Global Climate Change

THE INFLUENCE OF GLOBAL CLIMATE CHANGE ON THE SCIENTIFIC FOUNDATIONS AND APPLICATIONS OF ENVIRONMENTAL TOXICOLOGY AND CHEMISTRY: INTRODUCTION TO A SETAC INTERNATIONAL WORKSHOP

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Abstract — This is the first of seven papers resulting from a Society of Environmental Toxicology and Chemistry (SETAC) international workshop titled “The Influence of Global Climate Change on the Scientific Foundations and Applications of Environmental Toxicology and Chemistry.” The workshop involved 36 scientists from 11 countries and was designed to answer the following question: How will global climate change influence the environmental impacts of chemicals and other stressors and the way we assess and manage them in the environment? While more detail is found in the complete series of articles, some key consensus points are as follows: (1) human actions (including mitigation of and adaptation to impacts of global climate change [GCC]) may have as much influence on the fate and distribution of chemical contaminants as does GCC, and modeled predictions should be interpreted cautiously; (2) climate change can affect the toxicity of chemicals, but chemicals can also affect how organisms acclimate to climate change; (3) effects of GCC may be slow, variable, and difficult to detect, though some populations and communities of high vulnerability may exhibit responses sooner and more dramatically than others; (4) future approaches to human and ecological risk assessments will need to incorporate multiple stressors and cumulative risks considering the wide spectrum of potential impacts stemming from GCC; and (5) baseline/reference conditions for estimating resource injury and restoration/rehabilitation will continually shift due to GCC and represent significant challenges to practitioners. Environ. Toxicol. Chem. 2013;32:13–19. © 2012 SETAC

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INTRODUCTION

Global climate change (GCC) is a powerful advancing force [1,2] that can impact ecosystems and humans for decades to come [3–6]. It is likely that GCC will manifest as a suite of stressors, or a syndrome, impacting the abiotic, biotic, and socioeconomic [3] components of the landscape [7]. It is possible that changes in stressor regimes [8] and the potential for toxic effects will occur, as well as a need to revise assumptions about past conditions being models for current and future conditions [9,10]. In addition, changes in current methods and a reexamination of predictions and predictive tools for the fate and transport of chemical stressors [11] that are built on those assumptions [12,13] will be needed. These points are particularly important as the chemical fate and dynamics data are critical for the performance of human health risk assessment and ecological risk assessments [7,9,14] as well as the practice of damage assessment and restoration of natural resources in the United States [15,16] and Europe [3,17,18].

Recently, Wenning et al. [19] argued that environmental toxicologists and chemists, who have tended to be absent from much of the international debate on GCC and its effects, need to keep pace with these changing conditions [20] and join the debate. To address this point, a Society of Environmental Toxicology and Chemistry (SETAC) workshop was held to explore the potential influence of GCC on the foundation and applications of environmental toxicology and chemistry. Some 36 scientists, managers, policy makers, and students from 11 countries participated and answered two main questions: (1) What are the potential impacts of GCC on the scientific foundations of environmental toxicology and chemistry? (2) How might those impacts influence the application of the science to chemical risk and natural resource injury and recovery assessments?

This is the first of seven papers from this workshop and provides a short survey of the relevant literature, a description of the workshop’s organizational basis, and a summary of overarching consensus items. Detailed results from the workshop can be found in the individual papers [21–26].
To address the potential for changes in the practice of environmental toxicology and chemistry wrought on various scientific and regulatory levels by GCC, we organized the workshop around two major technical categories—foundations and applications. To focus our discussions further, the foundations category was divided into three major subcategories that provide data for regulatory assessments: chemical fate and modeling, toxicological mechanisms, and populations and communities. For this workshop, these three subcategories represented the technical inputs that are integrated into applications such as risk- and injury-assessment paradigms [27,28] and ultimately used to inform risk-management decisions. These same inputs are used not only in assessing injury to natural resources but also to help determine what actions may be needed to restore those harmed resources [29,30]. Similarly, managers of river basins in the European Union are required to consider both the sensitivity of aquatic ecosystems and the resilience of restoration measures to potential GCC impacts in their management plans for the future [31]. Restoration and rehabilitation efforts in Australia are based on similar technical inputs and frequently include an assessment of potential impacts from GCC [32,33]. Other subcategories of inputs to these types of assessments are possible, but the three foundations subcategories were considered most important to considering the potential influence of GCC on environmental toxicology and chemistry.

The application category included the conduct of human health and ecological risk assessments and the assessment of injuries to natural resources. Exploration of the influence of a changing environment on human health risk assessment, ecological risk assessment, and assessment of harm to natural resources required placing GCC in context, based on what is known to date from the current literature. For the purposes of this workshop, we viewed direct effects of GCC mostly as abiotic, including increased temperature [34] and modification of hydrological cycles, which then may have repercussions for local weather and runoff events [35]. In addition, there may be changes in soil characteristics [36], the intensity of fire and its frequency of occurrence, changes in the temperature and chemistry profiles of oceanic areas, in addition to rising sea levels [37]. As Solomon et al. [6] have detailed, additional direct impacts from GCC can be found on glacial and polar ice, snow pack, and duration that illustrate a general lack of stationarity in the variability of these physical and chemical endpoints.

