Climatic Change (2010) 100:87–101
DOI 10.1007/s10584-010-9827-4

# Bridging the gap: linking climate-impacts research with adaptation planning and management

**Michael D. Mastrandrea · Nicole E. Heller · Terry L. Root · Stephen H. Schneider**

Received: 3 March 2010 / Accepted: 3 March 2010 / Published online: 19 May 2010


**Abstract** A critical challenge in supporting climate change adaptation is improving the linkage between climate-impacts and vulnerability research and public and private planning and management decisions. We highlight the need for bottom-up/ top-down vulnerability assessment, bringing together bottom-up knowledge of existing vulnerabilities with top-down climate-impact projections, as a transparent basis for informing decisions intended to reduce vulnerability. This approach can be used to evaluate the likelihood of crossing identified thresholds of exposure, and to evaluate alternative adaptation strategies based on their ability to reduce sensitivity to projected changes in exposure and their robustness across uncertainty in future outcomes. By identifying thresholds for which adaptive capacity is limited in particular systems, adaptation and mitigation become complements where the magnitudes of climate change at which such thresholds cluster can help to define mitigation targets.

## 1 Adaptation and mitigation as complements rather than trade-offs

Rapid climate change is one of the widest reaching challenges modern society has faced. Its physical, ecological, economic, political, cultural and ethical dimensions have local, national, and global implications. Significant impacts resulting from rapid climate change are already evident, and pose increasing risks for many vulnerable

M. D. Mastrandrea (✉) · T. L. Root · S. H. Schneider
Woods Institute for the Environment, Stanford University, Y2E2, Mail Code 4205,
473 Via Ortega, Stanford, CA 94305, USA
e-mail: mikemas@stanford.edu

N. E. Heller
Climate Central, 895 Emerson Street, Palo Alto, CA 94301, USA

S. H. Schneider
Department of Biology, Stanford University, Stanford, CA 94305, USA

populations. Society faces immediate choices about how to reduce vulnerabilities, despite inherent uncertainties about the path of future greenhouse gas emissions, the response of the climate system, and the adaptive capacity of human and natural systems.

There is growing worldwide momentum to address climate change by reducing emissions significantly below current levels. But because of the inertia in social and physical systems, the climate will continue to change significantly for decades, even with aggressive global action to reduce emissions. As a result, society must also focus on enhancing its capacity to adapt to current and future impacts that cannot or may not be avoided. These adaptation strategies must be concurrent and complementary with mitigation efforts because, over the long term, emissions reduction choices will determine the severity of climate change, its impacts, and the degree of adaptation required in the future. Mitigation is also essential for avoiding impacts that exceed the capacity of human and natural systems to adapt effectively—rapid climate change, unchecked, is virtually certain to exceed many coping thresholds.

Consequently we see mitigation and adaptation primarily as complements: we must adapt soon to what is not easy or possible to be quickly mitigated and must mitigate over time to prevent crossing too many thresholds or irreversibilities above the coping capacity of key systems. The COP-15 Copenhagen Accord (UNFCCC 2009) has noted a target subjective threshold, above which further warming is deemed unacceptable, of 2°C above pre-industrial global surface temperatures. This is about 1.2°C above 2010 levels—a very challenging target, given that global emissions are still growing year by year.

## 2 Scientist–stakeholder linkages to improve vulnerability and adaptation analyses

Decision makers are becoming more interested in obtaining understandable information about climate change risks. In particular, planners and managers in various sectors are expressing the need for climate information that can support adaptation-related decision-making, provide straightforward estimations of uncertainty and is tailored to specific user groups. Such knowledge is ideally co-produced through sustained stakeholder–scientist interactions to develop information and tools in forms that decision makers are more likely to incorporate into their decision making processes or use as a basis for modifying those processes (Sarewitz and Pielke 2007; McNie 2007; van Kerkhoff and Lebel 2006; Lemos and Morehouse 2005; Turnpenny et al. 2004). More information about projected climate changes and potential impacts does little on its own to alter on-the-ground decision-making processes or influence public- or private-policy debates about how to handle risk (Rayner et al. 2005; Dessai and Hulme 2004).

A study investigating climate change awareness and preparedness among coastal managers in California reported that most managers do not use weather, climate, or sea level rise data in current decision-making, and that managers wanted more information on climate risks but only if provided in a form that fit "seamlessly" into existing procedures (Moser and Luers 2008). Recommendations for adaptation actions based on scientific research often fall short of providing information that can be directly useful in on-the-ground decision making. For example, a study of 22 years of scientific literature on biodiversity conservation finds hundreds of calls for adaptation of conservation practices to address climate change, but few recommendations with sufficient specificity to inform actual operations and implementation schemes (Heller and Zavaleta 2009). They call for the development of concrete strategies and case studies that illustrate how and where to link research agendas, conservation programs, and institutional practices. The key here is to link stakeholder input and scientific output at all stages of the information transfer process, from problem detection, to design, to format of the products, to implementation activities.

