially in Canada, Australia, and Brazil, and economic capacity are important contributors to the vulnerability-resilience indicators. For Bangladesh, ecosystem sensitivity dominates.

For Senegal as a nation, water sensitivity is also not the dominating indicator. That type of result shows that sub-national indicators might be more relevant. The northern part of Senegal, as part of the Sahel, is definitely water sensitive. Senegal shows significant settlement sensitivity based on the risk of the population to sea level rise in its coastal area, which, of course is not immediately relevant to the dry uplands of Senegal. One may still want to argue, though, that national policy makers need knowledge about all potential sensitivities and coping and adaptive capacities on a national level.

Aggregating sectoral indicators into overall climate sensitivity or coping and adaptive capacity indicators through geometric means of those sectoral indicators, in effect, dampens the impacts of extreme high values, like water sensitivity.

Vulnerability decomposed into proxies

We may take the decomposition of the vulnerability-resilience indicator one step further, to the proxy level. Figure 21 and Figures A-30 and A-31 show fertilizer use, water sensitivity, and GDP per capita as important in the global case. The three scenarios differ in the relative contributions of the proxies to the overall vulnerability-resilience indicator. Especially in the rapid growth scenario (A1v2) GDP per capita seems to be the dominant driver over time. In the local sustainability scenario (B2h), GDP per capita, sensitivity with regard to water availability and fertilizer use have similar absolute values, while in the delayed development scenario (A2A1) the latter two outweigh economic growth. In other words, a conclusion might be that land use in general, in the form of agricultural land and water quantity and quality, might need most attention if indeed the delayed development pathway is followed.

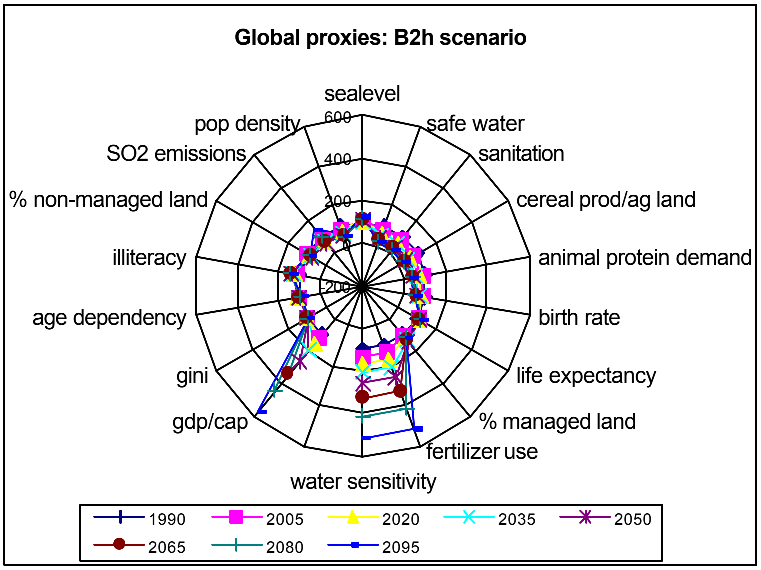

Figure 21 The global proxies in the local sustainability scenario

Individual countries differ in proxy contributions over time. Figures A-32 through A-37 illustrate this. When we focus on four of the previous 16 countries (Spain, Brazil, Mexico, and Senegal) for the local sustainability (B2h) scenario, we see different patterns of change. For Spain (Figure A-32) water sensitivity dominates over time. For Brazil, (Figure A-33), sulfur emissions and increase in GDP per capita are the main drivers for coping and adaptive capacity enhancement while increased fertilizer use slows resilience building. Water sensitivity is the major driver for Mexico's projected continuing vulnerability, while the projected GDP per capita increase contributes to reducing the projected vulnerability over time. The sulfur emissions for Brazil and Mexico (not illustrated) follow an inverse U-shaped path over time, resulting in a U-shaped contribution to increased resilience over time.

How much a particular proxy dominates among the proxies in contribution to the vulnerability-resilience indicator is made visible by paying attention to the scale of the radius of the radar graphs. For Spain that scale ranges up to 2800 units; for Brazil, the axes range up to 600; and for Mexico the axes range up to 1000.

Senegal's vulnerability is mainly driven by potential sea level rise (Figure A-35-A37). Sulfur emission reductions show a beneficial effect over time. The increase in GDP per capita and increase in cereal production are also shown to help reduce vulnerability.

When we analyze the differences among the three scenarios for Senegal, we find that the scenarios differ mostly with regard to the impact GDP per capita projections have on the increase in resilience over time. Resilience was projected as considerably increased over time in the rapid growth scenario and Figure A-37 illustrates the impact that the projected GDP per capita has, compensating in Senegal's case for the increase in sensitivity to climate due to projected sea level rise.

Observations

We have shown that the accuracy of baseline numbers is crucial because a particular year's anomalous high or low value will get propagated into the future in "compounded" form, resulting in a distorted projection. It might be considered necessary, therefore, to obtain baseline values from a best estimate value from a regression or other curve-fitting technique over a reasonable length of historical data. This seems especially important for the baseline value (the global or world value in our case) one indexes against.

Another note of caution pertains to the assumptions we have made about the proxies representing what we call "sensitivity" or "coping and adaptive capacity." Each of these aggregates is comprised of various proxies that might have different directionalities with regard to climate change at different localities or under different circumstances, that is, after different historical development. Table 15 summarizes the assumed functional relationships between the proxy variables and the sensitivity to, and coping and adaptive capacity with climate change for our vulnerability-resilience indicator prototype.

With regard to settlement and infrastructure sensitivity, sea level rise represents a definite increase in sensitivity. Access to better infrastructure is part of a general trend for all countries, albeit at variable speeds. Coping capacity will therefore increase with access to better infrastructure. The combination of the proxies results, as a consequence, not so much in a pure sensitivity measure but rather in a vulnerability-resilience measure, that is, as having both positive and negative effects. The same result was seen earlier (Figure 10) when the overall vulnerability-resilience indicator was calculated with and without access to clean water and sanitation. When we calculate settlement/infrastructure sensitivity for future dates, the speed of improvement in infrastructure might well overtake the speed of sensitivity to sea level rise without change in infrastructure. This kind of balancing implies we are indeed dealing with a vulnerability-resilience indicator for settlement/infrastructure and not just with sensitivity.

Another possible interesting example might be the human health sensitivity. Historical trends indicate a negative correlation between completed fertility or birth rates and life expectancy. A similar correlation occurs over all countries, e.g., the squared correlation coefficient for 1990 for our 38 countries processed so far amounts to 0.57 (Figure 22). Exceptions occur as is indicated by Yemen and Saudi Arabia having the highest birthrates and differences in life expectancy of 16 years. Other countries in the Middle East (Jordan, Iran, and Libya) have, like Saudi Arabia , high birthrates but not necessarily low life expectancies as is the case in some African countries. The question becomes, are we indeed representing human health sensitivity, or does the combination of both these proxies already represent inclusion of compensatory mechanisms?

A third example concerns food security. We have assumed that when animal protein demand increases, sensitivity to climate impact decreases. This proxy can also be assumed to be an aspect of human health. One might want to argue that with increased animal protein demand, land will need to be increasingly intensively cultivated for food with possible negative effects for natural carbon sequestration, water quality and the like, especially if assumed technological innovation in agriculture is lagging.

A fourth example pertains to sulfur emissions. An increase in sulfur emissions might indicate increased industrial productivity and be positive for economic development, but negative for human health and ecosystem coping capacity. If sulfur emissions are decreasing in a country, it might indicate that clean technology is applied, which also can be taken as positive for economic development, and positive for human health and ecosystem coping capacity.

These four examples illustrate the complicated nature of building a hierarchy of relevant indicators, a point we will revisit in the final discussion.