Indirect effects of GCC arise from modifications of ecological structures or processes by direct effects of GCC and can be demonstrated as combinations of direct and indirect effects such as desynchronization of forage/forager or predator/prey phenomenologies [38], elimination or displacement of historical ranges and assemblages of species [16], influx of invasive species or diseases that benefit from changing climate conditions [39], and formation of novel communities and ecosystems with new interspecies interactions [5]. Moreover, indirect GCC impacts can arise from changes in human activities in response to GCC. Humans, for example, can change energy development and agricultural practices through mitigation and adaptation effort [40] or move themselves in some cases to geographies less impacted by GCC. These latter points illustrate the need to understand the potential influence of GCC not only on the foundations of environmental toxicology and chemistry but also on the applications of these foundations in the assessment of chemicals in the environment.

A summary of key findings from the individual papers resulting from the workshop is provided in Table 1 and discussed, along with a brief synopsis of the relevant literature, in the following sections.

**Occurrence, fate, and availability of chemicals**

The effects of GCC on the occurrence, fate, and distribution of chemicals are anticipated to result in changes in exposures [21]. These include the potential for increased global transport of dust and pollution [41,42], increased erosion of soil and mobilization of legacy contaminants, alterations in the deposition and volatilization of chemicals, and altered flood and drought frequency and magnitude [5]. Indirect effects have the potential to significantly modify the magnitude and temporal exposure to chemical contaminants. For instance, the potential for increased incidence of toxic algal blooms occurring more frequently and more severely in (1) warming, higher-latitude waters [43]; (2) the influence of wind pattern-driven, upwelling processes leading to red tide or jellyfish-dominated offshore systems [44]; (3) changes in pesticide-use patterns in response to changing agricultural practices and distributions of pests [40]; and (4) modifications of food webs [45] leading to altered profiles of contaminant exposures. Moreover, GCC has allowed the opening of previously inaccessible resource-rich environments, which will inevitably lead to changing socioeconomic patterns of land use. Changes in the way that humans interact with environments will continue to lead to alterations in emissions of chemicals. For instance, as the ice-free season of the Arctic Ocean and the interior of Greenland increases [46], increased movement of ships through sensitive areas will increase the risk of spills or accidents. Iron and mercury sequestered in vegetation or detritus can be released by forest fires [47], while acidification of marine waters can release previously insoluble metals. The bioavailability of organic contaminants can be changed through alterations in pH or other biogeochemical processes, either increasing or decreasing depending on the chemical [48]. Alterations in primary productivity in warming Arctic regions provide a matrix for the uptake of mercury and organochlorine chemicals and their concentration into food webs [49,50]. Changing trophic relationships within ecosystems may result in shifts in the dynamics of food webs and therefore influence the flow and accumulation of toxicants [45]. Due to a variety of direct and indirect effects of GCC, it is anticipated that GCC will alter the distribution and bioavailability of chemical contaminants [51]. Much of the data developed on GCC-related impacts to the fate and dynamics of chemicals can be used in current fate and transport models or with models that have been modified to account for GCC. However, a major gap exists with respect to the lack of atmospheric, soil, surface water, and other types of chemical monitoring data from developing countries; as a result, models for those regions of the globe remain underdeveloped [21].

**Toxicology mechanisms**

Effects of chemicals on an organism are a function of the mechanism of action and disposition of chemicals [52]. The mechanism of action is the interaction of a chemical with its molecular target and the subsequent tissue, organ, and systemic perturbations that occur leading to a toxic response in an exposed organism [53]. This interaction can be influenced by temperature (particularly in poikilotherms) and local tissue conditions such as level of hydration, lipid environment, and the general homeostatic condition of the organism [54,55]. Chemical disposition is a function of four factors:
Table 1. Key consensus points related to the influence of global climate change (GCC) on the foundations and application of environmental toxicology and chemistry; additional details on each topic area can be found in the cited references

