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Classification of Climate-Change-Induced Stresses on Biological Diversity

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Abstract: *Conservation actions need to account for and be adapted to address changes that will occur under global climate change. The identification of stresses on biological diversity (as defined in the Convention on Biological Diversity) is key in the process of adaptive conservation management. We considered any impact of climate change on biological diversity a stress because such an effect represents a change (negative or positive) in key ecological attributes of an ecosystem or parts of it. We applied a systemic approach and a hierarchical framework in a comprehensive classification of stresses to biological diversity that are caused directly by global climate change. Through analyses of 20 conservation sites in 7 countries and a review of the literature, we identified climate-change-induced stresses. We grouped the identified stresses according to 3 levels of biological diversity: stresses that affect individuals and populations, stresses that affect biological communities, and stresses that affect ecosystem structure and function. For each stress category, we differentiated 3 hierarchical levels of stress: stress class (thematic grouping with the coarsest resolution, 8); general stresses (thematic groups of specific stresses, 21); and specific stresses (most detailed definition of stresses, 90). We also compiled an overview of effects of climate change on ecosystem services using the categories of the Millennium Ecosystem Assessment and 2 additional categories. Our classification may be used to identify key climate-change-related stresses to biological diversity and may assist in the development of appropriate conservation strategies. The classification is in list format, but it accounts for relations among climate-change-induced stresses.*

Keywords: adaptation of conservation strategies, adaptive management, climate change, conservation planning, conservation targets, hierarchical framework, threats to biological diversity

Clasificación de Estreses Inducidos por el Cambio Climático en la Diversidad Biológica

Resumen: *Las acciones de conservación requieren que se consideren los cambios que ocurrirán bajo los cambios climáticos y que se adapten para atenderlos. La identificación de de los tipos de estrés de la diversidad biológica (como la define la Convención sobre Diversidad Biológica) es clave en el proceso del manejo adaptativo para la conservación. Consideramos cualquier impacto de los cambios climáticos como un estrés porque tal efecto representa un cambio (negativo o positivo) en atributos ecológicos clave en un ecosistema o partes de él. Aplicamos un método sistemático y un marco de referencia jerárquico en una clasificación integral de los tipos de estrés de la diversidad biológica provocados directamente por el cambio climático global. Los identificamos mediante el análisis de 20 sitios de conservación en 7 países y la revisión de literatura. Agrupamos los tipos de estrés identificados de acuerdo con 3 niveles de diversidad biológica; aquellos que afectan individuos y poblaciones, aquellos que afectan comunidades biológicas y aquellos que afectan a la estructura y función del ecosistema. Para cada categoría de estrés, identificamos*

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3 niveles jerárquicos de estrés: clase de estrés (agrupación temática con la resolución más gruesa, 8); tipos de estrés generales (grupos temáticos de tipos de estrés específicos, 21) y tipos de estrés específicos (definición más detallada, 90). También compilamos una perspectiva general de los efectos del cambio climático sobre los servicios ecosistémicos utilizando las categorías del Millenium Ecosystem Assessment y dos categorías adicionales. Nuestra clasificación puede ser utilizada para identificar tipos de estrés clave relacionados con el cambio climático y puede ayudar al desarrollo de estrategias de conservación adecuadas. La clasificación está en formato de lista, pero toma en cuenta las relaciones entre los tipos de estrés inducidos por el cambio climático.

Palabras Clave: adaptación de estrategias de conservación, amenazas a la diversidad biológica, cambio climático, manejo adaptativo, marco de referencia jerárquico, objetivos de conservación, planificación de la conservación

Introduction

Anthropogenic climate change is one of the main contributors to the global loss of biological diversity (as defined in the Convention on Biological Diversity), and it has caused accelerated rates of species' extinctions and changes to ecosystems (Sala et al. 2000; Thomas et al. 2004; Pimm 2008). Climate change not only exacerbates conventional threats and stresses to biological diversity, such as habitat loss and fragmentation, but also creates new stresses (Pimm 2008). The importance of adapting conservation to climate change has been pointed out repeatedly (Peters & Darling 1985; Halpin 1997; Hannah et al. 2002). Adaptive management techniques could be used to address this challenge. Adaptive management is an iterative approach increasingly applied in conservation that has been formally included in the Convention on Biological Diversity Ecosystem Approach (CBD 2000). The Conservation Measures Partnership (CMP), a joint venture of 12 organizations and collaborators that are committed to improving the practice of conservation, has developed a set of guidelines for use of adaptive management--the Open Standards for the Practice of Conservation (CMP 2007, 2010). The Open Standards establish common concepts, approaches, and terminology to help practitioners better design, manage, and measure the effects of their conservation actions (CMP 2007). The development of the Open Standards is a participatory and ongoing process.

One of the most critical steps in conservation planning generally, and in the Open Standards in particular, is the conceptualization of the conservation project (i.e., conducting a situation analysis that identifies conservation targets and the threats to and stresses on them) (CMP 2007). Conservation targets are the biological entities (species, communities, or ecosystems) that a project is trying to conserve (Salafsky et al. 2002, 2008). Threats are human activities that negatively affect targets. Natural phenomena can also threaten targets if their negative effects are increased by human activities. A threat is pressure on or a source of stress for biological diversity (Salafsky et al. 2002; Salafsky et al. 2008). Stresses, by contrast, are "attributes of a conservation target's ecology that are impaired directly or indirectly by human activities (e.g., reduced population size or fragmentation of forest habitat). A stress is not a threat in and of itself, but rather a degraded condition or "symptom" of the target that results from a direct threat. Stresses are synonymous with degraded key attributes" (Salafsky et al. 2008).

