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A systems perspective on responses to climate change

Wesley W. Ingwesen
U.S. Environmental Protection Agency, ingwersen.wesley@epa.gov

Ahjond S. Garmestani
United States Environmental Protection Agency, garmestani.ahjond@epa.gov

Michael A. Gonzalez
US Environmental Protection Agency

Joshua J. Templeton
US Embassy Peru

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A systems perspective on responses to climate change

Wesley W. Ingwersen · Ahjond S. Garmestani · Michael A. Gonzalez · Joshua J. Templeton

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Abstract The science of climate change integrates many scientific fields to explain and predict the complex effects of greenhouse gas concentrations on the planet's energy balance, weather patterns, and ecosystems as well as economic and social systems. A changing climate requires responses to curtail climate forcing as well as to adapt to impending changes. Responses can be categorized into mitigation and adaptation—the former involving efforts to reduce greenhouse gas emissions, and the latter involving strategies to adapt to predicted changes. These responses must be of significant scale and extent to be effective, but significant tradeoffs and unintended effects must be avoided. Concepts and science based on systems theory are needed to reduce the risk of unintended consequences from potential responses to climate change. We propose expanding on a conventional risk-based approach to include additional ways of analyzing risks and benefits, such as considering potential cascading ecological effects, full life cycle environmental impacts, and unintended consequences, as well as considering possible co-benefits of responses. Selected responses to climate change are assessed with this expanded set of criteria, and we find that mitigation measures that involve reducing emissions of greenhouse gases that provide corollary benefits are likely to have less negative indirect impacts than large-scale solar radiation management approaches. However, because effects of climate change are unavoidable in the near and medium-term, adaptation strategies that will make societies more resilient in the face of impending change are essential to sustainability.

Keywords Climate mitigation · Adaptation strategies · Systems theory · Life cycle thinking · Risk–benefit analysis

Introduction

With the invention of the thermometer in the sixteenth and seventeenth centuries (Doak 2005), man was afforded the opportunity to measure and record the temperature of anything, and this eventually led to recording atmospheric temperatures. By the mid-twentieth century the resulting measurements allowed for identifying and establishing a global atmospheric temperature baseline. Using early balloon data, recent satellite data, and methods of historical temperature approximation (e.g., ice cores), a gradual rise in temperature during the twentieth century has been documented that continues today (Crawley 2003, 2008; Hulme et al. 2002). There is strong evidence to suggest that the increase experienced in global temperature over the past 100 years is primarily caused by man-made activities (anthropogenic) and that a response is necessary to prevent catastrophic impacts associated with this change.

The effects of global climate change include increases in global air and water temperatures, rising sea levels, and the reduction in the extent of sea ice (IPCC 2007). There is also evidence that heat waves, increased storm frequency and associated flooding, and increased drought are additional symptoms of climate change (IPCC 2007). As society continues to develop, the increased climate activity

W. W. Ingwersen (✉) · A. S. Garmestani · M. A. Gonzalez
National Risk Management Research Laboratory, Office of Research and Development, US Environmental Protection Agency, 26W Martin Luther King Drive, Cincinnati, OH 45268, USA
e-mail: ingwersen.wesley@epa.gov

J. J. Templeton
United States Agency for International Development, US Embassy Peru, Avenida La Encalada, Lima, Peru

endangers human life and ecosystems and also stymies growth and societal development.

There are numerous findings, reports (NAS 2010a, b) and literature accounts of technologies that reduce greenhouse gas emissions, policies that mitigate emissions, and efforts for climate change adaptation that will reduce the negative impacts associated with global climate change. As the topic continues to be researched and more solutions are proposed, it is becoming evident that no one solution will effectively control or reduce climate change. In addition, as the concept and role of sustainability becomes incorporated into the discussion, the objective of climate change response is to position the global system in a state that offers the greatest resilience to sustain critical function through impending climate change, while at the same time, working to reduce the source of the problem and the severity of the effects.