| Topic area | Summary of consensus points | Reference |
|------------|-----------------------------|-----------|
| Occurrence of chemicals | • Quantifying the influence of GCC on bioavailability of chemical contaminants represents an area of ongoing research.  
• It is critically important that high-quality monitoring networks in all regions of the world are established and maintained to improve our assessment of “baseline” conditions. The utility of the monitoring networks should be aimed at improving our overall understanding of processes that influence variability of data.  
• Output of environmental modeling implies that changes in human activity resulting in decreased or increased emissions to the environment of chemicals will have a more significant influence on exposure, as opposed to the effects of climate on the transport and fate of chemicals.  
• Uncertainty in input parameters for physical/chemical properties for use in models tends to be greater than uncertainty due to changes in the environment brought about by GCC.  
• Caution is needed when interpreting and/or speculating on the importance of GCC with respect to how changes due to GCC will influence the fate and bioavailability of chemicals. | [21] |
| Mechanisms of toxicity | • Mechanistic data, including new approaches in biological and computational sciences, can facilitate understanding how the effects of toxicants will interact with direct and indirect effects of GCC.  
• Adverse outcome pathways (AOPs) allow for identification of knowledge gaps and translation of complex mechanistic data on the interaction of toxicants and GCC into an outcome relevant to risk and damage assessments.  
• GCC can affect the mechanisms for both GCC and toxicant adaptation/acclimation. For example, toxicants can influence the sensitivity of organisms to climate, and climate can influence the sensitivity of organisms to toxicants.  
• The AOP approach can be applied to understanding the interactions of GCC with chemical toxicants. This can be done prospectively to predict potential effects in natural and susceptible populations/regions or retrospectively to discern mechanisms of damage to a particular ecosystem, population, or individual. It may also be used to predict effects in other systems subject to similar conditions resulting from or influenced by GCC. | [22] |
| Populations and communities | • Combined effects of contaminants and GCC are mediated by ecological and evolutionary processes at different spatial and temporal scales.  
• Indirect impacts of GCC may be more important than direct impacts.  
• Impacts from GCC may be slow and therefore difficult to distinguish from natural variation.  
• Ecological responses to environmental stressors are often nonlinear, and GCC may increase the risk of ecological systems exceeding thresholds/tipping points and reaching alternative stable states.  
• GCC may favor opportunistic species with high potential for reproduction and dispersal and may therefore benefit pest species.  
• Species and communities identified as vulnerable to GCC (e.g., amphibians, coral reefs, polar species) are likely to be particularly vulnerable to interactions between GCC and other stressors. | [23] |
| Human health risk assessment | • Small changes in exposure variability and/or vulnerability to chemicals or other toxicants can lead to large changes in risk and large uncertainties.  
• GCC is likely to lead to increases in variability and bidirectional changes in exposure of humans to chemicals and other toxicants. This may result from changes in human use patterns of pesticides as well as from changes in the fate and transport of those substances stemming from GCC.  
• Monitoring and sampling of exposures of humans to chemicals and other toxicants should be done with frequency sufficient to capture altered variability that may result from GCC.  
• Increased vigilance and action will be needed to lessen potential gaps in policies or regulatory actions to protect people from unacceptable exposure to chemicals and other toxicants in both developed and developing countries. | [24] |
| Ecological risk assessment | • Future ecological risk assessments will need to use a multistressor approach to reflect potential influences of GCC, including chemical and nonchemical stressors relevant to GCC.  
• Ecosystem services can and should be applied in the ecological risk-assessment process as assessment end points.  
• In the future, ecological risk assessments will need to consider management scenarios in the problem-formulation step, particularly as GCC impacts become manifest.  
• Systems will likely change to unprecedented extents and at unpredictable rates, meaning that monitoring, adaptive management, and ongoing ecosystem studies are essential to manage for high uncertainty.  
• Consideration for Type III error (asking the wrong question to begin with) will be important to include in ecological risk assessments.  
• Shifting and increased variability of baseline and/or reference condition will present increased challenges for damage assessment, restoration, and/or rehabilitation planning and implementation.  
• Incorporating insights from cumulative risk assessments will enhance the likelihood of successful restoration and/or rehabilitation efforts.  
• Assessments of vulnerability of important organisms and habitats to contaminants should be proactively undertaken to determine potential for damages to multiple resources and loss of ecosystem services in sensitive environments.  
• Species and habitats will become more valuable in light of GCC-induced shifts in biomes and predicted levels of the rates of extinction for certain species.  
• Assessment and restoration and/or rehabilitation will need to incorporate the potential for wide variation in physical forcing factors such as temperature, contaminants, storms, and water quality/quantity in a changing landscape.  
• The restoration and/or rehabilitation of ecosystem services in a changing landscape will require new and innovative approaches, adaptive management, and longer-term monitoring. | [25] |
| Damage to natural resources, their restoration/ rehabilitation | | [26] |
absorption, distribution, metabolism, and excretion in exposed organisms [56]. The interaction of these four processes determines potential dose in the target tissue [57]. Factors that modify the disposition of a chemical can increase uptake and retention or produce more reactive or toxic forms of the chemical. Dispositional factors are sensitive to temperature, water, and nutrient stresses that are anticipated with increased episodic occurrence of GCC-induced weather phenomena [58].

Both disposition and mechanism of action are influenced by a variety of factors such as water, food, temperature, competition, and predation. Physiological ecology, those biochemical and physiological processes that allow organisms to function within their ecological niche [59], may also be subject to the influence of GCC (e.g., changes in temperature) and from other environmental conditions that may be altered by GCC. These processes are key as their role in integrating internal homeostasis with the external environment represents a potentially important target for contaminants that is particularly sensitive to perturbations resulting from GCC [60].

Given the above discussion, biological responses to GCC and contaminants can be grouped into two major categories climate-induced toxicant sensitivity (CITS), where changes in climate may alter the ability of an organism to tolerate toxic insults, and toxicant-induced climate sensitivity (TICS), where exposure to toxic chemicals may alter the ability of an organism to tolerate the stressors associated with GCC [22]. Integrating the concept of CITS and TICS with the recently developed framework for adverse outcome pathways could be an important step that would help to improve the understanding of GCC’s potential influence on chemical contaminant toxicity as well as to demonstrate how contaminants might decrease the ability of an organism to withstand the effects of GCC [22]. The adverse outcome pathway approach allows for both prospective assessments of potential interactions between GCC and chemicals and retrospective evaluations of observed findings believed to have a GCC etiology.