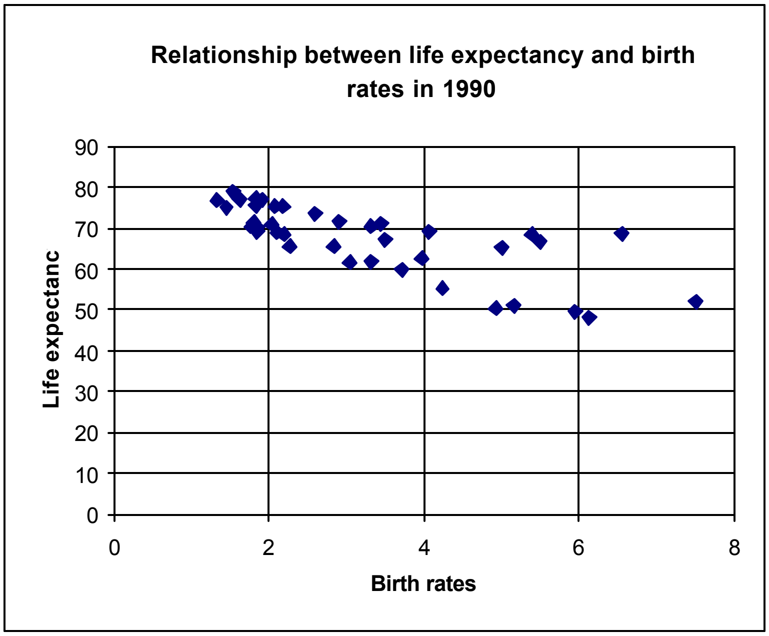

Figure 22 Relationship between life expectancy and birth rates in 1990 for 38 countries

Our last observation pertains to the weight potential of the different proxies in the overall vulnerability-resilience indicator. In our discussions on the decomposition of indicators into its components we have mentioned that we aggregate these components through calculations of geometric means, and that consequently high values weigh less than if we would have done the aggregation through arithmetic means. Secondly, we have pointed out that some of the sectoral indicators are comprised of three proxies, others of two, and one sectoral indicator of just one proxy, that is, the ratio of water consumption and water availability. The hierarchical combination of the proxies into sectors and sectors into the aggregate sensitivity and coping-adaptive capacity indicators determines the potential weight the different proxy values may have when the overall vulnerability-resilience indicator is calculated. Simply put: the proxies do not weigh equally and we, therefore, will test the consequences of the hierarchical structure of the calculations in the next section.

Table 15 Summary table of proxies and their relationships to sensitivity and coping and adaptive capacity to socioeconomic and climate change

Sensitivity or Adaptive capacity category	Proxy variables	Proxy for	Functional relationship
Settlement/ infrastructure sensitivity	Population at flood risk from sea level rise Population no access clean water/sanitation	Potential extent of disruptions from sea level rise Access of population to basic services to buffer against climate variability and change	Sensitivity ↑ as population at risk ↑ Sensitivity ↑ as population with no access ↑
Food security	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 ↑
Ecosystem sensitivity	% Land managed Fertilizer use	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
Human 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 ↓ Sensitivity ↓ as life expectancy ↑
Water resource	Renewable supply and inflow Water use	Supply of water from internal renewable resources and inflow from rivers Withdrawals to meet current or projected needs	Sensitivity calculated using ratio of available water used: Sensitivity ↑ as % water used ↑
Economic capacity	GDP(market)/capita Gini index	Distribution of access to markets, technology, and other resources useful for adaptation	Coping-adaptive capacity ↑ as GDP per capita ↑ 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-adaptive capacity ↓ as dependency ↑ Coping-adaptive capacity ↑ as literacy ↑
Environmental capacity	Population density SO_2/area % Land unmanaged	Population pressure and stresses on ecosystems Air quality and other stresses on ecosystems Landscape fragmentation and ease of ecosystem migration	Coping-adaptive capacity ↓ as population density ↑ Coping-adaptive capacity ↓ as SO_2 ↑ Coping-adaptive capacity ↑ as % unmanaged land ↑

FINDING THE DOMINANT OR LEADING PROXIES

In the sections above we discussed the so-called deterministic realizations of a model. Deterministic modeling does not take uncertainties of model input into account nor the uncertainty of the forcing functions, in our case changes over time. Moreover, in deterministic modeling the importance of parameter contribution, in our case proxy contribution, to model output can be analyzed only through a decomposition process, which implicitly assumes equal weights of those contributing parameters. This is not the case when the model has a hierarchical structure, as is the case with our prototype.

We performed Monte Carlo analyses of the model to test the impact of the structure of the model on the output and to analyze the impact of parameter uncertainty on the final output of a model output (Bartell et al. 1988). In a Monte Carlo analysis repeated simulations (calculations) are performed with random combinations of randomly sampled parameters from pre-defined probability distributions.

We define dominant or *leading proxies* as those proxies that, when having different values have significant impacts on final indicator values. We may identify leading proxies by evaluating the correlations between the sampled proxies and the calculated indicators; proxies with the highest explanatory power of the variance of the calculated indicators may be called leading proxies. By basing the uncertainty ranges of the proxies on their projected changes over time, we capture through our sampling from those ranges the different pathways the proxies might take over time, and which of the proxies will be most dominant (leading) in determining the final indicator values.

Methods

In general, varying input parameter best-estimate values 2% and propagating the variances around the parameters through a model is a way of testing the structure of a model.[8] Mean output values resulting from such as tests are, in general, very similar to the deterministic output. The effects of model structure can be analyzed by regressing the output values as dependent variables, against the sampled input parameters as independent variables (Rose et al. 1991). Those parameters explaining most to the variance of the output can thus be identified. Stratified Latin Hypercube sampling of the parameters ensures that each of the input parameters has its total predefined range represented because the procedure consists of dividing the range of each parameter into N strata of equal marginal probability 1/N and sampling once from each stratum with N=1000 in our case. Each of the N samples from each of the parameters are combined in a random manner and the indicators calculated a thousand times. When parameters are sampled from distributions representing their estimated actual uncertainty, i.e., from a variance larger than the 2% coefficient of variation, their impacts on the final model outputs change and different parameters contribute more or less to the uncertainty of the outputs depending both on model structure and uncertainties of the parameters. This, again, can be analyzed through ordinary least-squares regression (Gardner et al. 1983)

We performed two Monte Carlo analyses on the model. The first exercise consisted of sampling, at each point in time, each of the 17 proxies after indexing the proxies against the world baseline values, from narrow 2% coefficient of variation distribution around the proxies' indexed values and performed, for each point in time, a thousand Monte Carlo runs. We then calculated the

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[8] In the literature, this is called a sensitivity analysis of the model, a term we will not use given that we are using the term 'sensitivity' for sensitivity to climate change.

squared Pearson correlation coefficients between each of the proxies and the vulnerability-resilience indicator as a measure of proxy contribution to the uncertainty in vulnerability for that point in time for a country under a specific climate change scenario.

In the second exercise we sampled the proxies from distributions representing the 30-year change over time around the proxies' best-estimate values at each point in time. Those types of distributions are depicted in Figure 23. The upper and lower limits of the triangular distributions of the proxies are the values these proxies have either 15 years before or 15 years after the time of calculations. We then, again, calculated the squared Pearson correlation coefficients between each of the proxies and the vulnerability-resilience indicator as a measure of proxy contribution to the uncertainty in vulnerability for that point in time for a country under each of the scenarios.