## 3 Bottom-up/top-down vulnerability assessment

A critical challenge is improving the linkage, particularly in the context of adaptation, between climate-impacts and vulnerability research and public and private planning and management decisions. Toward that end, we highlight the need for *bottom-up/top-down vulnerability assessment*, bringing together bottom-up knowledge of existing vulnerabilities in the context of current decision making processes with top-down climate-impact projections. This approach joins scientists with stakeholders to identify and focus on key issues of concern: namely, stakeholder-assessed thresholds of climate change vulnerability that could well be exceeded in the future, and thus require attention in setting adaptation priorities in advance. Identifying key thresholds that could be exceeded requires drawing on vulnerability assessments for specific places or for specific sectors or groups to determine relevant thresholds (the bottom-up part), and assessing the likelihood of exceeding these thresholds by performing an analysis of existing archives of climate model projections produced under alternative emissions scenarios (the top-down part).

Most climate-impact assessments are "top-down." They are based on the output of global climate models driven by alternative scenarios for future global greenhouse gas emissions, land use patterns, demographic trends, policy choices, and economic and technological change. They examine projected changes in specific climate variables and their implications for ecological and social systems. The obvious uncertainty inherent in those socio-economic-development scenarios that drive future emissions is compounded by an additional set of uncertainties associated with the physical climate system. This includes uncertainties in the response of the climate system to increasing greenhouse gas concentrations or land use changes, the limited capacity of current global climate models to reproduce regional scale patterns with a high degree of confidence, and the resultant common use of various downscaling techniques to produce finer resolution projections. These downscaling methods still rely on the coarse-scale-global-model projections, and results are sensitive to the downscaling method employed (e.g., Maurer and Hidalgo 2008). Downscaled projections generally produce a wide range of projected changes in local climate conditions, particularly those beyond mean temperatures. In other words, there are two fans of uncertainty that jointly determine vulnerability and impacts: (1) human activities that create disturbances to the land and air, and (2) the response of the climate system to such drivers of change, that response being a property of the coupled human-natural system (e.g., Liu et al. 2007).

Most top-down impact studies use the range of greenhouse gas emissions associated with alternative future scenarios to project changes in climate and biophysical variables, but these studies often do not consider the implications for future vulnerability of the alternative socio-economic trends associated with each scenario, and the resulting implications for projected impacts. The linkage between vulnerability and development pathway is recognized, as it is highlighted, for example, in the Intergovernmental Panel on Climate Change Fourth Assessment Report Working Group II Summary for Policymakers (IPCC 2007), but beyond making this linkage, the literature is sparse. Vulnerability is often defined in terms of three components: exposure, sensitivity, and adaptive capacity (e.g., Adger et al. 2007; Adger 2006; Smit and Wandel 2006). *Exposure* refers to the nature and degree to which a system experiences stress (e.g., the frequency and intensity of heat waves in a given location, or the level of the sea). *Sensitivity* refers to the degree to which a system is affected or modified by that exposure, and varies across different regions, populations, and sectors (e.g., differences in sensitivity to heat waves across age groups or populations with differing access to air conditioning or coasts that are steep and have little area exposed to rising sea levels versus very flat coastlines that are highly sensitive to sea level rise). *Adaptive capacity* refers to the ability of a system to adjust to change, in terms of expanding the range of impacts with which it can cope, making modifications in ways that reduce its sensitivity to the changes, or both. Thus, increasing adaptive capacity can reduce sensitivity, and thereby reduce vulnerability.

Exposure is reduced primarily by mitigation. In general terms, there is a relationship between vulnerability to climate events and the development status of a nation (e.g. per capita GDP, access to education, life expectancy; IPCC 2007; Patt et al. 2009). In this way, the differences in social and economic trends associated with alternative future scenarios influence the vulnerability of socio-ecological systems.

Dessai and Hulme (2004) distinguish between assessments based on biophysical (top-down) versus social (bottom-up) vulnerability. As noted by these authors and others (e.g., Moser 2006), these approaches provide complementary information. Comprehensively assessing vulnerability to rapid climate change requires an integration of both approaches. Detailed bottom-up studies are necessary to provide understanding of the structural, institutional, psychological, financial, legal and other mechanisms, and cultural norms of impacted sectors, communities and management systems. In addition, studies are needed of the capacity and constraints, and access to coping mechanisms of those impacted in responding to changing climate conditions, and the influences of non-climatic stressors interacting with climate change (Tribbia and Moser 2008; Rayner et al. 2005).

Thus, the challenge is to develop integrative methods and to employ the resulting knowledge in order to inform decision-making (e.g., Vogel et al. 2007; Thomalla et al. 2006). We reiterate that this challenge necessitates direct partnerships between stakeholders and scientists, social scientists performing vulnerability assessments and climate scientists making explicit what is known and not known regarding the climate system response to given scenarios of development, and providing that climate information in a form relevant to aiding the interactions between decision-makers and scientists over time. Such partnerships can increase understanding of a system's response to climatic stress and identify potential intervention points for managing vulnerabilities.