Systems perspective on climate change

Understanding anthropogenically driven global climate change is complex because it involves integrating many traditionally independent sciences using tools from systems theory. These can be identified and termed earth systems science (Jacobson 2000), global change science (Cuff and Goudie 2009), or climate change science (McMullen et al. 2009). In addition, this may be more broadly considered a systems approach, with roots in general systems theory (von Bertalanffy 1950). Only with science built on this foundation can one develop an understanding of the interactions occurring among the living and nonliving components of the planet on a global scale. Therefore in global climate change models, emission projections are directly linked to atmospheric models that estimate global radiative forcing of combined anthropogenic and geogenic greenhouse gases sources. Radiative forcing is linked with temperature changes which are further linked to changes in the onset of seasons, precipitations patterns, ice cover, etc. (IPCC 2007). These changes are further linked to ecosystem-level responses, such as shifts in net primary productivity and coverage, which further drive community shifts and limit resource availability or undermines habitat quality for a species including our own. Responses to the affected components of the planet that in turn have further direct or indirect effects on other species, ecosystems, large-scale chemical cycles or even climate, are a part of climate change modeling. This chain of cause and effect involves unknowns and may be misunderstood or missed due to failure to integrated understandings from all relevant sciences, which invariably leads to failure to correctly understand and predict system dynamics. For the global climate system in particular, there is an element of complex variability that has foiled modeling effort in the past. As an illustration, stratospheric ozone began declining in the 1970s, but remained undetected because instrumentation which performed this analysis were programmed to ignore climate data that deviated from expectations (e.g., linear dynamics) (Carpenter et al. 2009). Statistical extrapolation is sometimes useful for climate modeling, as it is based upon analoges and models that assume which conditions lead to a perturbation. But statistical extrapolation based on past events is characterized by a high degree of uncertainty, which makes these values of questionable accuracy. Since there are aspects of the dynamics of systems, particularly the climate, that are impossible to compute, we must build resilience in order to avoid, or at least lessen the impacts of "unlikely" catastrophic events (e.g., Hurricane Katrina) (Carpenter et al. 2009). While the complexity of such systems science creates increased uncertainty in our ability to understand and predict change, and may in turn make it more difficult to communicate a straightforward message that facilitates a direct response, systems science is critical to understanding the complex changes increasing atmospheric greenhouse gas concentrations may indirectly trigger.

Climate scientists employ integrated assessment models (IAMs) to explore and predict the effects of technological and policy alternatives on future climate and economic outcomes. IAMs couple models from biological and atmospheric sciences with those from economics and social sciences and serve as the foundation for future scenario analysis used in the regular integrated assessments of the workings groups of the International Panel on Climate Change (IPCC 2007). These models are important in that the effects of scenarios explored serve as the basis for the prediction of potential responses to climate change. However, these models have recognized limitations in consideration of the true costs of mitigation approaches to society (Ackerman et al. 2009) and are limited in scope (like all models). Therefore, it is important that results from these models undergo further analysis for broader consideration of risks and benefits.

There are many important questions that need to be addressed when considering responses to climate change. These responses may also have negative and positive indirect impacts that might only be anticipated—like ecological changes triggered by changing climate variables—by seeing them in broad ecological, social, and economic contexts. In addition, because these responses could take place on large scales and at large expense, they need to be closely assessed in light of their potential effects on the global system.

Approach

The National Academy of Sciences has recommended a risk management approach to climate change (NAS 2010a, b), but particularly an approach that is more than just a traditional impact assessment or cost–benefit approach (NAS 2010a). This type of thinking has not yet matured into a quantitative, testable systems science, which leaves us to attempt to enrich the conventional perspective on responses to climate change using concepts from systems theory. We broaden a conventional risk–benefit analysis here with the addition of a systems theory perspective by integrating principles of systems theory and life cycle thinking to evaluate and discuss a broad range of mitigation strategies to respond to climate change. We begin with an overview of key systems concepts followed by a brief review of popular strategies that have been proposed for responding to climate change.

Background: systems concepts

Systems science has been advanced by many researchers with key concepts and tools having arisen independently. Here, we synthesize some of these concepts to define the origins of our perspective. Many of these concepts were developed around ecosystems within the field of ecology (Holling 1973; Odum and Odum 1953). These concepts have been expanded and recast for application in the context of human-dominated systems including social and political systems. With this is mind, we apply these concepts to "social–ecological systems", which is a term for linked systems of humans and nature (Berkes and Folke 1998). In this paper, we discuss the effects and responses to climate change in the broadest of terms, defining our social–ecological system of concern as the planet itself. Another perspective we integrate here, life cycle thinking, comes from the field of industrial ecology and underlies approaches to improve environmental management of a product or process, such as life cycle assessment (LCA) (Graedel and Allenby 2003).