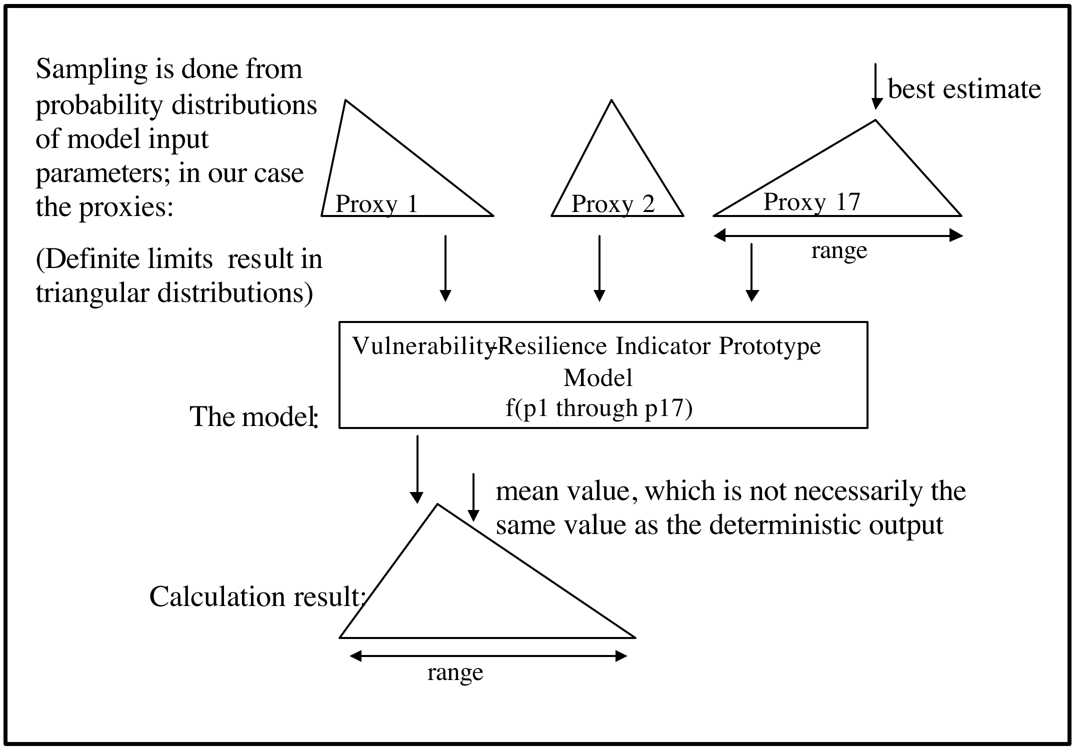

Figure 23 Monte Carlo modeling

Results

- We first will present results of sampling the proxies from a narrow 2% coefficient of variation distribution around the proxies' best estimates.
- Secondly, we will present the results of sampling the proxies from distributions representing the 30-year change over time around the proxies' best-estimate values at each point in time.

Results from sampling the proxies from narrow probability distributions

We varied each of the indexed proxies through stratified Latin hypercube sampling from narrow normal probability distributions amounting to a 2% coefficient of variation around the best estimate and performed a thousand Monte Carlo runs at each point in time. We then calculated the squared Pearson correlation coefficients between each of the proxies and the vulnerability-resilience (VR) indicator as a measure of the percentage proxy contribution to the uncertainty in vulnerability for a point in time for a country under a specific climate change scenario.

The potential of the percentage contribution by each individual proxy to the variances of the sensitivity and coping-adaptive capacity, and therefore to the overall vulnerability-resilience indicator uncertainty due to the model structure can be explained with the help of Figure 24. The bar graphs in the figure (and in all figures below) are the stacked squared Pearson correlation coefficients between the indicators at each point in time and the proxies. When the global proxies are indexed in the baseline year 1990 to the world baseline values the proxies have values of 100. Sensitivity is comprised of five sensitivity (vertical composite bars 3-7) and three coping-adaptive capacity (vertical composite bars 9-11) sectoral indicators. Figure 24 shows that when sectoral indicators are calculated as geometric means of two or more proxies with similar means (100), and coefficients of variation (2%) the proxies contribute evenly to the uncertainty of the sectoral indicators. The variances around these sectoral indicators are, in turn, evenly propagated to the aggregated sectoral indicators, that is, to the sensitivity (composite bar 2) and coping-adaptive capacity (composite bar 8) indicators.

This is very straightforward, percentage-wise, for the coping-adaptive capacity. The indicators for economics, the GDP per capita and the Gini coefficient contributions are 50% each, (bar 9); for human resources, population in the work force or age dependency and literacy are 50% each (bar 10), and for environmental coping capacity (% unmanaged land, sulfur emissions and population density are 33% each (bar 11). And they contribute to the uncertainty of the coping-adaptive capacity, percentage-wise, as expected (bar 8).

For the sensitivity sectoral indicators the same holds true except for settlement sensitivity (bar 3). For that indicator, access to safe water and sanitation was first averaged as geometric mean, followed by averaging that average with the risk of the population to sea level rise. The result is an uneven contribution of the three proxies to the settlement sensitivity uncertainty, with access to safe water and sanitation contributing less. The variance of the sensitivity to water availability is based on only one proxy (bar 7).

The proxies that correlate negatively with the vulnerability-resilience are presented as negative contributions for interpretation and display purposes, although the values are squared correlation values. Summation of all (absolute values of) contributions ought to add up to roughly 100%.

The contributions by the sampled proxies to the uncertainties of the sensitivity (bar 2) and coping-adaptive capacity (bar 8) indicators are propagated in a similar fashion to the uncertainty of the overall vulnerability-resilience indicator. The vulnerability-resilience indicator is calculated as the arithmetic difference between sensitivity and coping-adaptive capacity for each Monte Carlo run. Thus, when each of these indicators have values around 100 (calculated as geometric means of the sectoral indicators), which is the case when the proxies are sampled from narrow distributions after indexing, proxy contributions to the uncertainty of the global vulnerability-resilience indicator for the year 1990 is equally divided (50% contributions) by those proxies standing for sensitivity to climate and those proxies standing for coping and adaptive capacity (Figure 24 far left composite bar in the graph is identical to the bar on the far left in Figure 25).