**Populations and communities.** A challenge for ecotoxicologists is to predict how joint effects of climatic stress and toxicants measured at the individual level (e.g., reduced survival or reproduction) will be transferred to the population (e.g., abundance, population growth rate, and extinction risk) and community (e.g., species richness, biodiversity, and food-web structure) levels [61]. Increased temperature and other environmental impacts of GCC are also impacting processes in ecosystems and interactions between species (e.g., disrupting the timing of predator–prey interactions). Given the complexity and variability of impacts on the environment resulting from GCC, general predictions for interactions of GCC and toxicants at higher levels of biological scales may not be feasible at this time [23]. Instead, it may be useful to consider different ecological mechanisms that are likely to influence responses to toxicants at the population and community levels under GCC. Stress due to altered climatic conditions may reduce the potential for tolerance to and recovery from exposure to toxicants. Long-term exposure to a toxicant may result in species being able to acquire tolerance to this stressor at the population or community level, but an associated “cost of tolerance” may be a reduced ability to tolerate subsequent climatic stress (or vice versa). Moreover, climate change induces large-scale shifts in the ranges of many species and thereby in community composition, which may affect the vulnerability of communities to other stressors. Ecological modeling based on species traits (representing life history, population vulnerability, sensitivity to toxicants, and sensitivity to climate change) can be a promising approach for predicting impacts of climate change and toxicants on populations and communities.

**Human health risk assessment.** In human health risk assessments, effects endpoints are typically more sensitive than mortality, reproductive disruption, and decreased growth, endpoints commonly assessed in nonhuman organisms. Human health effects are measured as increases in a wide variety of disease states and evaluated for the general population as well as highly susceptible subpopulations such as children, pregnant women, the elderly, and workers in high-exposure scenarios [62]. Some exposure models incorporate details that mimic the lifestyles of the most sensitive individuals. Modeling of dose responses under conditions of GCC will, therefore, depend heavily on understanding how GCC modifies the exposure of humans to chemicals and other toxicants as well as the fate and transport of those chemicals or other toxicants in the human body. Unlike most organisms, humans have the ability to mitigate some, but not all, of their exposures to the stressors associated with GCC [24]. As such, they represent a receptor that will challenge current approaches to characterizing exposure and effects in the conduct of human health risk assessment.

For both humans and nonhuman organisms, one possible scenario could arise where GCC-induced heat co-occurs with another stressor [34,63] such as ozone, which can exacerbate the potential toxic effects of chemical contaminants. Poleward movement of disease vectors with a warming climate promises to increase the occurrence of vector-borne diseases into areas that previously had been free of them [64]. Although weather and disease stressors are not new to public-health researchers, the frequency and range of occurrence will likely be increasing, demanding a better understanding of their effects on humans and sensitive subpopulations. These co-occurring stressors can affect the sensitivity of humans to chemicals and could be incorporated into the risk-characterization step of a human health risk assessment, evaluated in the uncertainty analysis or accounted for by using additional safety factors or other modifiers when establishing reference doses. With time and greater experience and understanding of the consequences of GCC to human health, epidemiologic studies could be designed to provide additional information on modeling parameters that could then account for major GCC effects in human health risk assessment [40].

**Ecological risk assessment.** In contrast to the singular human focus in human health risk assessments, an ecological risk assessment has a broader scope in its evaluation of risk, often integrating exposure and effect assessments over many species and biological scales, delineating criteria protective of varying proportions of species in the wild [27]. The ecological risk-assessment analysis phase incorporates both exposure and effects assessments, making it amenable to using data that incorporate the effects of GCC in their development. Approaches to the assessment of risks from the effects of GCC, in the absence of chemicals, continue to develop and can provide inputs for contaminant-oriented assessments in the future [9,14,65]. The ability to model the influence of GCC across exposure data is likely within grasp as much of the effort will focus on modifications of the bioavailability of contaminants. Alternatively, such modeling for adjusting effects endpoints will require a greater body of knowledge on how the variety of anticipated GCC stressors interact with contaminants in living organisms.

Assessments of ecological risks that are focused on GCC-induced stressors and endangered species, or those already documented to be adversely influenced by such stressors, are
under development by a number of governmental agencies [4,33,66] and offer a logical mechanism by which assessments of contaminants might be incorporated. Depending on the focus of the ecological risk assessment, substantial effort may be required during the problem-formulation stage to ensure that all possible GCC stressor information, relevant to species or habitats of concern, is available for the assessment [25]. It will also be important that future ecological risk assessments consider the risk-management scenario during the problem-formulation step to insure that the potential for GCC is included in the assessment.

Assessment of injury to natural resources and restoration ecology. Assessment of damage to and restoration of natural resources presents some of the more challenging situations, yet exciting opportunities, associated with the influence of GCC [26]. Assessments of damage to natural resources share some characteristics with ecological risk assessments, particularly in the use of data on exposure and effects that can be influenced directly and/or indirectly by GCC [29,67]. Extensive data are used to characterize the spatial and temporal nature of damage to natural resources, incorporating past damage or harm since the initiation of contamination as well as projecting future losses of the resources until ecological restoration are complete. Differentiating the impacts of GCC on natural resources from those arising from exposure to chemical contamination is complicated but could be accomplished using historical data on anthropogenic stressors, where available, or in their absence estimating their types and magnitude that existed prior to the advent of GCC. Work will also be needed to understand the synergistic or antagonistic interactions between exposure to chemical contaminants and the effects of GCC (see previous discussion on CITS and TICS) and if the severity of chemical-induced damage may be influenced by differing GCC scenarios [68].