Concepts from systems theory

System organization, control, and cascading effects

All social–ecological systems can be demonstrated to organize according to their available energy sources and other essential resources (e.g., water, nutrients). These systems further organize in a hierarchical manner such that primary energy flow is from bottom (lower trophic levels) to top (higher trophic levels) and as a result of thermodynamic limitations there is less energy available at the top of the hierarchy (the level of social systems) than at the bottom (photosynthesizers). This results with the top of the hierarchy being dependent upon the bottom and its structure and function limited by the quality and quantity of components on the bottom (Odum 2007). The top does, however, provide feedback to the bottom (a "feedback loop"), and this feedback can be represented at a global scale by anthropogenic climate change, where the emissions from burning fossil fuels by human systems have altered the planetary carbon cycle, which is in turn affecting the lowest levels of the planetary hierarchy. This is also an example of how lower-level patterns and processes are dominated by higher-levels in the hierarchy, which is called "top-down" control (Rosemond et al. 1993). An alternative theory of organization called panarchy has been developed to explain system responses that cannot be explained by the top–down control pattern. Panarchy differs from hierarchy, with respect to complex systems, in that conditions can arise which trigger a "bottom-up" change within the system (Gunderson and Holling 2002). This model of social–ecological systems more accurately captures the "surprise" or uncertainty inherent in such systems, as the components of social–ecological systems are bound by their dependence on the other components of the system for energy and essential resources (Garmestani et al. 2009b). When one component is severely affected, it will likely trigger effects that "cascade" to other components of the system (Meffe 2002). Cascading effects can be difficult to predict because they can propagate far beyond the components directly affected. Thus, there are inherent limitations to modeling that preclude the ability to create failsafe predictions. Decisions are based upon available information, a concept known as bounded rationality (Simon 1957). Heuristics are used to make a good choice, but not necessarily the best choice. Given the reality that we face "unknown unknowns", there will always be a fundamental level of uncertainty associated with any attempt to model future scenarios. If the policy objective is a reduction in vulnerability to climate change and climate variability, it is necessary to look beyond the impacts and mitigation of climate change. Climate change policy has typically involved a characterization or rationalization associated with the tradeoffs between adaptation and mitigation (Tompkins and Adger 2005). Tompkins and Adger (2005) contend that trade-offs that matter are the investment in technological innovation versus encouraging society to modify its behavior.

So, how do we deal with this fundamental uncertainty in our future projections? By managing for resilience in linked social–ecological systems (Garmestani et al. 2009a). In order to manage for resilience, we must acquire more information about the regimes we seek to manage, and the thresholds that govern those regimes. Since we now understand the climate system is a complex system characterized by nonlinear dynamics, it has become readily apparent that uncertainty and "surprise" need to be better integrated into modeling, and therefore climate policy (Schneider 2004). For example, cumulative impacts have the capacity to "scale up", in terms of their effect (Ruhl et al. 2007). With respect to climate change, greenhouse gases have accumulated in piecemeal fashion, with each car, cow, power plant, etc., having a minor effect. However, combining these small-scale impacts, through space and time, has manifested in large-scale effects that affect the entire planet (Ruhl et al. 2007). In order to reduce the risk of catastrophes associated with climate change, policymakers should account for uncertain, but catastrophic events (Schneider 2004). Thus, when modeling a system to estimate thresholds of a regime, it is sound policy to use multiple models, instead of one model, to increase the probability of estimating thresholds in complex systems (Bennett et al. 2008).

Complexity, non-linearity, and unintended consequences

Social–ecological systems are considered complex systems or complex adaptive systems (Cowan et al. 1994) which are characterized by a high degree of uncertainty, because not all relationships within the system are known or understood and thus the outcome from perturbations cannot be easily predicted. Another explanation of this uncertainty is the nonlinear nature of the relationships between components. Linear systems typically respond to small changes in a manner proportionate to the change experienced (Rial et al. 2004). Nonlinear systems, on the other hand, may respond with dramatic change (i.e., a regime shift) to a similar small change that has little effect on a linear system (Rial et al. 2004). Nonlinear effects are commonly associated with the climate system. The climatic record demonstrates that regime shifts in climatic conditions are evidence of nonlinear dynamics (Burkett et al. 2005). The nonlinear nature exhibited in social–ecological systems results in responses that do not occur in sync with the forces driving the change; often there are lag times, or delays between a driver and a consequence due to the different rates at which systems components respond to change. The nature of feedback loops mean that responses can be hastened. For example, if the carbon cycle is significantly disrupted (i.e., thresholds are crossed), the atmospheric conditions could be driven in a much more rapid fashion than expected (i.e., nonlinear change) and push the earth's atmosphere into an alternative regime which may not be favorable for human existence (Steffen 2006). Further, not only is the timing of responses difficult to predict because of nonlinearities, social–ecological systems may also exhibit responses that are unpredictable and unintended. These types of effects could be called "unknown unknowns" (Carpenter et al. 2006) as opposed to "known unknowns" which are effects that are known to be possible although it may be difficult to predict the timing of their occurrence.

Life cycle thinking

Life cycle thinking (LCT) provides an understanding of how a concrete action (a service or product) has direct and indirect consequences based on the resource acquisition, production, use and disposal of the goods or services that support that action, without performing a full quantitative assessment like a life cycle assessment (LCA) or a site-specific study of the impacts of the action such as an environmental impact assessment. Any response to climate change will involve mitigation or adaptive actions that themselves may have environmental consequences apart from the outcome of the action itself. Such consequences include life cycle environmental impacts, which are environmental impacts that occur due to resources use or a pollutant release at during the production, use, or disposal of a technology or any intermediate produce used to make a technology. Substituting biofuels for petroleum, for instance, could potentially result in a net increase in greenhouse gases (GHGs) when considered from a life cycle perspective as well as having other indirect environmental or economic consequences (FAO 2008). This consequence is not typically identified by either a risk-management approach or through extension of the social–ecological systems theories mentioned above, thus integration of LCT further enriches the systems perspective on climate change responses.