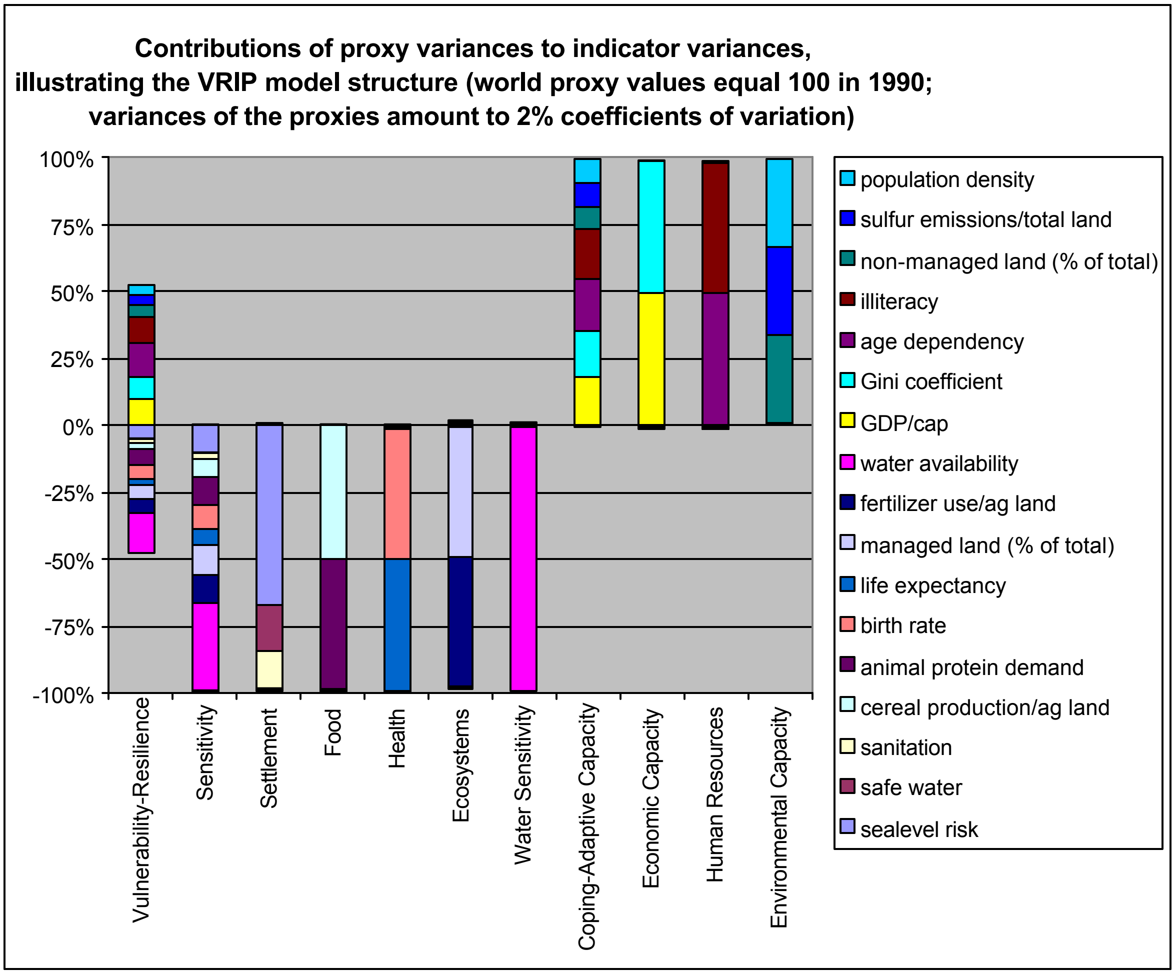

Figure 24 Percentages contribution by the world proxy values set to 100 and varied 2%, to the uncertainty of the global 1990 indicators

Over time the balance between climate sensitivity and coping-adaptive capacity changes (Figure 25) because some of the proxies are projected as increasing, others as decreasing, and all at unique rates. Through the process of changes in values, the balance between (negative) sensitivities and (positive) coping-adaptation capabilities changes as the uncertainty of the indicators change. That is, when over time the coping-adaptive capacity proxies change more than the sensitivity proxies, their contribution to the explanation of the uncertainty of the vulnerability-resilience indicator increases accordingly.

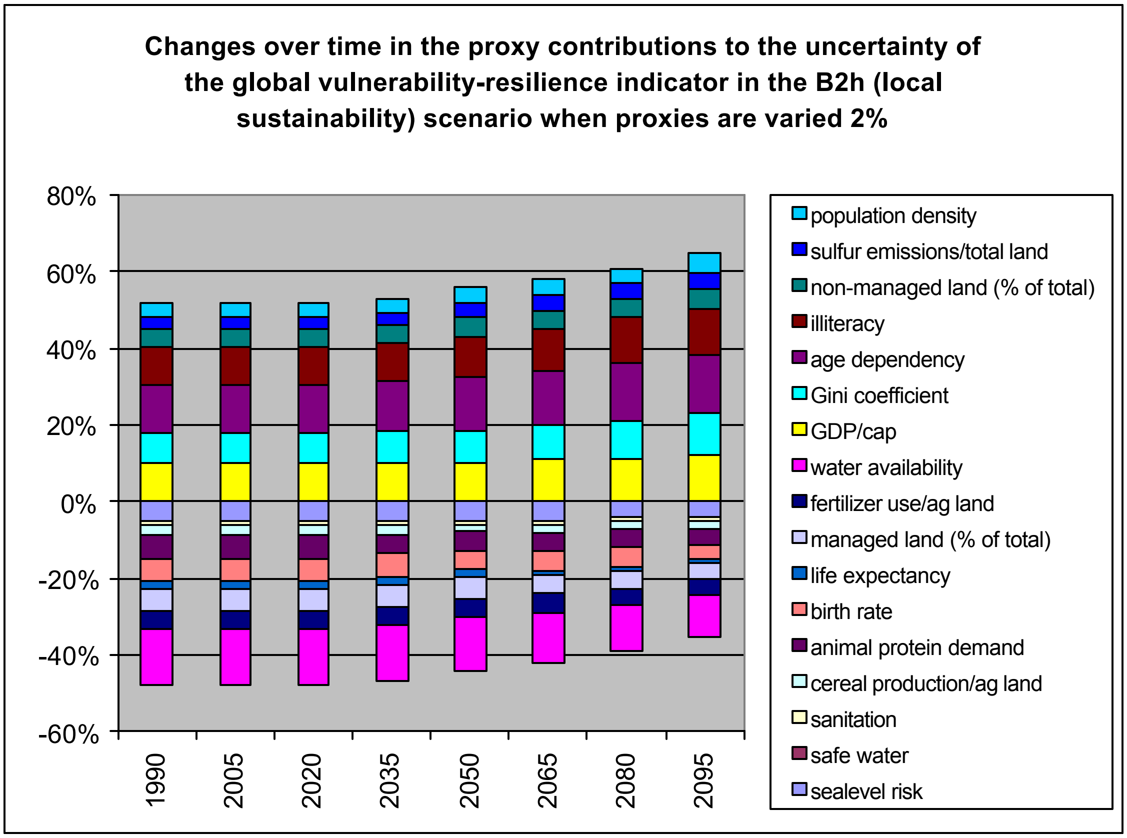

Figure 25 Percentages contribution by proxies, when varied 2%, to the uncertainty of the global vulnerability-resilience indicators from 1990 through 2095 for the local sustainability scenario

Changes in proxy values over time are scenario specific. The consequence is that proxy contributions to the uncertainty of the vulnerability-resilience indicator are scenario specific (Figure 25 and Table 16). For the rapid growth (A1v2) scenario, we find, by the year 2095, that 75% of the uncertainty of the vulnerability-resilience indicator explained by the proxies representing the coping-adaptive capacity compared to 25% by the proxies representing the sensitivity to climate impact (only contributions equal or larger than 5% are listed). For the local sustainability (B2h) scenario these contributions are 65% and 35% and for the delayed development (A2A1) scenario these contributions are about 56% and 44%, respectively. The GDP per capita, the number of people in the work force, and literacy proxies are mainly responsible for the increase in the coping capacity's increased contribution to uncertainty, while the sensitivity's contribution to the uncertainty in vulnerability is mainly due to the proxy for water sensitivity.

The differences among the scenarios indicate that the proxy values are playing a role and not just the model structure. What the analysis also shows is a first indication that we might be able to get insight into leading or dominant proxies for a country for a scenario with regard to coping and adaptive capacity and sensitivity to climate impacts.

Table 16 Percentages contribution by proxies, when varied 2%, to the uncertainty of the global vulnerability-resilience indicator in 1990 and in 2095 for the three scenarios (note that the table's first column with values is for 1990)

	Percentage contribution by proxies, when varied 2%, to the uncertainty of the global vulnerability-resilience indicator in 1990 and in 2095 for the three scenarios			
	1990	**2095**	**2095**	**2095**
		A1v2 Rapid growth scenario	**B2h** Local sustainability scenario	**A2A1** Delayed development scenario
Sea level rise resulting in number of people at risk	-5			-5
% of the population with access to safe water				
% of the population with access to sanitation				
Cereal production/ agricultural land				
Animal protein demand per capita	-6			-5
Birth rate	-6			-5
Life expectancy				
Managed land (as % of total land)	-6			-6
Fertilizer use/area cropland	-5			-5
Water sensitivity, based on availability and consumption	-15	-7	-11	-14
GDP per capita	10	14	12	10
Income distribution equity	9	12	11	9
% Population in the workforce or age dependency	13	17	15	14
Illiteracy	10	14	12	11
Non-managed land (as % of total land)	5	6	5	5
Sulfur emissions per unit total land area		6		
Population density		6	5	

Our radar graphs, when we decomposed the VR indicator into its contributing sectors and/or proxies, presented us with the idea that water availability, and secondly, GDP per capita were the proxies determining overall vulnerability-resilience in most cases. This first uncertainty analysis tells us (see Table 16) that water availability is indeed a dominant player in determining the uncertainty of the vulnerability-resilience in our analyses of the global proxies. By the year 2095, GDP per capita and the other coping-adaptive capacity proxies contribute significantly to the vulnerability-resilience uncertainty. And so does age dependency, that is, what percentage of the population is dependent on the working population. With either strong increases in birth rates or in life expectancy, the age structure of a population changes, which, in our case manifests itself in the age-dependency proxy showing its impact on the uncertainty.