Ecological restoration and rehabilitation of previously contaminated sites will face challenges and opportunities in a future influenced by GCC. Shifting in the ranges of species and their assemblages (including migratory pathways and timing) resulting from changes in temperature and precipitation and the changes in habitat they engender, along with the ubiquity of some invasive species, will create increasingly difficult targets for restoration action [69]. In some cases, it may become more difficult to find habitats suitable for restoration action, and some species may be forced into less desirable habitats as a result. Restoring ecosystem structure, function, and services may preclude the ability to completely restore assemblages of species that existed prior to the damage [70,71]. In developing diverse restored ecosystems with functional redundancy, it will be important to strive for the resilience necessary to buffer the dramatic climate changes predicted for the future [72]. However, mitigating GCC and fostering adaptation to it can be achieved through the encouragement of restoration actions that optimize carbon sequestration (e.g., forest development on retired agricultural land) or provide corridors or expanded habitat for species with ranges stressed by GCC-altered temperature or hydrological patterns. Additional challenges will occur if GCC unfolds at different speeds and intensities around the globe, shifting baseline conditions and challenging assessments of damage to natural resources as well as how to restore those lost resources.

CONCLUSION, UNCERTAINTIES, AND AREAS FOR RESEARCH

Human health and ecological risk assessments will become increasingly important in the anticipated development and evaluation of future actions that may be taken to support mitigation and adaptation to GCC. Such activities will require careful consideration of their repercussions (both positive and negative) and development of thorough assessments prior to and during implementation. For example, a risk assessment of GCC adaptation efforts in Bangladesh encouraging dike construction for flood control would need to consider how similar activities in that country have led to extensive leaching and contamination of groundwater with arsenic. Unfortunately, widespread arsenic poisoning in the country has resulted [73]. Similarly, strategies to mitigate GCC that involve nano-iron seeding of ocean waters to stimulate algae growth and carbon sequestration may lead to extensive formation and release of neurotoxic domoic acid from diatom blooms [74]. Such large-scale efforts to mitigate GCC are technically attractive but will undoubtedly test our ability to apply risk assessments and restoration strategies at landscape and global scales. Should GCC-induced tipping points be exceeded, it could lead to widespread or catastrophic environmental effects. At that point, risk assessors may be confronted with proposed mitigating or adaptive actions under emergency conditions with scant data to perform technically robust assessments.

Uncertainties remain in a number of factors that will need to be addressed in future decisions on research and policy. These include the rate at which GCC progresses as well as its spatial and temporal extent and variability, all of which will impact assessment of the fate and effects of chemicals as well as efforts on restoration and rehabilitation. The limited amount of GCC-relevant environmental data (e.g., monitoring of chemicals in the atmosphere, soils, and surface water) from developing areas of the world, where the impacts of GCC may be the most severe, increases uncertainty and represents a significant data gap that needs to be filled. The worldwide economic downturn at the time of this writing threatens funding at all levels [75] and, if not resolved, will lead to an ever-increasing number of data gaps, failures to improve monitoring and assessment techniques, and delays of restoration, rehabilitation, mitigation, adaptation, conservation, and protection projects that might otherwise alleviate or forestall the impacts of GCC. Funding for research and data collection that will lead to more targeted, cost-effective mitigation are issues that will challenge policy makers and governments around the globe.

Given the observed and predicted speed with which GCC is progressing [8], it is likely that many of the ideas developed now will be tested in the near future, leading to efforts to evaluate progress and update approaches and procedures in years to come. Future discussions and decisions dealing with important technical issues in environmental toxicology and chemistry would benefit from greater involvement of climate change scientists so that the potential for GCC to impact those technical issues is considered sooner rather than later. The reverse is true as well—it will become increasingly important for climate change scientists to involve environmental toxicologists, chemists, ecologists, and ecotoxicologists in their future assessments of impacts of GCC on humans and the earth’s ecosystems.

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REFERENCES

1. Oreskes N. 2004. The scientific consensus on climate change. Science 306:1686.

2. Carpenter SR, Cole JJ, Pace ML, Batt R, Brock WA, Cline T, Coloso J, Hodgson JR, Kitchell JF, Seckell DA, Smith L, Weidel B. 2011. Early warning signs of regime shifts: A whole-ecosystem experiment. Science 332:1079–1082.

3. Mabey N, Gulledge J, Finel B, Silverthorne K. 2011. Degrees of Risk: Defining a Risk Management Framework for Climate Security. Third Generation Environmentalists, London.

4. Richardson K, Steffen W, Schellnhuber HJ, Alcamo J, Barker T, Kammen DM, Leemans R, Liverman D, Munasinghe M, Osman-Elasha B, Stern N, Waever O. 2009. Synthesis report. Climate change: Global risks, challenges, and decisions. Proceedings, United Nations Framework Convention on Climate Change, Copenhagen, Denmark, March 10–12.

5. Parry ML, Canziani OF, Palutikof JP, van der Linden PJ, Hanson CE. 2007. 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 University Press, Cambridge, UK.

6. Solomon S, Qin D, Manning M, Chen Z, Marquis M, Averyt KB, Tignor M, Miller HL. 2007. Climate Change 2007: The Physical Science Basis Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press, Cambridge, UK.