Overview of the proposed strategies

The primary threats from climate change are in the future, but these causes stem from present, past, and future actions. Strategies to reduce societal vulnerability to climate change must consider both present and future actions; and can generally be grouped as mitigation or adaptation strategies. Mitigation involves reducing GHGs through their prevention as emissions or removal from the atmosphere. Adaptation involves an intentional change in the organization, structure, and function of social–ecological systems to maintain function in light of climate change-related impacts. Table 1 summarizes these activities by strategy, action areas, and provides example actions for each.

Mitigation strategies

Mitigation strategies can be divided into sub-levels of source reduction, atmospheric carbon dioxide removal, and solar radiation management. Some of these mitigation activities are already in common practice; others are only proposed and are detailed in Table 1.

Table 1 Summary of selected responses to climate change

Strategy	Substrategy	Action area	Example action(s)
Mitigation	Source reduction	Substitution—Electricity	Replacement of coal-based electricity with low Carbon generation technology
Mitigation	Source reduction	Substitution—Transp. fuels	Use of biofuels with significant reductions in life cycle CO_2
Mitigation	Source reduction	Efficiency—Electricity	Combined cycle power plants; Smart grid technologies
Mitigation	Source reduction	Efficiency—Transportation	Cars with higher MPG
Mitigation	Source reduction	Efficiency—Buildings	Green building techniques for reduced energy consumption
Mitigation	Source reduction	Demand reduction	Reduction in miles driven in single passenger cars
Mitigation	Atmospheric CO_2 Removal—biological	Enhanced biomass sequestration	Reforestation
Mitigation	Atmospheric CO_2 Removal—biological	Soil management	No-till practices, terracing, erosion control
Mitigation	Atmospheric CO_2 Removal—biological	Phytoplankton biomass	Iron-spiking of oceans
Mitigation	Atmospheric CO_2 Removal—chemical	Carbon Capture & Storage (CCS)	Capture and storage at coal-power plants
Mitigation	Radiation management	Extra-atmospheric	Space mirrors
Mitigation	Radiation management	Stratospheric	Injection of sulfate particles
Mitigation	Radiation management	Tropospheric	Cloud seeding
Mitigation	Radiation management	Ground level	Reflective surfaces
Adaptation	Reactive	Emergency response	Temporary relocation of peoples; provision of essential services
Adaptation	Proactive	Social capital	Providing opportunities for those dependent on professions at risk
Adaptation	Proactive	Infrastructure protection	Levees
Adaptation	Proactive	Ecosystem protection/restoration	Watershed management activities

Source reduction

Source reduction is the practice of reducing the emissions of GHGs, and these strategies can be grouped in one of the three action areas—substitution, efficiency, or demand reduction. Substitution primarily entails meeting energy demands with sources that do not result in the release and addition of GHGs to the atmosphere. Nonfossil energy sources including sources based on renewable energy flows (e.g., solar, wind, hydropower) or those based on biomass (e.g., bioelectricity, biofuels) are those that meet these criteria. Less GHG intensive fuels (natural gas vs. coal) may also play a role. Substitutions of fuel sources in the electricity and transportation sectors are estimated to have the largest potential benefits. However, unless GHG reductions through substitution are demonstrated to reduce GHG concentrations from a broad enough view of the life cycles of fuel use, direct reductions may be canceled out by increases in indirect emissions. Improved efficiency in the use of energy, in its production, and delivery implies reduced use of energy for return of the same benefit, which directly results in emission of less GHGs. Efficiency improvements in buildings and transportation systems are estimated to have large benefits (Princiotta 2011). Additional benefits of reduction in energy demand implies a reduced requirement for energy apart from a change in efficiency, primarily through avoidance of energy consumption (e.g., turning off an un-utilized light), but in general requires a behavioral change and the intentional avoidance of energy usage.

Carbon dioxide removal

Carbon dioxide (CO_2) removal from the atmosphere is another example of a mitigation strategy. Carbon dioxide, the most prevalent of greenhouse gases, is the greatest total contributor to the radiative forcing that is the source of climate change (IPCC 2007). Removing CO_2 from the atmosphere can be performed by nonbiological and biological mechanisms. There are various nonbiological methods for CO_2 removal (Flannery et al. 1997). CO_2 removal would be theoretically most effective if removed from concentrated sources at the point of release. Until recently, technologies for separating CO_2 from large sources (e.g., power plant stacks) were nonexistent, but recently technology has been developed to both capture CO_2 and store it below ground in geological formations that are understood to be able to prevent its escape into the atmosphere indefinitely (IPCC 2005). Such mechanisms have been proposed primarily for implementation at coal-based power plants in areas within a manageable distance to a storage location (US EIA 2010). Once CO_2 is dispersed into the atmosphere, mechanical means of removing it are less feasible. However, facilitating chemical removal by accelerating the weathering of minerals such as carbonate is one mechanism that has been proposed (Lackner 2002). Another method is the alkalization of oceans with minerals that have an affinity to CO_2 to promote its chemical fixation, precipitation, and sinking of carbon as carbonates to the ocean bottom (Harvey 2008).