What we do not see in the radar graphs but do see in bar graphs (Figures 24 and 25) is the role the model structure plays in quantifying the vulnerability-resilience indicator. Water availability is a single proxy for the water sensitivity sector while, for example, GDP per capita and the Gini coefficient comprise the economic coping capacity and settlement sensitivity is composed of three proxies. When sectoral indicators are comprised of more than one proxy, the uncertainty (and actual value) of those proxies can only be propagated according to their share in the sectoral indicator, as explained above, and variances (perturbations) in those proxies are less directly visible. The hierarchy of calculating indicators by aggregating proxies may result in lessening the weights of high-value proxies. Consequently, the emergence of potential leading proxies will be model-structure dependent. This also becomes apparent when we see the persistent proxy rankings in the country graphs (Spain, Brazil, Mexico and Senegal) in the Appendix (Figures A38 –A41). All four countries depicted there show similar proxy patterns, differing only to the degree they affect either the sensitivity or the coping-adaptive capacities of the countries. Thus, the more vulnerable a country is, the greater the emphasis on the proxies representing the sensitivity to climate impact, while the more resilient a country is, the emphasis is on the proxies representing coping and adaptive capacity. Spain is a country with high coping-adaptive capacity; and so is Brazil, while Mexico, for which the proxies are projected over time through the same regional forecasts as for Brazil, remains much more climate-sensitive. Senegal also shows high vulnerability and a relatively large change over time compared to the other countries as was also noted in Tables 11 and 12.

Results from sampling the proxies from ranges based on the changes in the proxies' values over time

Secondly, we present the results of sampling the proxies from distributions representing the 30-year change over time around the proxies' best-estimate values at each point in time. We defined leading proxies as proxies that, when having different values, have significant impacts on final indicator values. We determine the different possible values of the proxies by sampling from proxy value ranges determined by their forecasted changes over time. Triangular probability distributions reflect best the type of distribution to sample from, such that the mode is coincidental with the best-estimate proxy value for the time of analysis and the minimum and maximum values determined by proxy values either 15 years before or after that point in time (Figure 23). For the first and last years, proxy value minimum or maximums were calculated as being 10% above or below the best estimate values.

For this analysis we performed, besides the usual forecasting, backcasting for two points in time (1961 and 1975) for a limited number of countries. The backcasting was performed with historical data, collected in the same manner as the baseline (1990) data described previously. Indexing was done against 1990 world baseline data.

The projected changes by MiniCAM and Sustain differ for each time period and among the scenarios. When changes are large, the variances of the proxies for that point in time are large; when changes are slow, the uncertainty or variance will be less. Proxy variances will be reflected in the variances of the vulnerability-resilience indicators (Figure 26). Contributions by the proxies to the uncertainties of the global vulnerability-resilience indicators at each point in time for all three scenarios are depicted in Figures 27, 28, and 29. For the first two sets of years (1961, 1975) the variance of the indicators and the contributions by the proxies to the uncertainty of the vulnerability-resilience indicators are the same. For 1990 they differ slightly, given that the proxy values in 2005 are scenario dependent and those values form the upper bound of the triangular probability distributions the 1990 proxy values are sampled from. After 1990 the proxy contributions differ for each scenario, but with GDP per capita and water availability dominating (see Table 17). However, timing and degree of each's dominance differ. For example, in the delayed development scenario (Figure 29) the potential beneficiary aspect of SO_2 reduction does not play a role, but is detected by 2050 in the rapid growth scenario (Figure 27) and 15 years later in the local sustainability scenario (Figure 28). GDP per capita only shows by 2050 in the delayed development scenario while always dominant in the rapid growth scenario. Sensitivity to water availability weighs less in the rapid growth scenario, but heavily in the delayed development scenario. Differences between 1961, 1975 and 1990 seem gradual, but by 2005 sensitivity to available water seems suddenly strong.

Table 17 Percentage contributions by proxies, when varied according to their change over time, to the uncertainty of the global vulnerability-resilience indicator in 1990 and in 2095 for the three scenarios

	Percentage contribution by proxies, when varied according to their change over time, to the uncertainty of the global vulnerability-resilience indicator in 1990 and in 2095 for the three scenarios			
	1990	**2095**	**2095**	**2095**
		A1v2 Rapid growth scenario	**B2h** Local sustainability scenario	**A2A1** Delayed development scenario
Sea level rise resulting in number of people at risk				
% 0f the population with access to safe water				
% of the population with access to sanitation				
Cereal production/ agricultural land	-14			-6
Animal protein demand per capita		-5	-7	-8
Birth rate	-8			
Life expectancy				
Managed land (as % of total land)				
Fertilizer use/area cropland	-21		-6	-9
Water sensitivity, based on availability and consumption		-14	-21	-30
GDP per capita	13	43	23	24
Income distribution equity				
% Population in the workforce or age dependency	6	6	5	5
Illiteracy	13			
Non-managed land (as % of total land)				
Sulfur emissions per unit total land area		5	18	
Population density	11			

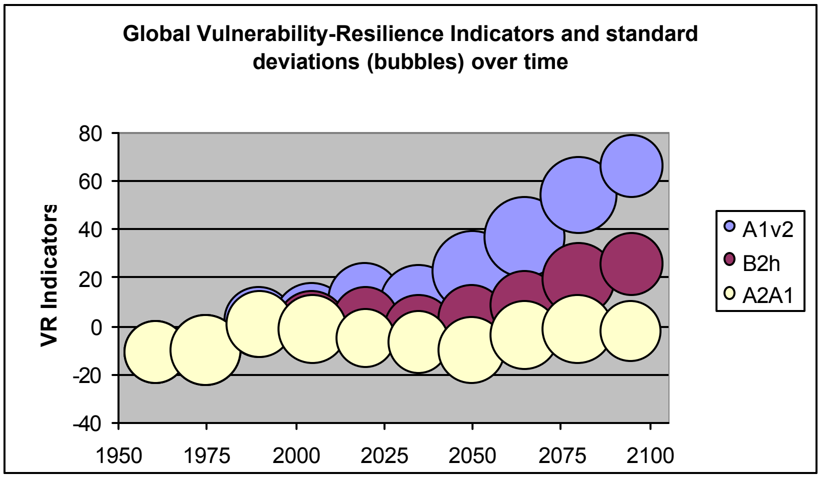

Figure 26 Uncertainty of global vulnerability-resilience indicators in the three climate scenarios when proxies are sampled from ranges determined by changes in proxy values over time