An approach to link scientists with stakeholders having expertise related to specific regions, sectors or populations, what we have coined *bottom-up/top-down vulnerability assessment*, requires at a minimum the three following steps. First, assess historical and current exposure and sensitivity to a wide range of climatic conditions and resulting impacts, both experienced (e.g. property damage or loss of life) and perceived (e.g. heightened sense of danger, loss of public trust). Second, assess existing adaptive capacity and existing decision making processes (e.g. how fast or the extent to which policies or behavioral practices changed in response to climatic stresses) and the extent to which communication pathways allow a free flow of information. These steps together provide indicators of thresholds of exposure that would prove challenging for a particular system to adapt to, and thus provide a basis for defining current, and potential future, vulnerability thresholds associated with climatic exposure. In some cases, existing scientific research or decision maker/stakeholder experts may already have identified such thresholds. In other cases, such information may not yet be available. Third, integrate this information with future climate change projections and associated socio-economic development pathways. Ensembles of projections that reflect uncertainty in future climate change under specified emissions scenarios (across global climate models and downscaling methods) can be employed to construct probability distributions of relevant climate variables (exposure) and calculate likelihoods of crossing thresholds of exposure. Finally, this information can be combined with the development pathways associated with those specified emissions scenarios in order to examine how both exposure and sensitivity may change over time, and thus how vulnerability thresholds based on climatic exposure may change in the future.

To summarize, bottom-up analysis of concerning thresholds can be mapped against the databases of top-down models driven by high, medium and low emissions scenarios in order to estimate the likelihood of crossing these stakeholder-defined local thresholds as a function of emissions scenario. Finally, pathways for future development associated with these emissions scenarios can be incorporated to estimate changes in future vulnerability that may affect these stakeholder-defined thresholds. In this way planners can estimate the likelihood of changes outside of their estimated coping ranges, and can do this as a function of emissions scenario and development pathway, thereby providing the opportunity to consider adaptation and mitigation decisions in complementary terms. For example, if there were a clustering of such bottom-up thresholds being breached by some given degree of warming, that would help to define a mitigation level for the complementary nature of mitigation and adaptation actions.

Our *bottom-up/top-down vulnerability assessment* provides a transparent basis for vulnerability assessment and informing decisions intended to reduce vulnerability. This, in turn, could benefit numerous planning and management decisions by improving linkages with climate change research. Alternative adaptation strategies can be identified through this process and evaluated based on their ability to reduce sensitivity to projected changes in exposure, and their robustness across uncertainty in future outcomes. In addition to biodiversity conservation mentioned above, examples of other impacted sectors include water supply infrastructure planning and water resource management that will be affected by changes in water availability and quality, coastal protection in areas threatened by sea level rise and intensifying storm surges, cropping and agricultural management practices affected by changing temperature and precipitation patterns, wildfire regimes in various regions, and disaster preparedness with risk management for more frequent and intense heat waves, heavy storms, and other extreme events. This type of bottom-up/top down linked analysis can also be used to examine the vulnerability of specific communities or population groups rather than sectors, such as indigenous peoples in the Arctic or high mountains, or women in farming communities in developing countries.

We also note, however, that this approach may not reveal important thresholds of vulnerability related to future conditions with no analog in the past or present. Emerging risks posed by nonlinearities in the climate system, rates of change in climate conditions faster than those experienced in the past, and novel combinations of stressors are likely to reveal "surprises," vulnerabilities not or not fully foreseen based on past experience (see, e.g., Schneider et al. 2007).

## 4 Vulnerability: internal "versus" external framing

*Climatic Change*, owing to its interdisciplinary approach across a broad spectrum of problems and disciplines related to climate, has been a major player in building the extensive body of literature characterizing the impacts of climate change, as well as research related to improving the understanding of how and to what extent climate change research can inform mitigation and adaptation strategies to respond to climate risks. However, with a few notable exceptions, that body of literature has been focused primarily on either top-down or bottom-up analysis. One of the exceptions is Dessai et al. (2004) who argued:

> There are therefore at least two contrasting perspectives on dangerous climate change, what we term 'external' and 'internal' definitions of risk. External definitions are usually based on scientific risk analysis, performed by experts, of system characteristics of the physical or social world. Internal definitions of danger recognize that to be real, danger has to be either experienced or perceived—it is the individual or collective experience or perception of insecurity or lack of safety that constitutes the danger. A robust policy response must appreciate both external and internal definitions of danger.

They provided a figure (Fig. 1 below) to characterize the dichotomy between internal and external approaches, in this context, to defining what constitutes "dangerous anthropogenic interference" with the climate system.

Our approach owes much to this creative framing of the vulnerability debate, and builds from it. As we have argued, we accept this established recognition of the lack of integrated efforts between stakeholders, policymakers, managers on the ground and natural and social scientists. Our extension of this concern is to connect the bottom-up (within both the external and internal-like levels in the Dessai and Hulme framing) to define thresholds of concern and then to map these to the existing top-down literature in climate modeling to estimate the likelihoods that such stakeholder defined thresholds could be exceeded. We acknowledge how the literature advancing over time in *Climatic Change* has provided an excellent base to build such a bottom-up/top-down framework.

## 5 Examples of scientist–stakeholder linkages

To further illustrate these ideas, we present two examples where this approach might be applied.