Biological fixation is currently the dominant carbon capture and removal pathway. One example of atmospheric CO_2 fixation is by photosynthetic organisms. Enhancing biological fixation is the most commonly considered method for removing CO_2 from the atmosphere since this method is an enhancement of a natural cycle. “Iron-spiking of oceans” is one method considered to enhance biological fixation in the oceans (Pollard et al. 2009). While phytoplankton in oceans already absorb more CO_2 annually than all CO_2 absorbed by terrestrial photosynthesizers combined, oceans are limited in a primary nutrient required by the phytoplankton, iron (Fe). Massive addition of iron to the ocean surface could yield significant increases in primary production of phytoplankton, which would result in more CO_2 sequestration (Pollard et al. 2009). However, the most common means of biological sequestration is still through terrestrial plant biomass. Planting trees, either for silviculture or reforestation, is the dominant approach toward carbon sequestration. Preventing the loss of forest resources by conserving forests is a passive means of preserving opportunities for forest carbon sequestration as well as protecting carbon sinks.

Solar radiation management

Solar radiation management is controlling and thus reducing the amount of light being absorbed by earth’s surface. This strategy of altering the global solar radiation balance is sometimes referred to as “geoengineering”, and implies either modifying solar irradiance (incoming sunlight), earth’s average albedo (reflectance of sunlight), or the emissivity of the earth’s atmosphere (amount of heat escaping the atmosphere) (Hemming and Hagler 2011). Schemes for solar radiation management have been proposed that range from deflecting light at the surface of the earth to the reduction of light entering the earth’s atmosphere from space. Deflection of more light at the earth’s surface would result in less heat being absorbed by the ground. Methods proposed for this include covering areas of the ocean with floating reflective material or whitewashing land surfaces (Flannery et al. 1997). Artificially increasing cloud formation is a method that has been proposed to increase albedo in the lower atmosphere (Hemming and Hagler 2011). Increasing the albedo in the upper atmosphere (stratosphere) could be accomplished by releasing massive quantities of small particles (aerosols) imitating the natural phenomena of ash release from major volcanic eruptions like the Mt. Pinatubo eruption in 1991 (Keith et al. 2010; Kosugi 2012). At the extra-atmospheric level, the positioning of large reflective mirrors at the L1 point (a point of gravitational equity) 1,500 million km between the earth and the sun could block up to 1.8 % of incoming radiation (Angel 2006).

Adaptation

Adaptation to climate change entails decisions to prepare society to become less vulnerable to climate change impacts. Adaptation measures may refer to a vast number of responses including nonhuman-aided ecological changes. However, for the purposes of this discussion, the measures are limited to intentionally planned efforts to alter human-dominated systems to reduce present and future predicted impacts of climate change. One quality that marks adaptation practices is their continuous nature—actions are not taken in isolation but generally involve a sequence of actions. And, they are generally done with consideration not only of climate change effects but often in preparation for natural climatic phenomena or in conjunction with efforts to improve sustainable development (Adger et al. 2007).

Adaptation will be a universally necessary measure but it will vary in the degree of burden it places on different nations and their populations. On some small islands and in lower coastal areas (Mimura et al. 2007), or in some areas strongly affected by drought, adaptation can at the extreme mean abandonment of communities. In other areas, it could mean changes in water management practices, crop varieties, disease prevention practices, etc. Capacity for adaptation is also likely to differ between nations and in different regions within nations, due to differences in governance, economic resources, education, etc. (Smit and Wandel 2006). There is consensus the least developed countries (LDCs) will have the least capacity to adapt to climate change, because they have fewer resources to do so, with many south Asian, sub-Saharan African, and small Pacific island nations being the most at risk (ref is WG II, 7.2). However, large differentials in adaptive capacity will likely exist within even wealthier societies, based on aspects such as age, social status, gender, etc. (Adger et al. 2007).