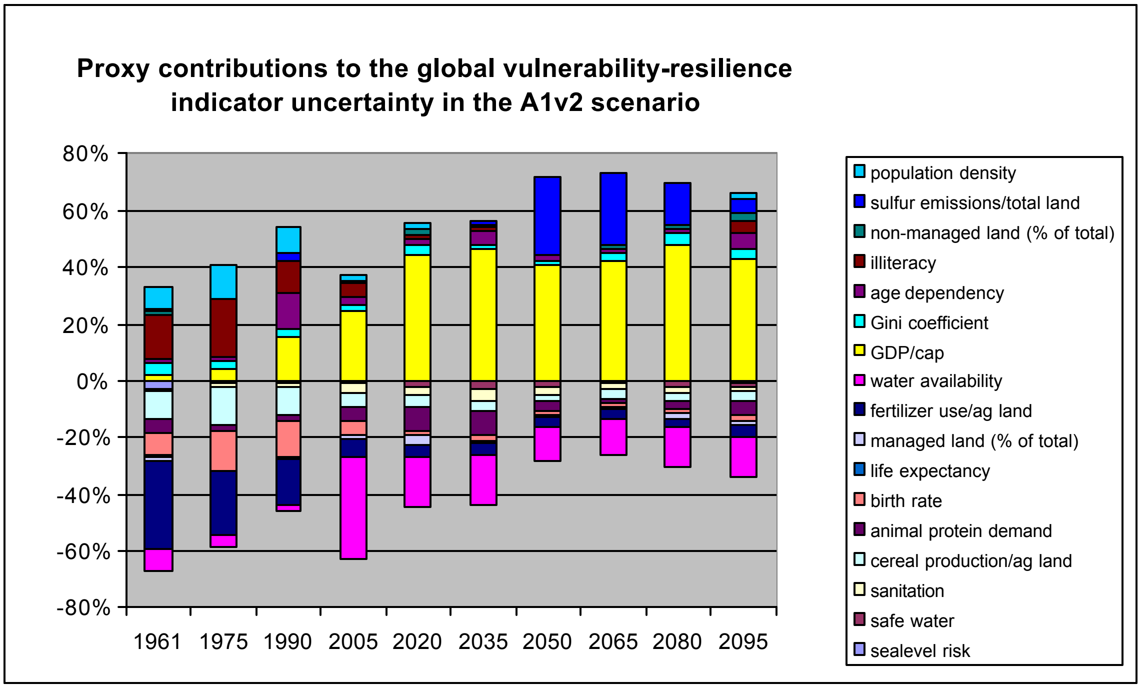

Figure 27 Percentage contributions by proxies to the uncertainty of the global vulnerability-resilience indicators from 1961 through 2095 for the rapid growth scenario with proxies sampled from ranges determined by changes in proxy values over time

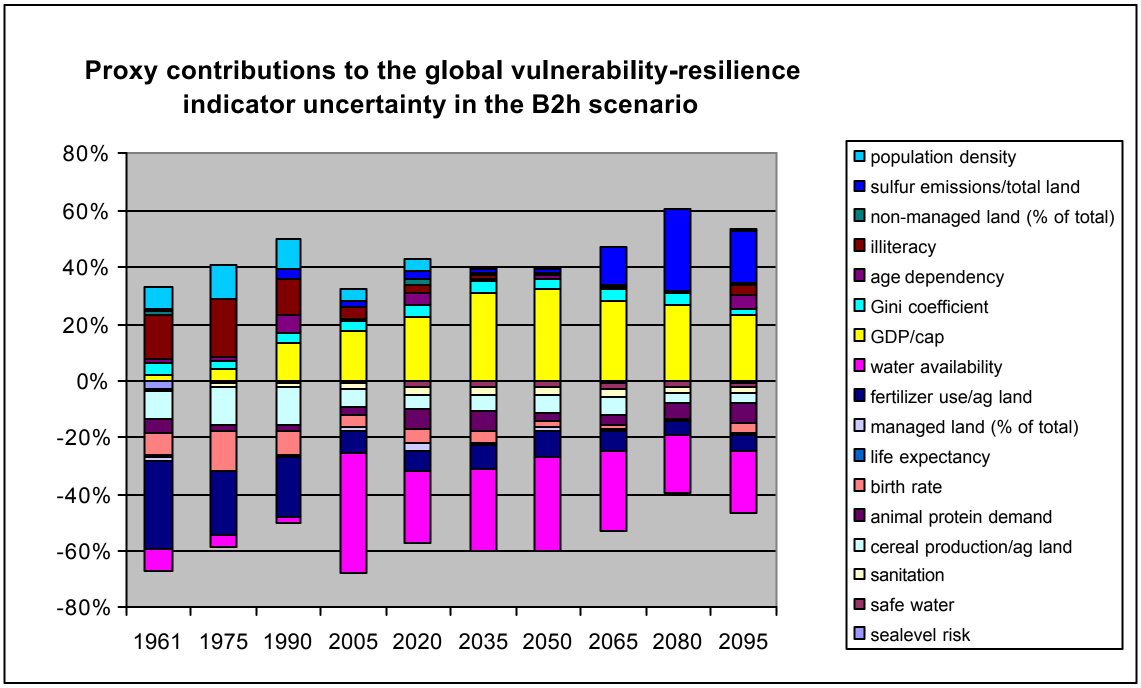

Figure 28 Percentage contributions by proxies to the uncertainty of the global vulnerability-resilience indicators from 1961 through 2095 for the local sustainability scenario with proxies sampled from ranges determined by changes in proxy values over time

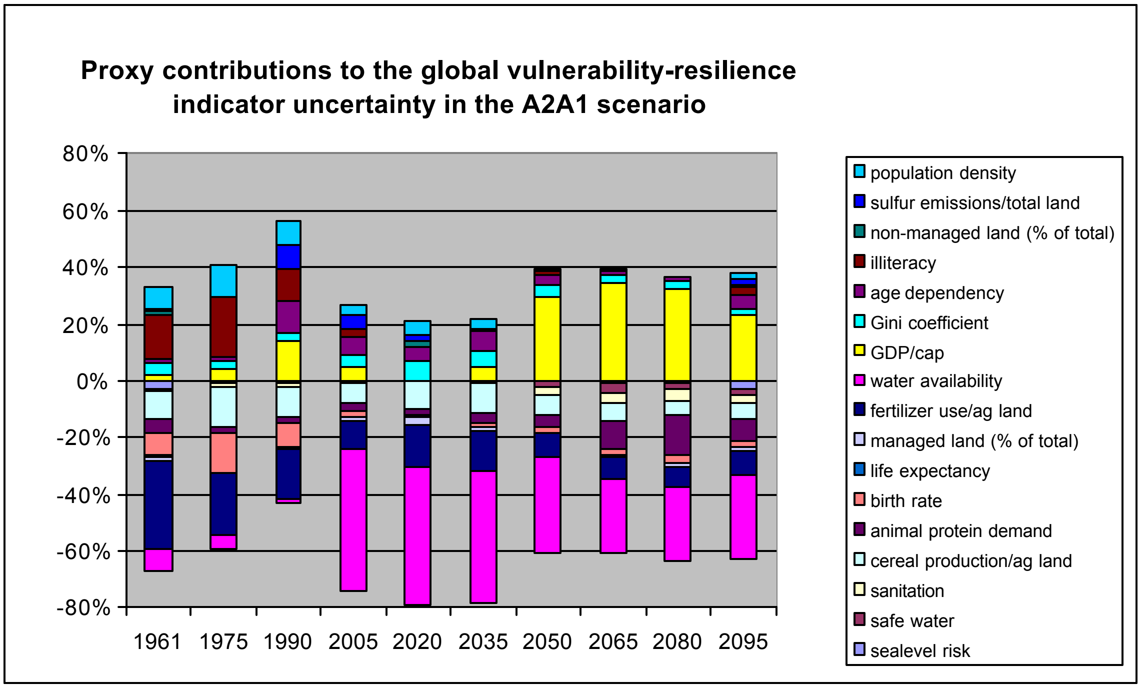

Figure 29 Percentage contributions by proxies to the uncertainty of the global vulnerability-resilience indicators from 1961 through 2095 for the delayed development scenario with proxies sampled from ranges determined by changes in proxy values over time

Sudden changes in proxy contributions are also apparent between 1990 and 2005 in Spain's explanation of the uncertainty in the vulnerability-resilience indicators by proxy variances (Figure 30). Between 1975 and 1990 reported access to safe water and especially sanitation greatly improved. Moreover, sampling from a triangular distribution based on historical or projected change may skew distributions, resulting in a difference between the mean of the distribution and the best estimate of the proxy or parameter. In the case of Spain, this happens for the access to clean water and sanitation proxies. The reported (close to) zero percent no-access by 1990 results in a significant impact on the uncertainty of the VR indicator and a shift in the mean VR indicator to a lower value than in the deterministic case. By the year 2005 this access amounted to 100% and uncertainty in the proxies was assumed minimal. The result is that at that point the projected change in sulfur emissions begins to contribute strongly to the uncertainty in the vulnerability-resilience indicators in 2005 and 2020, followed by the dependency of the population to the percentage people in the workforce by 2065.