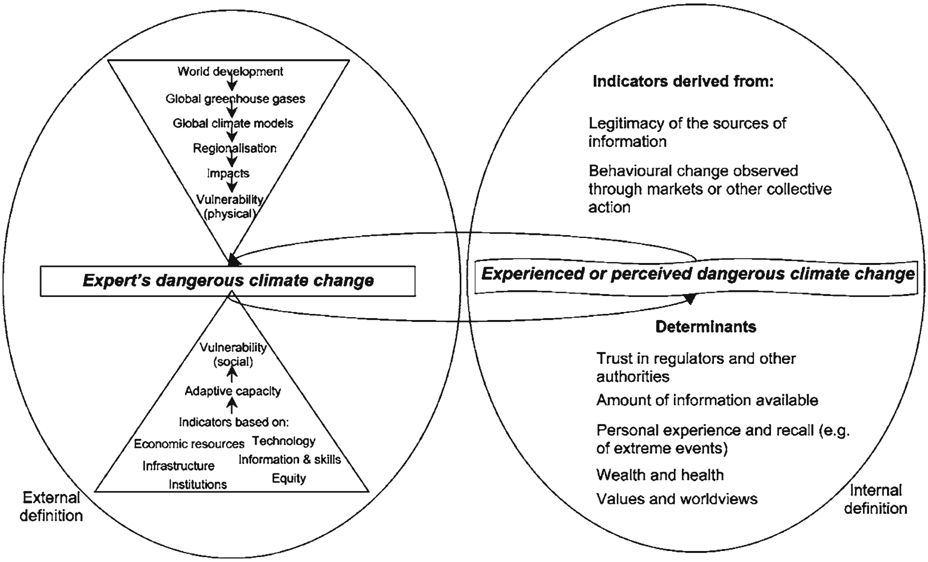


**Fig. 1** Components of external and internal definitions of dangerous climate change. From Dessai et al. (2004)

## 5.1 Biodiversity conservation and managed relocation

Biodiversity is highly vulnerable to climate changes. However, species are differentially vulnerable, and some even could take advantage of climate changes up to a point. This makes managing species to avoid the irreversibility of extinction more difficult. All living organisms are affected both directly and indirectly by climatic factors, such as temperature and precipitation. In general, species occur in areas where they expend the least amount of energy to stay alive. As such, temperature affects and may also limit the ranges of many species (Root 1988a, b). Consequently, as species are exposed to higher temperatures due to rapid warming, those that are most sensitive to temperature change (e.g., those in the foothills of mountains or with the poleward boundary of their range limited by temperature) should be able to adapt by shifting up in elevation or poleward, assuming that the habitat through which they must move is not too hostile (e.g., a small mammal on an island can rarely cross the ocean to get to another hospitable habitat, or a reptile cannot easily walk across factories, freeways and other features of urban settlements). An elegant example has it origin in the early 1900s when Joseph Grinnell recorded species along several altitudinal transects in the Sierra Nevada mountain range. Repeating those transects in the early 2000s, Tingley et al. (2009) found that 48 out of 53 (90%) bird species have indeed shifted up significantly in elevation, which allowed them to remain within their thermal niche.

An increase in average global temperature of only 0.6 to 0.8°C, since the beginning of the 20th century, has already caused many plants and animals to adapt—demonstrating that they are indeed sensitive to seemingly small changes in climate. Since 1990 locational shifts at the northern boundary of the ranges of various plants was noted by the National Arbor Day Foundation. Knowing when to plant particular species in a given location is key for this Foundation. They found that the 1990 USDA Plant Hardiness Zone Map, which historically has been used to determine planting dates, needed to be updated to be reliable due to the warming of the globe. Hence, they redrew the map themselves (Fig. 2). A comparison of the 1990 and 2006 maps reveals that the hardiness of plants has obviously changed significantly over the intervening 16 years.

Not only are plants and animals shifting north and up in elevation throughout the US, but species are also changing their phenology, or the timing of life events, such as blossoming flowers or laying eggs. In the beginning of the 21st century, species around the globe were found to be overwhelmingly (80%) changing in the manner expected with global warming (Root et al. 2003). Studies continue to find significant responses of species to warming in the last century (Parmesan 2006), and the number of studies making recommendations for how resource managers should adapt their practices to maintain biodiversity in the face of these changes has grown rapidly (Heller and Zavaleta 2009). Unfortunately, most of those studies are not providing the decision makers with the type of information they need to manage species in peril (Heller and Zavaleta 2009). This is exactly where a bottom-up/top-down vulnerability assessment is needed. Using climate models projections (top-down) with observations on species responses (bottom-up) will better allow managers to understand species changes in a manner that helps them invoke appropriate management.

As the globe continues its rapid warming (with temperature increase likely to be uncomfortably larger over the 21st century), a considerable fraction of plants and animals around the globe may not be able to adapt quickly enough on their own, and their survival may require direct human intervention. For example, species on low-lying islands threatened by rising sea levels may only avoid extinction if moved by humans to alternative suitable habitats. Those species that managers are able to be relocate into more hospitable areas will likely need careful management to ensure they get established in the new habitat (Richardson et al. 2009). In the authors' value system, which we believe is shared by a large fraction of humanity, we do not want many species to go extinct (the final irreversibility). However, the sheer number of species needing help compared to the limited resources societies typically allocate to conservation and restoration will not allow us to save all species.