Another level of complexity in anticipating adaptation practices is that areas directly affected by climate often

Table 2 Summary of expanded risk–benefit analysis of selected climate change mitigation responses

No	Response	Risk					Benefit		
		Risk of cascading ecological effects	*Potential life cycle environmental impacts*	Economic Cost	Technical risk	*Likelihood of unintended consequences*	Magnitude of mitigatory effect	*Achieves multiple objectives*	Feasible near-term implementation
1.	Shift to majority renewable energy sources for electricity	•	•	••	•		•••	•	•
2.	Replace gasoline with bioethanol	•	••	•••	•••	•	•	••	•
3.	Increase efficiency of buildings and appliances	unk	•	••	•		••	••	•••
4.	CO_2 capture and storage for coal-power plants	unk	••	••	••	•	••		•
5.	Inject sulfate into the stratosphere	•••	•••	•	•	••	•••		••
6.	Deploy light-scattering extra-atmospheric object	•••	•	••	•••	•••	•••		••

Italicized criteria are unique contributions from this approach

Scale by criteria

Risk of cascading ecological effects (see System organization, control, and cascading effects): •, low risk; ••, medium risk; •••, high risk

Potential life cycle environmental impacts (see Life cycle thinking): •, life cycle impacts possible but more local or regional, perceivable but of low significance in comparison with existing systems; ••, life cycle impacts significant but local or regionalized; or impacts low but global; •••, life cycle impacts could be wide scale and very significant in comparison with existing systems

Economic costs: •, high initial costs that are recouped over time; no risk of negative indirect economic impact; ••, High initial costs are only partially recouped; risk of other indirect economic impact; •••, high costs and high risk of economic impact

Technical risk (*risk of technology not being developed or failing*): •, low risk; ••, medium risk; •••, high risk

Likelihood of unintended consequences (see Complexity, non-linearity, and unintended consequences): blank, none; •, low; ••, medium; •••, high

Magnitude of mitigatory effect: •, 1 GT C or equivalent; ••, 2 GT C or equivalent; •••, 3 GT C or equivalent

Achieves multiple objectives (see Evaluating the risks and benefits of proposed strategies): blank, none; •, 1 other major environmental or economic impact; ••, 2 other major environmental or economic impacts; •••, 3 other major environmental or economic impacts

Feasible near-term implementation: •, within 40 years; ••, within 20 years; •••, within 10 years

unk unknown risk or benefit that is assumed to be negligible

Action description

1. Assume a switch to a renewable-dominated energy mix in A1B scenario, which assumes rapid economic growth, global population peaking in mid-century, and rapid improvement in mitigation technology (IPCC 2007)
2. Replacement of 2 billion reference gas vehicle-eq consumption with EtOH (CMI 2010)
3. Widespread use of high-efficiency appliances and enhanced energy management and insulation of buildings (Princiotta 2011)
4. Use CCS for 1,600 GW of baseline coal-power, capture, transport and store CO_2 using natural geological reservoirs (CMI 2010)
5. Assume scenario where 5 MT SO_2/year put into tropical stratosphere (Keith et al. 2010)
6. Install a reflective surface at the L1 point to reduce incoming solar radiation by approximately 1.5 % (Angel 2006)

face added challenges, brought on by social issues such as poverty, disease, political instability, or environmental problems such as the scarcity or collapse of an environmental resource (Karunanithi et al. 2011). Adaptation is typically anticipatory or proactive and may involve scenario planning and preparation for action but can also be reactive. Anticipatory action is more likely to be effective especially for adaptation solutions that require long-term investment or a complex set of policies to support adaptation that cannot be implemented rapidly (Smith 1997).

However, there are many barriers to anticipatory action, including the costs, uncertainty of climate impacts, and lack of consensus.

Responding to climate change

System goal

Each of these two categories of response to climate change (mitigation and adaptation) is associated with an end goal. Mitigation is most often associated with the goal of avoiding the incidence or at least reducing the severity of climate change impacts. This goal can be understood or envisioned as risk aversion. Adaptation is very frequently associated with the goal of reducing the vulnerability of human populations and ecosystems to climate change impacts. This can be concisely stated as reducing vulnerability, where we adopt Adger's definition of vulnerability to be "the state of susceptibility to harm from exposure to stresses associated with environmental and social change and from the absence of capacity to adapt" (Adger et al. 2007). As mentioned, these strategies will both be necessary, and therefore elements of each approach must be a component of any recommendation.

A broader goal to unify these two strategies could be stated as sustaining social–ecological systems, or the more popular term of 'sustainability' of social–ecological systems, for which we adopt the EPA's definition of sustainability: "the satisfaction of basic economic, social, and security needs now and in the future without undermining the natural resource base and environmental quality on which life depends"(US EPA 2010a). We define the objectives regarding climate change response within this goal, both to reduce the climate pressure exerted by the anthropogenic imbalance of the carbon cycle (mitigation) and to reduce the risk of potential impacts and the uncertain future this imbalance might bring by managing for resilience in social–ecological systems through adaptation strategies that make these systems less vulnerable to anticipated changes, more adaptive, and self-sufficient.