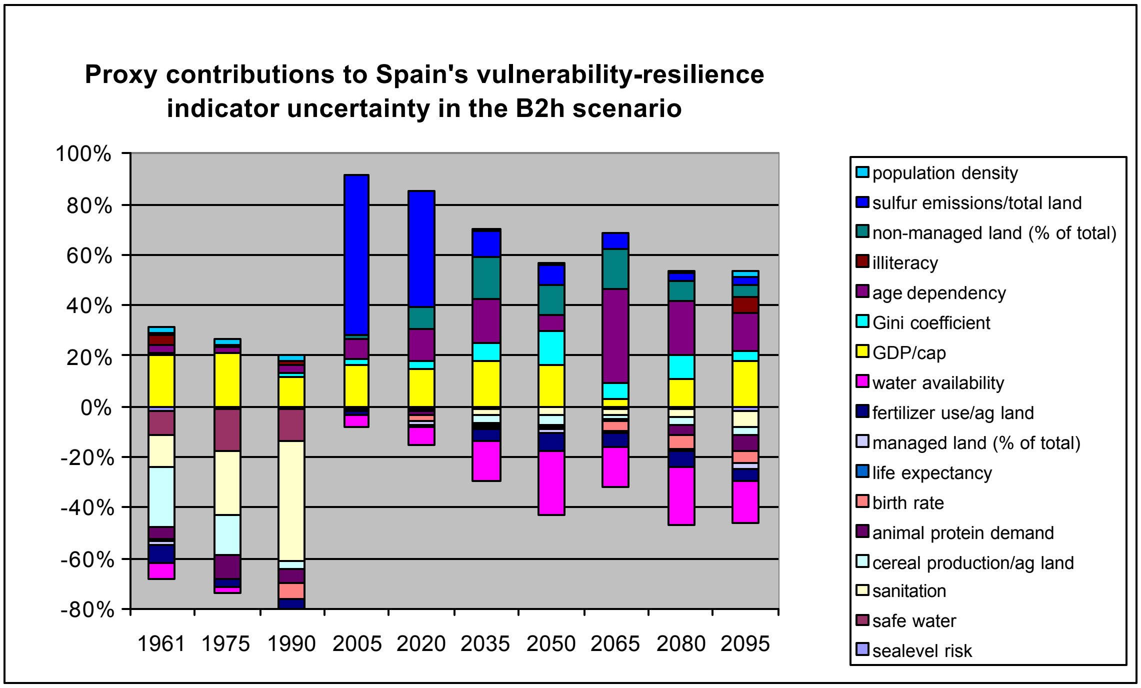

Figure 30 Percentage contributions by proxies to the uncertainty of Spain's vulnerability-resilience indicators from 1961 through 2095 for the local sustainability scenario with proxies sampled from ranges determined by changes in proxy values over time

Other examples of leading proxies are shown in Figures 31 and 32. For Brazil's local sustainability scenario GDP per capita dominates. Age dependency (population in the work force) and population density also plays a role, and reduction in sulfur emissions shows a significant impact on resilience around year 2065 (Figure 31). Reduction of illiteracy is calculated as having had an important impact in increasing resilience in Senegal between 1961 and 1990 while GDP per capita is expected to impact resilience in the future (Figure 32).

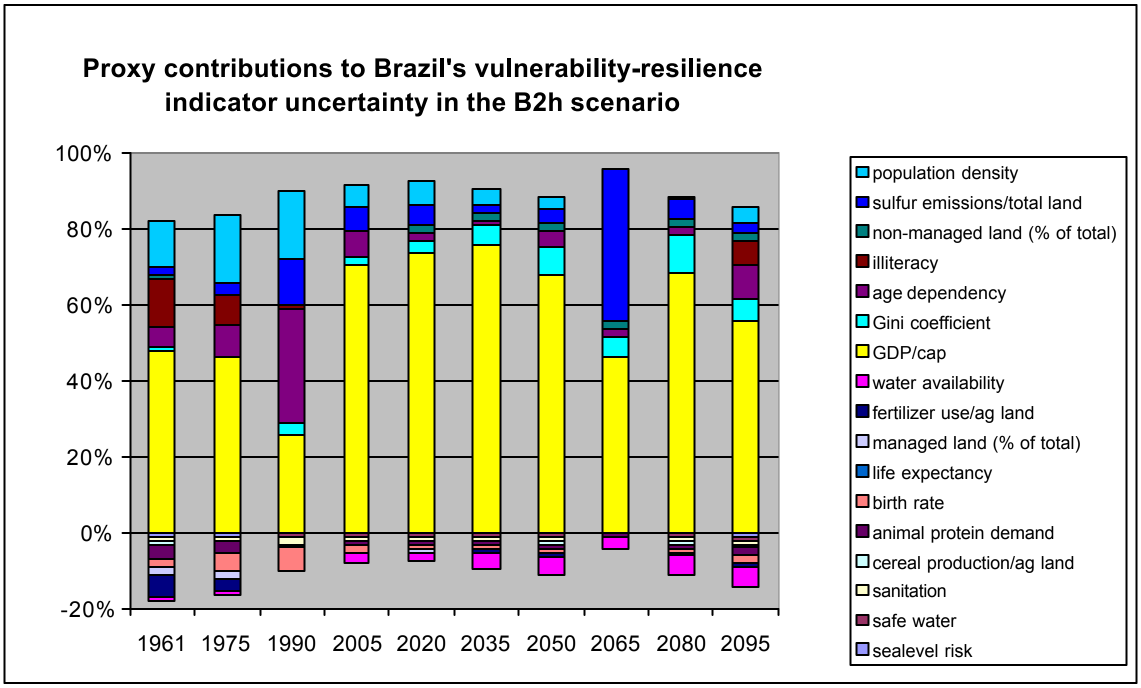

Figure 31 Percentage contributions by proxies to the uncertainty of Brazil's vulnerability-resilience indicators from 1961 through 2095 for the local sustainability scenario with proxies sampled from ranges determined by changes in proxy values over time

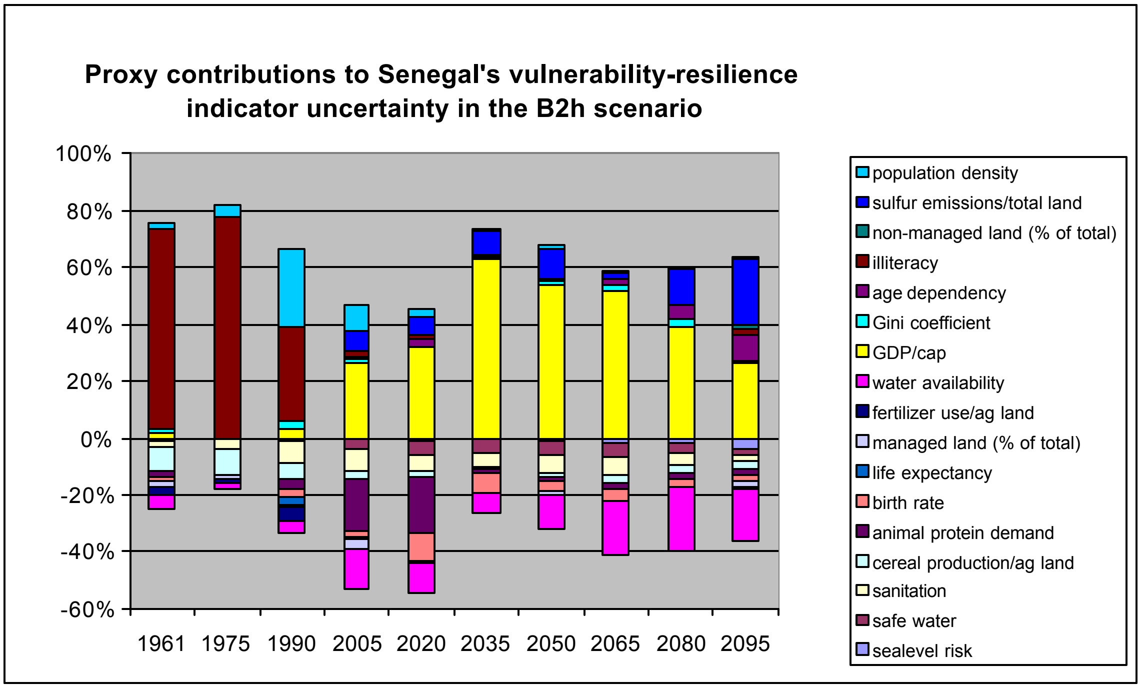

Figure 32 Percentage contributions by proxies to the uncertainty of Senegal's vulnerability-resilience indicators from 1961 through 2095 for the local sustainability scenario with proxies sampled from ranges determined by changes in proxy values over time