7. Schneider SH, Semenov S, Patwardhan A, Burton I, Magadza CH, Oppenheimer M, Pittock AB, Rahman A, Smith JB, Suarez A, Yamin F. 2007. Assessing key vulnerabilities and the risk from climate change. In Climate Change 2007: Adaptation and Vulnerability Contribution of Working Group II to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press, Cambridge, UK, pp 779–810.

8. Parks N. 2009. UN update: Climate change hitting sooner and stronger. Environ Sci Technol 43:8475.

9. Jones RN. 2001. An environmental risk assessment/methodology framework for climate change impact assessments. Natural Hazards 23:197–230.

10. Milly PC, Betancourt J, Falkenmark M, Hirsch RM, Kundzewicz ZW, Lettenmaier DP, Stouffer RJ. 2008. Stationarity is dead: Whither water management? Science 319:573–574.

11. United Nations Environmental Program. 2001. Climate change and POPs: Predicting the impacts. Report of the UNEP/APAM Expert Group. Stockholm, Sweden.

12. Wiegand J, Raffaelli D, Smart JC, White PC. 2010. Assessment of temporal trends in ecosystem health using a holistic indicator. J Environ Manag 91:1446–1455.

13. Borga KS, Tuomo M, Ruus A. 2010. Simulating climate change-induced alterations in bioaccumulation of organic contaminants in an arctic marine food web. Environ Toxicol Chem 29:1349–1357.

14. Carter TR, Jones RN, Lu X, Bhadwal S, Conde C, Manns LO, O’Neill BC, Rousevell MD, Zurek MB. 2007. New assessment methods and the characterization of future conditions. In 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 University Press, Cambridge, UK, pp 133–171.

15. Shoo LP, Olson DH, McMenamin SK, Murray KS, Van Sluys M, Donnelly MA, Stratford D, Terhiuvo J, Merino-Viteri A, Herbert SM, Bishop PJ, Corn PS, Dovey L, Griffiths RA, Lowe K, Mahony M, McSharry J, McCrimmon S, Simpkins C, Skerratt LF, Williams SE, Hero J. 2011. Engineering a future for amphibians under climate change. J Appl Ecol 48:487–492.

16. Hof C, Levinsky I, Araujo MB, Rahbek C. 2011. Rethinking species’ ability to cope with rapid climate change. Glob Change Biol 17:2987–2990.

17. European Union. 2004. On environmental liability with regard to the prevention and remedying of environmental damage. Directive 2004/35/CE of the European Parliament and of the Council. European Union, Brussels, Belgium, pp 56–75.

18. European Commission. 2010. Report from the Commission to the Council. European Parliament, European Economic and Social Committee and Committee of the Regions. Vol COM (2010) 581 final. European Commission, Brussels, Belgium.

19. Wenning RJ, Finger SE, Guilhemmno L, Helm RC, Hooper MJ, Landis WG, Menzie CA, Munns WR, Rombke J, Stahl RG. 2010. Global climate change and environmental contaminants: A SETAC call for research. Integr Environ Assess Manag 6:197–198.

20. National Research Council. 2009. Informing decisions in a changing climate. Panel on strategies and methods for climate-related decision support, Committee on the Human Dimensions of Global Change. National Academies Press, Washington, DC.

21. Gouin T, Armitage J, Cousins I, Mair DC, Ng CA, Tao S. 2012. Influence of global climate change on chemical fate and bioavailability: The role of multimedia models. Environ Toxicol Chem 32:20–31 (this issue).

22. Hooper MJ, Ankley G, Cristo D, Maryoung L, Noyes P, Pinkerton K. 2012. Interactions between chemical and climate stressors: A role for mechanistic toxicology in assessing climate change risks. Environ Toxicol Chem 32:32–48 (this issue).

23. Moe J, de Schumpelreae K, Clemens WH, Sorensen M, van den Brink P, Liss M. 2012. Combining and interactive effects of global climate change and toxicants on populations and communities. Environ Toxicol Chem 32:49–61 (this issue).

24. Babbus J, Boxall A, Fenske RA, McKone T, Zeise L. 2012. Implications of global climate change for the assessment and management of human health risks of chemicals in the natural environment. Environ Toxicol Chem 32:62–78 (this issue).

25. Landis WG, Durda J, Brooks ML, Chapman PM, Menzie CA, Stahl RG Jr, Stauber JL. 2012. Ecological risk assessment in the context of global climate change. Environ Toxicol Chem 32:79–92 (this issue).

26. Rohr JR, Johnson P, Hickey CW, Helm RC, Fritz AR, Brasfield S. 2012. Implications of global climate change for natural resource damage assessment, restoration, and rehabilitation. Environ Toxicol Chem 32:93–101 (this issue).

27. Barnhouse L.W. 2008. The strengths of the ecological risk assessment process: Linking science to decision making. Integr Environ Assess Manag 4:299–305.

28. Suter GW. 1997. Integration of human health and ecological risk assessment. Environ Health Perspect 105:1282–1283.

29. Gaia W, Lipton J, Cernera P, Ginn T, Haddad R, Renning M, Jahn K, Landis WG, Mancini E, Nicoll J, Peters V, Peterson J. 2009. Ecological risk assessment and natural resource damage assessment: Synthesis of assessment procedures. Integr Environ Assess Manag 5:515–522.