Indeed saving all species is impossible, even if managers understood how and what to do for every species, which is obviously impossible. The resources needed for managed relocations of species are not only monetary, but also include factors such as improving our understanding of how and when to intervene, and how to relocate and successfully maintain particular species. Additionally lacking for an effective and comprehensive effort to save as many species as possible is people power to carry out the work, political will to finance support for such learning and management, and other factors still to be identified. An unfortunate message from this for managers and decision makers is that species conservation efforts need to be prioritized, something that we are doing to a considerable extent already (e.g. funds allocated to help get species off the US endangered species list, the order in which land is acquired for conservation, and the space provided in zoos and botanical gardens).

When species do go extinct it is frequently not due to a failure of one particular factor—a particular manager or management scheme. Most failures, however, can be traced to not having sufficient resources to deal with the ever-growing number

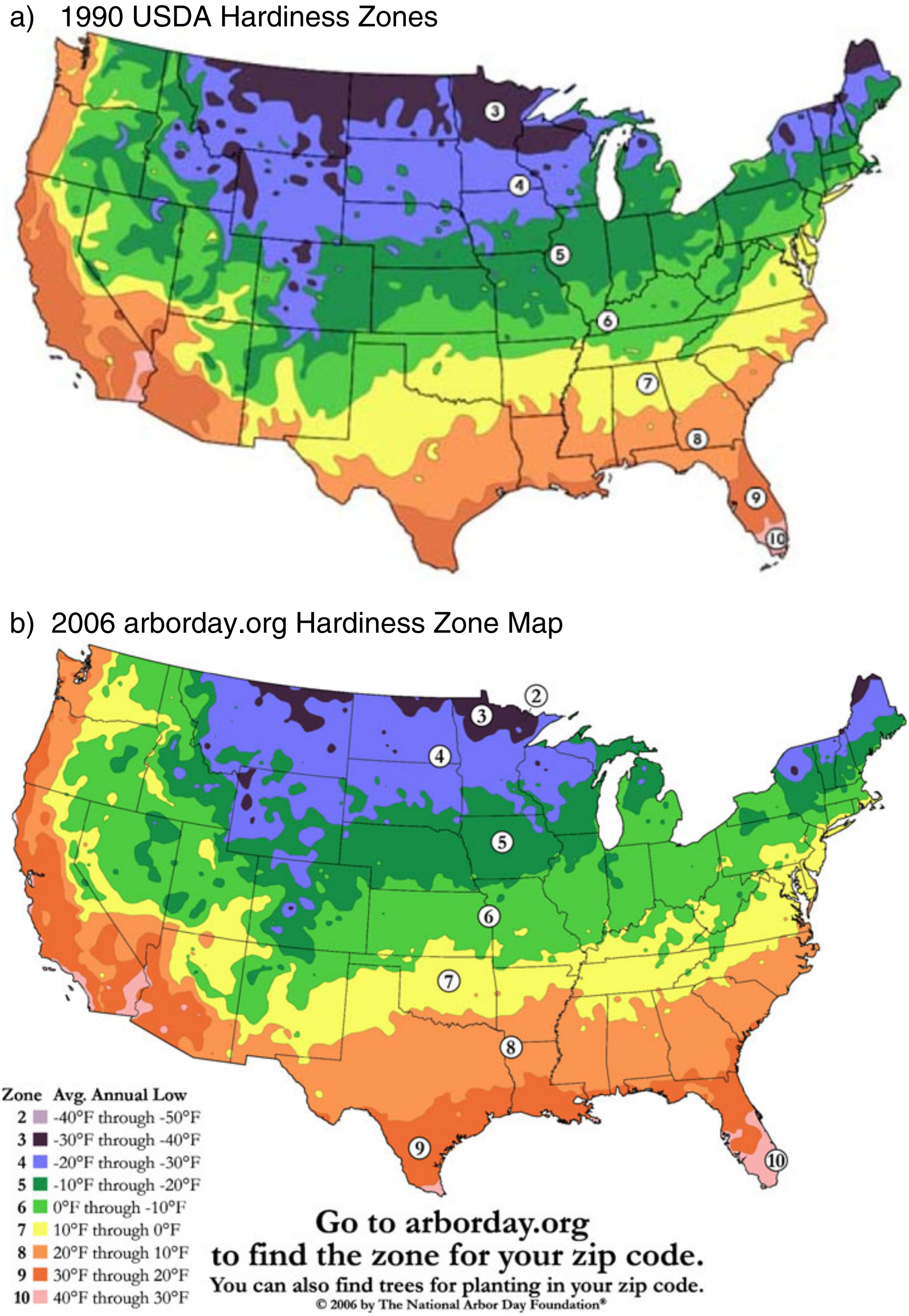


**Fig. 2** Comparison of 1990 USDA Hardiness Zone Map and 2006 Arbor Day Foundation revision. 1990 map after USDA Plant Hardiness Zone Map, USDA Miscellaneous Publication No. 1475, Issued January 1990. 2006 map copyright by The National Arbor Day Foundation, available at: http://www.arborday.org/media/zones.cfm

of species in distress. What we must do is focus on those that we can save and not risk them by siphoning off resources for other species less likely to be protected by feasible interventions. This is exactly what is already occurring because of the very fact that we, for example, prioritize the species on the endangered species list because funding or another factor is not available to do what is needed for all at-risk species. Some species, however, have been managed in a manner that increased their abundances to the extent they are no longer considered endangered. That is a handful of species out of a depressingly long list endangered species. While considering such horrific choices to "triage" species, protection efforts for a species are clearly a value judgment about which species are "valuable enough" to get the investments for protection or "less valuable" and thus lower priority for attention. The proposals for scientific criteria to aid in making these sorts of judgments have already been suggested (Richardson et al. 2009). These include a variety of social and ecological issues as can be seen in Table 1 from Richardson et al. (2009).