In the appendix (Figures A42, and A45-A55) we show for other countries the patterns of proxy contributions for the local sustainability scenario. In the USA sulfur emissions and water availability are leading proxies with land use (% unmanaged land) appearing in 2065. Cereal production only becomes evident after the variance in for example sulfur emissions are of a similar magnitude. For Canada age dependency and GDP per capita are leading proxies. For Japan the pattern is very varied over time with sulfur emissions, water availability, GDP per capita and age dependency clearly leading. For Australia, its high coping and adaptive capacity can be explained by the land use proxy, the GDP per capita and age dependency while in 2050 fertilizer use negatively affects Australia's sensitivity. For Poland we find by the year 2020 economic growth dominating while after 2065 reductions in sulfur emissions have a beneficial effect. China's leading proxies are economic growth for all points in time, and reduction in sulfur emissions after 2050, while water availability is also an important proxy. For Jordan population density is important. For Egypt percentage managed land is a very important proxy until the year 2020 when a relative large variety of proxies share in the explanation of the variance of the VR indicator. For Mexico it is largely GDP per capita, water availability and sulfur emissions. For Bangladesh a relatively large number of the sensitivity proxies are important, e.g., access to safe water and sanitation, cereal production, fertilizer use, birth rate and water availability. In 2065 land use becomes evident, and after 2065 sulfur emissions. GDP per capita plays a role at each point in time. For India it is similar, except that land use does not show in 2065 and the balance between the sensitivity and coping-adaptive proxies differs somewhat. For Thailand the coping and adaptive capacity is larger, manifesting itself in the GDP per capita proxy and the sulfur emissions.

Thus, by performing this type of uncertainty analysis with proxy variances based on historical or projected trends, we see all aspects from our previous analyses emerge: model structure effect remains apparent, the proxy values themselves play their role in determining proxy contributions to the uncertainty of the final indicator and in addition it is now shown that when the proxies change significantly over any 30-year period, the proxies show up as potentially explaining more of the variance and value of the final indicator but that that contribution is still model structure dependent.

Observations

What we have found is that leading proxies can be identified through the Monte Carlo approach if the model structure represents socioeconomic changes and climate impacts well.

We defined dominant or leading proxies as proxies that, when having different values, have significant impacts on final indicator values.

We identified these leading proxies by evaluating the correlations between the sampled proxies and the calculated indicators; proxies with the highest explanatory power of the variance of the calculated indicators may be called leading proxies. By basing the uncertainty ranges of the proxies on their projected changes over time, we captured through sampling from those ranges the different pathways the proxies might take over time, and which of the proxies will be most dominant (leading) in determining the final indicator values.

We found that the proxies change over time in their dominance, and that these changes are scenario- and country-specific. The potential of the emergence of their dominance is model-structure dependent. The visual representation of the changes of proxy dominance over time present immediate information on the balance of sensitivity versus coping and adaptive capacity of a country, and within these main sectoral aggregates, the proxy roles.

CONCLUSIONS

Quantitative vulnerability-resilience indicators are a theoretically sound and technically feasible way of assessing vulnerability to a first approximation. The results of modeling vulnerability-resilience indicators could be used to identify leading proxies, directing research and analysis toward sectors where resilience-building and adaptive strategies are relative priorities.

The transparency of the model, its processes, and the results is of prime importance to researchers and policymakers. Comparing single numbers among nations is likely to be irrelevant, if not misleading, since the single numbers represent a complex reality with highly diverse circumstances and likely highly diverse policy strategies and costs.

A framework for vulnerability assessment that includes both quantitative indicators and qualitative, local data can be extremely useful at regional and local scales, both in assessing vulnerability and in pointing toward appropriate and feasible adaptation strategies.

A framework for vulnerability assessment that includes both quantitative indicators and qualitative, local data can be extremely useful at regional and local scales, both in assessing vulnerability and in pointing toward appropriate and feasible adaptation strategies.

We have shown that decomposition of the vulnerability-resilience indicator into its sectoral indicators or into its proxies assumes equal contributions to the final indicator by its components. This is only a first step in analyzing proxy contributions to the final indicators of interest. By positioning the calculations of the vulnerability-resilience indicator in a Monte Carlo framework, we illustrate a means of capturing the impact of the proxy values, their projected changes over time and the structured relationships of the model elements. Through this approach we can identify those proxies with the largest impact on the final indicator and thus can identify leading indicators that subsequently can be verified, at least historically.

In summary:

- The assumptions made about what individual proxies represent and the meaning of their changed values over time (increases/decreases) are shown in Table ES-1. For the whole set of indicators, we looked for possible domination of one or several proxies through their implicit representation in other proxies; for example, wealth or population may drive the overall results if several proxies are driven by either wealth or population. Similarly, proxies might have to be represented in more than one sector; for example, water availability may influence how agricultural proxy values ought to change over time, while water sensitivity may be represented as a sector in its own right. Moreover, when sectors are aggregated to sensitivities (negatives) or coping-adaptive capacity (positives), the complex nature of proxies becomes an issue. Increases in agricultural yields feeds more people, but if this development also displaces traditional farmers, creates new urban poverty, and depletes the land, a simple proxy cannot account for all these positive and negative changes. The aggregation issue becomes more serious at the highest level, when one number is calculated for vulnerability. The single number should always be understood as representing multiple complexities.
- The prototype model yields unique vulnerability pathways for countries, even those within the same MiniCAM regions, from which projections are derived.
- Wealth is neither a necessary nor a sufficient determinant of vulnerability and resilience. Although country vulnerability-resilience indicators correlate with national GDP per capita, more than 20% of the countries studied show no significant correlation.

- Country-level results are useful for first-order comparisons, but subnational studies will be needed to craft meaningful national policies.
- Comparisons of scenario projections suggest that an emphasis on general development is an appropriate approach to building resilience to climate change.
- Scenario projections, based on IPCC scenarios, seem optimistic when compared with case studies of the same areas, while linear extrapolations, either of improvement or degradation, are probably not realistic descriptions of the future either.
- Our lack of knowledge about inequality in societies and potential inequality in the future hampers our ability to assess who in a society is vulnerable and to what.
- Many, perhaps all, proxies include both negative and positive implications. Vulnerability assessment needs to account for tradeoffs.

The next steps in development of the vulnerability indicators model include both analytic and technical/scientific tasks:

- Thoroughly review the set of proxies and sectors in light of the analyses detailed in this report. Add, delete, and modify as necessary. Consider especially overrepresentation of population data. Account for scale issues by using ratios/percentages wherever possible.
- Revise the model structure and mathematical processes to ensure that proxies are appropriately weighted in the indicators.
- Perform several case studies at a regional or local level (e.g., watershed, urban area, semi-arid plateau), developing specific indicators relevant to the case and using relevant data from the area.
- Involve local stakeholders (e.g., policymakers, business persons, workers, members of NGOs) in the determination of relevant proxies and weights.
- Use the model results in a larger framework of vulnerability assessment.

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