Evaluating the risks and benefits of proposed strategies

Table 2 summarizes our risk–benefit analysis of responses to climate change using a risk management approach that has been extended via application of concepts from systems theory and life cycle thinking. We evaluate selected responses from our categorization in Table 1 that have been described in the literature. The responses are global in scope for mitigation. US-based responses are described for adaptation (because of its regional nature), but these are not fully described in the literature and have not been evaluated. Still the mitigation responses are included here because they can be assessed using the same approach. The responses are evaluated in light of their economic and technical risks (risk of proposed technology not being successfully developed or risk of technology failure) as well as the magnitude of mitigatory effect and readiness of implementation. The addition of the risk criteria for the "risk of cascading ecological effects", "potential life cycle environmental impacts", and "potential for unintended consequences", as well as the additional benefit criteria of "achieves multiple objectives" are based on the application of systems concepts. Risks and benefits are referenced from many sources in the literature and we estimate the magnitude of those risks and benefits for each of the responses according to a scale of 0–3 defined for each of the criteria. Reference information for each ranking is provided in Table 3 in the Appendix.

Since responses to climate change are necessary, it is imperative to balance their associated risks with the magnitude of benefits and co-benefits, as well as to understand how quickly the actions can be implemented. A portfolio and timeline of responses should be chosen to minimize the sum of expected costs from climate change policy implementation and any unmitigated climate change. Potential costs of catastrophic scenarios should be weighted to account for risk aversion. Global responses to mitigate or adapt to climate change are actions that require consensus and significant inputs of skills and resources. To justify these actions, in light of the many other priority global issues, such as security, economic productivity, provision of basic services, health care, etc., such responses need to address the demand of other important global issues as well. Thus, there is a necessity to promote actions that have the potential of achieving multiple objectives. This is a further argument for a systems thinking response to a global issue, such as climate change. These effective responses to global climate change thus need to be considered in light of potential benefits not just in counteracting climate change but how they can benefit objectives such as human development, environmental quality, and resource efficiency.

Below we use this approach to illustrate how assessing risks and benefits with a systems perspective of some selected responses (Table 2) can be used to identify those that are the most sustainable action.

Mitigation actions

Actions to reduce CO_2 emission from current point sources have various associated risks with their action. These risks have been evaluated in this manuscript for a number of selected actions. An example is the replacement of current sources for electricity with mostly renewable sources, including hydro, wind, solar, and geothermal sources, as described by the IPCC's A1B scenario (IPCC 2007).

Hydropower has the potential to make up a significant portion of a global renewable electricity portfolio, but would require the construction of additional dams. These newly constructed dams have the potential to contribute additional hydraulic pressure on river systems and estuaries from fragmentation effects (Nilsson et al. 2005), which can cause localized cascading ecological effects. Other renewable energy technologies, particularly solar, are currently more expensive, require less abundant metals, and provide low returns in areas with less sunlight availability, so rapid-expansion would imply some socio-economic risk (Kosugi 2012; Princiotta 2011). A significant shift to renewable sources of electricity is not likely to occur in the next 10 years, because there is an abundance of capital-intensive fossil fuel power infrastructure with dependent supply chains that have not yet exceeded their estimated lifespan (Ackerman et al. 2009; IEA 2008). But shifts to renewable power are likely to reduce the potential for unintended consequences associated with concentrated fossil and nuclear energy sources (Kosugi 2012). Replacement of liquid petroleum transportation fuels with renewable sources is more risky on a large scale, due to current technical limitations to fuel development from cellulosic feedstocks, the additional pressure exerted on ecosystems from agricultural intensification, and the potential additional pressure on food markets from increased competition with biofuel feedstocks (FAO 2008). A less risky and more productive means of providing emissions reductions can be sought in increasing building and appliance energy efficiency, thus lowering total energy demand from residential and commercial buildings (Princiotta 2011; Thompson et al. 2011). Using higher efficiency lighting and appliances, and reducing heat loss through improved insulation are options that are potential cost saving and provide substantial emission reductions on a large scale (Thompson et al. 2011). While these improvements can be costly, they are readily implementable in the near future (Ackerman et al. 2009). In scenarios where GHG emissions are not directly reduced, they can be mitigated through carbon sequestration. Sequestering carbon from coal power plants prior to emission into the atmosphere and storing this carbon in geological reservoirs is one potential action that can result in significant carbon mitigation (IPCC 2005). However, this technological approach is still not being implemented today on a large-scale and has some potential consequences, including increasing energy requirements, higher costs for producers, and potential failure risk in the escape of stored sequestered carbon (Cannell 2003; IPCC 2005; Miller and Gage 2011).

While these source reduction actions offer clear and significant benefits, they do not exhibit the same level of failure risk that solar radiation management actions potentially have. Proposals to manipulate the earth's radiation budget could have particularly negative ecological consequences and environmental impacts, and could present a very significant risk (Hemming and Hagler 2011; Keith et al. 2010). Releasing large quantities of sulfate particles into the stratosphere is technically feasible, but has the potential for many environmental consequences including the generation of acid rain, stratospheric ozone reduction, and increase in ocean acidification (Hemming and Hagler 2011; Kosugi 2012). Deploying a light-scattering object that reduces the amount of radiation entering the earth carries substantial technical and failure risk (Hemming and Hagler 2011). These solar radiation management technologies are particularly risky from a systems perspective, because they involve manipulation of conditions that affect all photosynthetic organisms on which all other organisms, social, and economic systems depend. These activities furthermore increase the probability of "unknown unknowns," or unintended effects on the planet, because they involve manipulations of a type and scale for which we cannot anticipate their repercussions.