The examples used to illustrate this proposed decision-making process explained by Richardson and co-authors (2009) are formulated from hypothetical stakeholders and published information about a few species of concern, for which the quality of the information about the likelihoods of outcomes are based on sparse data and little formal analysis. For this model to be applied in practice and used for making high-stakes conservation decisions, a bottom-up/top-down vulnerability assessment, such as the method described above, will greatly help produce the range of information, quantified with the appropriate levels of certainty, needed to assess the categories listed in the table.

### 5.2 Coastal management and climate change

Coastal populations are highly sensitive to climate changes and sea level rise. Erosion, storm events, flooding, and saltwater intrusion into groundwater, estuaries, and septic systems persistently threaten people, property, flora and fauna. Ten percent of the world's human population lives along a coastline that is less than 10 m above sea level. Even so, coastal areas have some of the fastest rates of urbanization (McGranahan et al. 2007). This development puts high numbers of people at risk, and limits the adaptive capacity of wetland and other coastal ecosystems to migrate inland and cope with sea level rise. Habitat loss results in further vulnerability because coastal ecosystems provide numerous services to communities (e.g. attenuating waves and flooding associated with storm events, food, carbon sequestration, pollutant regulation). Recent studies in the US with coastal managers highlight that awareness of climate change impacts, tools and resources to plan accordingly, as well as the institutional capacity to adapt are scarce (Moser and Luers 2008). In developing nations, these resources are even scarcer, though economically poor populations may have access to coping strategies, such as flexibility in resource use, social structures and mobility, which may provide resilience (Adger 1999; Berkes and Jolly 2001).

A recent report by the San Francisco Bay Area Conservation and Development Commission (SFBCDC) outlines a number of governance limitations to adaptation, institutional practices, and specific knowledge gaps that create vulnerability along shores (SFBCDC 2009). Adjacent to the Bay, a great deal of valuable infrastructure is built at sea level, on reclaimed marshland, including roads, ports, airports, and commercial and residential buildings. It is argued that current insurance practices act to encourage development in risky floodplains where risk is increasing due to climate change and not decreasing as was thought in the past due to various human

**Table 1** Ecological and social considerations for evaluating individual cases of managed relocation (MR), wherein the goal is to prevent the loss of a species or population

| Ecological criteria | Social criteria |
|---|---|
| Focal impact[a] | |
| Likelihood of outcome: | Likelihood and consequence of outcome: |
| Extinction | Cultural importance of the target and its community (e.g., Is the target a flagship or iconic species? Is the historic integrity of the community important?) |
| Decline in geographic distribution | Equity of the impact on particular groups of people |
| Decline in abundance within geographic distribution | Concerns about the harm to individual organisms subjected to MR |
| Indirect effects of decline on community members and community composition | Financial loss whether focal unit declines in abundance or goes extinct |
| Consequence of outcome: | |
| Uniqueness (phylogenetic, functional, etc.) | |
| Geographic distribution (common versus rare; small versus large range) | |
| The potential for reversibility (e.g., if no action were taken and the species went extinct in the wild, are there ex situ individuals available for population reestablishment) | |
| Collateral impact[b] | |
| Likelihood of outcome: | Likelihood and consequence of outcome: |
| Decline or extinction of native species in recipient region | Cultural importance of the target and its community (e.g., Is the target a flagship or iconic species? Is the historic integrity of the community important?) |
| Decline or loss of ecological functions in recipient region | Equity of the impact on particular groups of people |
| | Concerns about the harm to individual organisms subjected to MR |
| | Financial loss whether focal unit declines in abundance or goes extinct |
| Consequence of outcome: | |
| Uniqueness of affected focal units | |
| Geographic distribution of affected focal units | |
| Effect on existing conservation efforts | |
| Degree to which effects are reversible (e.g., whether the focal unit could be easily controlled or managed once established in the recipient region) | |

**Table 1** (continued)

| Ecological criteria | Social criteria |
|---|---|
| Feasibility[c] | |
| Degree to which the target can be captured, propagated, transported, transplanted, monitored, or controlled | Economic cost |
| Availability of appropriate sites for translocation | Legal or regulatory obstacles (permits, etc.) that would hinder or restrict the capacity to conduct MR |
| Sustainability of MR in achieving conservation objectives (e.g., whether MR for a given focal unit would need to be performed iteratively to match changes in environmental conditions) | Regulations or laws that facilitate MR |
| Acceptability[d] | |
| NA | Willingness to accept potentially irreversible consequences (cultural, aesthetic, or economic) |
| | Willingness to support action |
| | Trust and acceptance of ecological information |
| | Aesthetic, cultural, and moral attitudes toward focal and collateral units |
| | Concern that a focal unit's protection will restrict land in the recipient region from being managed or developed |
| | Willingness to support new laws and policies that encourage or enable MR |