30. String D, Borja A, Carstensen J, Carvalho L, Elliott M, Feld CK, Hejzlar AS, Johnson RK, Mo J, Pont D, Solheim AL, de Bund W. 2010. The European Water Framework Directive at the age of 10. Sci Total Environ 408:4007–4019.

31. Moe J, Barkved L, Blind M, Makropoulos C, Vurro M, Ekstrand S, Rocha J, Mimikou M, Ulstein M. 2010. How can climate change be incorporated in river basin management plans under the WFD? EurAqua Conference, 2008, NIVA, Oslo, Norway.

32. Natural Resource Management Ministerial Council. 2010. Biodiversity. A summary of Australia’s biodiversity conservation strategy 2010-2030, Australian Government, Department of Sustainability, Environment, Water, Population and Communities, Canberra.

33. Threatened Species Scientific Committee. 2010. River Murray—Darling to sea ecological community. Expert Technical Workshop report. July 1-3, 2009, Adelaide, Australia. Department of the Environment, Water, Heritage and the Arts, Canberra, Australia.

34. Parry ML, Canziani OF, Palutikof JP, van der Linden PJ, Hanson CE. 2007. Cross-chapter case study. In 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 University Press, Cambridge, UK, pp 843–868.

35. Frey AE, Olivera F, Irish JL, Dunkin LM, Kaihatu JM, Ferreira CM, Edge BL. 2010. Potential impact of climate change on hurricane flooding inundation, population affected and property damages in Corpus Christi. J Am Water Res Assoc, DOI 10.1111/j.1752-1688.2010.00475.

36. Mitchell MJ, Likens GE. 2011. Watershed sulfur biogeochemistry: Shift from atmospheric deposition dominance to climatic regulation. Environ Sci Technol 45:5267–5271.
Introduction to global climate change and ecotoxicology

37. Hallegraeff GM. 2010. Ocean climate change, phytoplankton community responses, and harmful algal blooms: A formidable predictive challenge. *J Phycol* 46:220–235.

38. Stenseth NC, Myrstad A, Ottersen G, Hurrell JW, Chan K-S, Lima M. 2002. Ecological effects of climate fluctuations. *Science* 297:1292–1296.

39. Rohr JR, Dobson AP, Johnson PT, Kilpatrick AM, Paull SH, Raffel TR, Ruiz-Moreno D, Thomas MB. 2011. Frontiers in climate change–disease research. *Trends Ecol Evol* 26:270–277.

40. Boxall AB, Hardy A, Beulke S, Boucard T, Burgin L, Falloon PD, Haygarth PM, Hutchinson T, Kovats RS, Leonard G, Levy LS, Nichols G, Parsons SA, Potter L, Stone D, Topp E, Turley DB, Walsh K, Wellington EM. RJ. 2009. Impacts of climate change on indirect human exposure to pathogens and chemicals from agriculture. *Environ Health Perspect* 117:508–514.

41. Garrison VH, Shinn EA, Foreman WT, Griffin DW, Holmes CW, Tietge JE, Villeneuve DL. 2010. Adverse outcome pathways: A conceptual framework to support ecotoxicology research and risk assessment. *Environ Toxicol Chem* 29:730–741.

42. Witt EL, Kolka RK, Nater EA, Wickman TR. 2009. Forest fire effects on greenhouse gas, upwelling favorable winds, and the future of coastal ocean upwelling ecosystems. *Glob Change Biol* 16:1213–1228.

43. McKinney MA, Peacock E, Letcher RJ. 2009. Sea ice–associated diet change increases the levels of chlorinated and brominated contaminants in polar bears. *Environ Sci Technol* 43:4334–4339.

44. Torrice M. 2009. Science lags on saving the arctic from oil spills. *Science* 325:1335.

45. Witt EL, Kolka RK, Nater EA, Wickman TR. 2009. Forest fire effects on mercury deposition in the boreal forest. *Environ Sci Technol* 43:1776–1782.

46. Ng CA, Gray KA. 2010. Forecasting the effects of global climate change scenarios on bioaccumulation patterns in Great Lakes species. *Glob Change Biol* DOI 10.1111/j.1365-2486.2010.02299.

47. Dachs J, Eisenreich SJ, Hoff RM. 2000. Influence of eutrophication on air–water exchange, vertical fluxes, and phytoplankton concentrations of persistent organic pollutants. *Environ Sci Technol* 34:1095–1102.

48. Carrie J, Wang F, Sanei H, Macdonald RW, Bogens P, Chan K-S, Lima M. 2002. Ecological effects of climate fluctuations. *Science* 297:1292–1296.

49. Rohr JR, Dobson AP, Johnson PT, Kilpatrick AM, Paull SH, Raffel TR, Ruiz-Moreno D, Thomas MB. 2011. Frontiers in climate change–disease research. *Trends Ecol Evol* 26:270–277.

50. Boxall AB, Hardy A, Beulke S, Boucard T, Burgin L, Falloon PD, Haygarth PM, Hutchinson T, Kovats RS, Leonard G, Levy LS, Nichols G, Parsons SA, Potter L, Stone D, Topp E, Turley DB, Walsh K, Wellington EM. RJ. 2009. Impacts of climate change on indirect human exposure to pathogens and chemicals from agriculture. *Environ Health Perspect* 117:508–514.