Adaptation actions

The uncertainty surrounding climate change is compounded with the uncertainty surrounding its associated impacts, which is further compounded with the uncertainty surrounding the appropriateness and the likelihood of success of any adaptive approaches. Adaptation is more regionally specific, but climate impacts are difficult to accurately predict at a regional scale. This unpredictability leads to even less certainty about the appropriateness of planned actions. However, when particular adaptive actions are proposed, they can be evaluated for their risks and benefits. Reactive actions cannot be directly assessed a priori, but roughly assessed via analogous actions. For example, a large scale disaster response including the relocation of affected persons, such as the Hurricane Katrina aftermath, might be considered an analogy to a climate-related disaster of a similar scale, and thus used to approximate risks and benefits associated with this type of response. These reactive actions may be evaluated not so much in regard to whether or not to implement them, because they necessarily would need to be implemented, but in light of how sustainable they may be with respect to other proactive adaptation approaches.

Various proactive adaptation strategies for the United States have been suggested by the National Academy of Sciences in Adapting to the Impacts of Climate Change (NAS 2010a). Nevertheless, these actions have not been fully described, so they cannot be fully evaluated. Understanding these strategies can and should be evaluated in a common framework may, however, promote their elaboration to permit fuller consideration.

Conclusions

The response of the global climate system to anthropogenic greenhouse gas emissions and the perturbations this response causes to ecological, economic, and social systems can only be understood with an integrated systems approach. Societal responses to mitigate climate forcing or adapt to climate-driven changes need be considered with an equally broad systems perspective, such that responses can be selected that provide not only a remedy for existing problems, but if possible, prevent subsequent harm to other components of a global social–ecological system. Responses will need to be a mix of adaptation and mitigation, but both types of responses can be considered with this framework despite their very distinct natures. Expanding a traditional risk–benefit analysis to consider proposed actions using criteria derived from systems theory and life cycle thinking was the method proposed here. This expanded criteria included indirect negative impacts on ecological systems (cascading effects) and socio-economic systems, technology life cycle-related impacts, and the possibility of unintended consequences, as well as the additional positive impacts that actions can have on the global system. The assessment of six proposed mitigation actions here is only an initial example that might lead to more thorough assessments that need to take place before selecting the most appropriate mitigation and adaptation actions.

Appendix

See Table 3.

Table 3 References for Table 2

		Risk					Benefit		
No.	Response	Risk of cascading ecological effects	Potential life cycle environmental impacts	Economic costs	Technical risk	Likelihood of unintended consequences	Magnitude of mitigatory effect	Achieves multiple objectives	Feasible near-term implementation
1.	Shift to majority renewable energy sources for electricity	WCD (2000), Miller and Gage (2011)	Miller and Gage (2011), Princiotta (2011), Kosugi (2012)	Princiotta (2011), Kosugi (2012)	Princiotta (2011), Miller and Gage (2011)	Kosugi (2012)	IPCC (2005), Princiotta (2011)	Ölz et al. (2007)	Princiotta (2011), IEA (2008)
2.	Replace gasoline with bioethanol	FAO (2008)	FAO (2008)	FAO (2008)	US EPA (2010b), Miller and Gage (2011)	FAO (2008)	CMI (2010)	FAO (2008)	FAO (2008)
3.	Increase efficiency of buildings	Thompson et al. (2011)	Thompson et al. (2011)	Thompson et al. (2011)	Thompson et al. (2011), Miller and Gage (2011)	Thompson et al. (2011)	Princiotta (2011), Thompson et al. (2011)	Princiotta (2011)	Princiotta (2011), Thompson et al. (2011)
4.	CO_2 capture and storage for coal-power plants	Miller and Gage (2011)	James (2011), Miller and Gage (2011)	James (2011)	IPCC (2005)	IPCC (2005)	CMI (2010)	Princiotta (2011)	Princiotta (2011)
5.	Inject sulfate into the stratosphere	Hemming and Hagler (2011)	Hemming and Hagler (2011)	Keith et al. (2010)	Hemming and Hagler (2011)	Keith et al. (2010)	Keith et al. (2010)	Keith et al. (2010)	Keith et al. (2010)
6.	Deploy light-scattering extra-atmospheric object	Hemming and Hagler (2011)	Hemming and Hagler (2011)	Hemming and Hagler (2011)	Hemming and Hagler (2011)	Hemming and Hagler (2011)	US EPA (2010b)	Hemming and Hagler (2011)	Hemming and Hagler (2011)

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