This list is illustrative, not exhaustive, and will vary by case and stakeholder group. Additional criteria would be needed to consider MR if the goal was to replace a species complex or ecological function that had been lost from a system. In the case of focal and collateral impact, risk is measured by the likelihood of an outcome times the consequence of that outcome. Table from Richardson et al. (2009)

*NA* not applicable

[a]Impact on focal unit and its community from climate change and exacerbating effects of MR

[b]Effect of focal unit in recipient region

[c]Constraints on or opportunities for MR

[d]Societal willingness to pursue MR

built protections, such as levees. This is in part because US Federal Emergency Management Agency flood risk maps, which are used to set insurance premiums and guide development of shoreline protections, are based on historic observations, without yet integrating changes in flood risk from projected sea level rise and climate change. The shoreline around the Bay is highly fragmented by different jurisdictional agencies, and no regional agency has a mandate to protect the Bay from sea level rise. Ironically, SFBCDC, the one state agency with a regional scope operates under a mandate to ensure the Bay does not shrink beyond what was lost as of 1965, but they have no mandate to let it grow larger.

This vulnerability assessment for the San Francisco Bay Area was enabled in part through top-down impacts research, much of which was supported by the California government. Knowles (2009) presents high-resolution maps of the San Francisco Bay Area highlighting areas vulnerable to inundation from sea level rise under one future scenario, from which SFBCDC was able to begin assessment and identify bottom-up constraints to adaptation (e.g. lack of mandates, inaccurate depiction of risk, lack of stakeholder awareness). This assessment, however, is limited in key ways.

Knowles acknowledges that the analysis does not provide quantification of the future risk of inundation. Further, the analysis does not examine the likelihood of crossing stakeholder-defined thresholds of vulnerability across future scenarios and modeled responses of the climate system, nor does it incorporate changes in risk as a result of alternative adaptation strategies. Taking these additional steps can help to make transparent what levels of risk to the public good are inherent in alternative management and development decisions, and can help to provide clear rationale for prioritization of policy changes. Further, this process will no doubt expose major technical and social uncertainties, and tensions arising from separate attention to mitigation and adaptation. For example, urbanized estuaries like the San Francisco Bay have mitigation mandates to prevent sprawl and reduce transportation footprints, thus encouraging development near the already congested Bay, while at the same time adaptation options highlight the need to conserve and restore coastal habitat to protect existing communities from sea level rise and climate changes.

## 6 Going forward

The extra work of translating projected changes in climate variables into relevant, sector specific information is critical given the often extreme monetary and staffing constraints, institutional inflexibility, and limited knowledge and technological capacity of decision makers (Moser and Luers 2008; Rayner et al. 2005). Such managers face significant challenges in their jobs without factoring in climate change, as the literature has clearly indicated, but even when aware of climate change-induced threats of increased vulnerability, these managers often do not have the information they perceive they need to alter their strategies in response to these risks.

Here we have proposed that scientists work with such managers and stakeholders to define the kinds of exposure thresholds they would find difficult for their particular system to adapt to (and thus, potential “dangerous” thresholds of vulnerability), and then have climate scientists point out the relative likelihood of exceeding such thresholds given a range of emissions resulting from alternative land-use, and social, technological and economic futures.

If, as noted earlier, these thresholds clustered about a particular temperature increase level above present, that would also serve to inform the mitigation debate about avoiding “dangerous” climate changes. In this sense, we argue that adaptation assessment becomes a complement to mitigation planning, not simply a trade-off as it so often framed in the economics literature. Furthermore, stakeholders and managers informed about the likelihood of various exceedences of adaptive capacity could better identify key challenges and prioritize actions.

*Climatic Change* was originally set up 100 volumes ago to be a principal venue for the publication of just such interdisciplinary analyses, and has and will, of course, be very welcoming to any efforts that attempt to advance our knowledge of the internal–external or bottom-up/top-down analyses that are likely to prove crucial to the reduction of vulnerability of human and natural systems as climate change intensifies.

## References

Adger WN (1999) Social vulnerability to climate change and extremes in Coastal Vietnam. World Dev 27:249–269

Adger WN (2006) Vulnerability. Glob Environ Change 16:268–281

Adger WN, Agrawala S, Mirza MMQ, Conde C, O'Brien K, Pulhin J, Pulwarty R, Smit B, Takahashi K (2007) Assessment of adaptation practices, options, constraints and capacity. In: Parry ML, Canziani OF, Palutikof JP, van der Linden PJ, Hanson CE (eds) Climate change 2007: impacts, adaptation and vulnerability. Contribution of Working Group II to the fourth assessment report of the Intergovernmental Panel on Climate Change, Cambridge, UK, pp 717–743

Berkes F, Jolly D (2001) Adapting to climate change: social-ecological resilience in a Canadian Western Arctic Community. Conserv Ecol 5:18

Dessai S, Hulme M (2004) Does climate adaptation policy need probabilities? Clim Policy 4:107–128

Dessai S, Adger WN, Hulme M, Turnpenny J, Köhler J, Warren R (2004) Defining and experiencing dangerous climate change. Clim Change 64:11–25

Heller NE, Zavaleta ES (2009) Biodiversity management in the face of climate change: a review of 22 years of recommendations. Biol Conserv 142:14–32