51. Garrison VH, Shinn EA, Foreman WT, Griffin DW, Holmes CW, Tietge JE, Villeneuve DL. 2010. Adverse outcome pathways: A conceptual framework to support ecotoxicology research and risk assessment. *Environ Toxicol Chem* 29:730–741.

52. Gregus Z. 2008. Mechanisms of toxicity. In Klassen CD, ed, *Cassarette and Doll’s Toxicology: The Basic Science of Poisons*. McGraw-Hill, New York, pp 45–106.

53. Ankley GT, Bennett RS, Erickson RJ, Hoff DJ, Hornung MW, Johnson RD, Mount DR, Nichols JW, Rasmussen CL, Schmidt PK, Serrano JA, Tietge JE, Villeneuve DL. 2010. Adverse outcome pathways: A conceptual framework to support ecotoxicology research and risk assessment. *Environ Toxicol Chem* 29:730–741.

54. Beyers DW, Rice JA, Clements WH. 1999. Estimating physiological cost of chemical exposure: Integrating energetics and stress to quantify toxic effects in fish. *Can J Fish Aquat Sci* 56:814–822.

55. Beyers DW, Rice JA, Clements WH. 1999. Evaluating biological significance of chemical exposure to fish using a bioenergetics-based stressor-response model. *Can J Fish Aquat Sci* 56:823–829.

56. Carere M, Miniero R, Cicero MR. 2011. Potential effects of climate change on the chemical quality of aquatic biota. *Trends Anal Chem* 30:1214–1221.

57. Lehman-McKeeman LD. 2008. Absorption, distribution, and excretion of toxicants. In Klassen CD, ed, *Cassarette and Doll’s Toxicology: The Basic Science of Poisons*. McGraw-Hill, New York, pp 131–159.

58. Yamada NS. 2010. Effects of seawater acidification on hydrolytic enzyme activities. *J Oceanogr* 66:233–241.

59. Karasov WH, Martinez-del Rio C. 2007. *Physiological Ecology—How Animals Process Energy, Nutrients and Toxins*. Princeton University Press, Princeton, NJ.

60. Noyes PD, McElwee MK, Miller HD, Clark BW, Van Tienh LA, Walcott KC, Erwin KN, Levin ED. 2009. The toxicology of climate change: Environmental contaminants in a warming world. *Environ Int* 35:971–986.

61. Hart EM, Gotelli NJ. 2011. The effects of climate change on density-dependent population dynamics of aquatic invertebrates. *Oikos* 120:1227–1234.

62. Faustman EM, Omenn GS. 2008. Risk assessment. In Klassen CD, ed, *Cassarette and Doll’s Toxicology: The Basic Science of Poisons Seventh Edition*. McGraw-Hill, New York, pp 45–106.

63. Voorhees AS, Fann N, Fulcher C, Dolwick P, Hubbell B, Bierwagen B, Morefield P. 2011. Climate change–related temperature impacts on warm season heat mortality: A proof-of-concept methodology using BenMap. *Environ Sci Technol* 45:1450–1457.

64. National Institute of Medicine. 2008. *Global Climate Change and Extreme Weather Events: Understanding the Contributions To Infectious Disease Emergence*. National Academies Press, Washington, DC.

65. Galbraith H, Dixon MD, Stromberg JC, Price JT. 2010. Predicting climate change risks to riparian ecosystems in arid watersheds: The upper San Pedro as a case study. In Kapustka LA, Landis WG, eds *Environmental Risk Assessment and Management from a Landscape Perspective*. John Wiley & Sons, Hoboken, NJ.

66. U.S. Fish and Wildlife Service. 2010. Rising to the challenge—Strategic plan for responding to accelerating climate change. U.S. Department of the Interior, Washington, DC.

67. Munns WR, Helm RC, Adams WJ, Clements WH, Curley M, DiPinto LM, Johns DM, Seiler R, Williams L, Young D. 2009. Translating ecological risk to ecosystem service loss. *Integr Environ Assess Manage* 5:500–514.

68. Hojer R, Bayley M, Damaagd CF, Homstrup M. 2001. Stress synergy between drought and a common environmental contaminant: Studies with the collembolan *Folsomia candida*. *Glob Change Biol* 4:705–715.

69. Harris JA, Hobbs RJ, Higgs E, Asesson J. 2006. Ecological restoration and global climate change. *Restor Ecol* 14:170–176.

70. Marris E. 2011. *Rumbunctious Garden—Saving Nature in a Post-Wild World*. Bloomsbury, New York, NY, USA.

71. Marris E. 2009. *Ragamuffin earth*. National Academies Press, Washington, DC.

72. Turner WR, Oppenheimer M, Wilcove DS. 2009. A force to fight global warming. *Nature* 462:278–279.

73. Newmann RB, Ashfaque KN, Badruzzaman AB, Ali MA, Shoemaker JA, Shaw J. 2011. Ecological effects of climate fluctuations on soil microbial community function and global climate change. *Trends Ecol Evol* 26:270–277.

74. Tricka CG, Bill BD, Cochlan WP, Wells ML, Trainer VL, Pickell LD. 2010. Iron enrichment stimulates toxic diatom production in high-nitrate, low-chlorophyll areas. *Proc Natl Acad Sci USA* 107:5887–5892.

75. Schnoor JL. 2011. The U.S. environmental budget. *Environ Sci Technol* 45:4659–4659.