IPCC (2007) Summary for policymakers. In: Parry ML, Canziani OF, Palutikof JP, van der Linden PJ, Hanson CE (eds) Climate change 2007: impacts, adaptation and vulnerability. Contribution of Working Group II to the fourth assessment report of the Intergovernmental Panel on Climate Change, Cambridge, UK, p 19

Knowles N (2009) Potential inundation due to rising sea levels in the San Francisco Bay Region. PIER Research Report CEC-500-2009-023-F

Lemos MC, Morehouse B (2005) The co-production of science and policy in integrated climate assessments. Glob Environ Change 15:57–68

Liu J et al (2007) Complexity of coupled human and natural systems. Science 317:1513–1516

Maurer EP, Hidalgo HG (2008) Utility of daily vs. monthly large-scale climate data: an intercomparison of two statistical downscaling methods. Hydrol Earth Syst Sci 12:551–563

McGranahan G, Balk D, Anderson B (2007) The rising tide: assessing the risks of climate change and human settlements in low elevation coastal zones. Environ Urban 19:17–37

McNie E (2007) Reconciling the supply of scientific information with user demands: an analysis of the problem and review of the literature. Environ Sci Policy 10:17–38

Moser SC (2006) Climate scenarios and projections: the known, the unknown, and the unknowable as applied to California. Synthesis Report of a workshop held at the Aspen Global Change Institute, 11–14 March 2004 in Aspen, Colorado, Elements of Change series, AGCI, Aspen, CO

Moser SC, Luers AL (2008) Managing climate risks in California: the need to engage resource managers for successful adaptation to change. Clim Change 87(Suppl 1):S309–S322

Parmesan C (2006) Ecological and evolutionary responses to recent climate change. Ann Rev Ecolog Evol Syst 37:637–669

Patt AG, Tadross M, Nussbaumerc P, Asante K, Metzger M, Rafael J, Goujon A, Brundrit G (2009) Estimating least-developed countries' vulnerability to climate-related extreme events over the next 50 years. PNAS 107:1333–1337

Rayner S, Lach D, Ingram H (2005) Weather forecasts are for wimps: why water resource managers do not use climate forecasts. Clim Change 69:197–227

Richardson DM, Hellmann JJ, McLachlan J, Sax DF, Schwartz MW, Brennan J, Gonzalez P, Root T, Sala O, Schneider SH, Ashe D, Camacho A, Clark JR, Early R, Etterson J, Fielder D, Gill J, Minteer BA, Polasky S, Safford H, Thompson A, Vellend M (2009) Multidimensional evaluation of managed relocation. Proc Natl Acad Sci 106:9721–9724

Root T (1988a) Energy constraints on avian distributions and abundances. Ecology 69:330–339

Root T (1988b) Environmental factors associated with avian distributional limits. J Biogeogr 15: 489–505

Root TL, Price JT, Hall KR, Schneider SH, Rosenzweig C, Pounds JA (2003) Fingerprints of global warming on animals and plants. Nature 421:57–60

San Francisco Bay Conservation and Development Commission (2009) Living with a rising bay: vulnerability and adaptation in San Francisco Bay and on its shoreline, draft staff report, April 7

Sarewitz D, Pielke RA Jr (2007) The neglected heart of science policy: reconciling supply of and demand for science. Environ Sci Policy 10:5–16

Schneider SH, Semenov S, Patwardhan A, Burton I, Magadza CHD, Oppenheimer M, Pittock AB, Rahman A, Smith JB, Suarez A, Yamin F (2007) Assessing key vulnerabilities and the risk from climate change. In: Parry ML, Canziani OF, Palutikof JP, van der Linden PJ, Hanson CE (eds) Climate change 2007: impacts, adaptation, and vulnerability—contribution of working group II to the Intergovernmental Panel on Climate Change fourth assessment report. Cambridge University Press, Cambridge, pp 779–810

Smit B, Wandel J (2006) Adaptation, adaptive capacity and vulnerability. Glob Environ Change 16:282–292

Thomalla F, Downing TE, Spanger-Siegfried E, Han G, Rockström J (2006) Reducing hazard vulnerability: Towards a common approach between disaster risk reduction and climate adaptation. Disasters 30:39–48

Tingley MW, Monahan WB, Beissinger SR, Moritz C (2009) Birds track their Grinnellian niche through a century of climate change. Proc Natl Acad Sci U S A 106:19637–19643

Tribbia J, Moser SC (2008) More than information: what coastal managers need to plan for climate change. Environ Sci Policy 11:315–328

Turnpenny JR, Haxeltine A, O'Riordan T (2004) A scoping study of user needs for integrated assessment of climate change in the UK context: part 1 of the development of an interactive integrated assessment process. Integrated Assessment 4:283–300

United Nations Framework Convention on Climate Change (UNFCCC) (2009) Copenhagen accord. http://unfccc.int/files/meetings/cop_15/application/pdf/cop15_cph_auv.pdf. Accessed 17 Mar 2010

van Kerkhoff L, Lebel L (2006) Linking knowledge and action for sustainable development. Annu Rev Environ Res 31:12.1–12.33

Vogel C, Moser SC, Kasperson RE, Dabelko G (2007) Linking vulnerability, adaptation and resilience science to practice: players, pathways and partnerships. Glob Environ Change 17: 349–364