Many threats to biological diversity that result in stress are similar worldwide. Hence, it would be helpful to have a common classification system for those threats to facilitate thorough situation analysis and a knowledge exchange that would improve conservation efforts. Salafsky et al. (2008) proposed a general classification of direct threats to biological diversity that brought together earlier classification efforts by the CMP and International Union for Conservation of Nature (IUCN). They classified 11 high-level categories of direct threats (e.g., residential and commercial development, transportation and service corridors, pollution). They included the threat category climate change and severe weather into their classification scheme, but the 4 subcategories within the climate change category (habitat shifting and alteration, drought, temperature extremes, storms, and flooding) cannot fully capture the complexity of changes triggered by climate change. Besides the classification of threats, Salafsky et al. (2008) propose a general and unspecified classification of stresses. Although this broad classification of stresses may be sufficient for developing conservation responses aimed at reducing or eliminating threats to biological diversity, it is less applicable to management of the effects of threats, especially in situations in which there are effect chains of stresses between threats and conservation targets. We considered any effect of climate change on biological diversity a stress because it represents a change to an element of biological diversity and thus a change in its key ecological attributes.

In most reviews of the effects of climate change on biological diversity, only responses of specific species and ecological systems to climate change are described (e.g., Walther et al. 2002; Parmesan 2006; Campbell et al. 2009). Thus, we devised a systematic, global classification of climate-change-induced stresses on biological diversity. Measures to mitigate or promote adaptation to climate change, such as conversion of land for renewable energy production and changes in land and water management to increase carbon sequestration, may also threaten biological diversity. We did not, however, consider these measures in our classification.

The concept of hierarchy provides a pragmatically robust conceptual framework for biodiversity assessment and monitoring and management of complex systems (Noss 1990; Vasishth 2008). Biological diversity can be considered a hierarchy of nested systems. Each organizational level represents a system made of smaller and interacting subsystems and is itself a component of a greater system (Allen & Starr 1982; Ahl & Allen 1996; Allen 2008). If biological diversity is considered to be hierarchical, the effects of environmental change, such as global climate change, are expressed in different ways at different levels of organization (Noss 1990). Thus, we used a hierarchical framework to classify climate-change-induced stresses of biological diversity.

Methods

We refined a conceptual model of how climate change affects conservation targets in protected areas (Ibisch & Kreft 2009a, 2009b) by reviewing direct and indirect stresses related to climate change identified in conservation planning processes for 20 conservation sites in 7 countries (Supporting Information). This review informed our classification of climate-change-induced stresses of biological diversity.

We also searched the literature for empirical evidence and other references to additional direct and indirect effects of climate change on biological diversity. For this we used the keywords of stresses we identified through the previous review (e.g., *interactions*, *community*, *ecosystem*, *behavior, competition, sea-level rise, snow, fire*, *evaporation* [Table 1]) and terms related to climate change (e.g., *climate change*, *global warming*) as search terms. We thus compiled a comprehensive list of references for all the specific stresses we identified (Supporting Information).

We grouped the stresses according to 3 levels of biological diversity: individual and population level, community level, and ecosystem level. These levels are those recommended by the Open Standards for the Practice of Conservation for selection of conservation targets (CMP 2007) and are commonly used in conservation projects (e.g., Zacharias & Roff 2000; Ibisch et al. 2007).

Within each level of biological diversity, we categorized stresses on 3 hierarchical levels, from coarse to fine resolution: stress class (thematic grouping with the coarsest resolution), general stress (thematic group of specific stresses), and specific stress (most detailed definition of a stress). We sorted the categories under stress class and general stress from the most direct effects to the most indirect effects on a given level of biological diversity (individuals and populations, communities, ecosystems).

Additionally, we compiled an overview of effects of climate change on ecosystem services as categorized by the Millennium Ecosystem Assessment (MA 2005). We consider ecosystem services "the benefits human populations derive, directly or indirectly, from ecosystem functions" (Costanza et al. 1997) or "the benefit people obtain from ecosystems" (MA 2005). This concept represents an alternative perspective on the change of biological diversity and is gaining acceptance (TEEB 2010). Ecosystem services are increasingly being used as conservation targets (but see Salafsky 2010). We considered 2 additional categories of ecosystem services not included in the Millennium Ecosystem Assessment's categories: regulation of gases (carbon sequestration and regulation of atmospheric elements and compounds including carbon dioxide, oxygen, and ozone) (Costanza et al. 1997; de Groot et al. 2002) and seed dispersal (Wallace 2007).

Results

We classified climate change-induced stresses into 8 stress classes, 21 general stresses, and 90 specific stresses across 3 levels of biological diversity: individuals and populations, communities, ecosystems (Table 1). The effects of global climate change were directly discernable only in alterations of local abiotic components of ecosystems (Table 1, 3.1), including climatic means, seasonality, and variability (3.1.1) as well as water (3.1.2–3.1.4) and soil (3.1.5). Changes in abiotic components influenced individual organisms directly, affecting their physiology, phenology, behavior, and reproduction (1.1). Individual-level effects sometimes translated into changes in population dynamics (1.1.2). Populations were also affected indirectly by climate change via shifts in habitat location, quantity, or quality (1.2). The resulting changes in abundance, fitness, competitiveness, and distribution of individuals and populations of a species then led to alterations in the biological community (2) they comprised or became part of. Such community changes included the loss, development of new, and modification of species interactions (e.g., trophic relations, symbioses, and competition [2.1]) and changes in community structure (species composition and abundances [2.2]). Biotic habitat changes sometimes caused further stresses in previously unaffected species because resource availability (1.2.2.4) or species interactions (2.1) were changed.

The concurrence of abiotic and biotic changes (i.e., stresses) caused changes in ecosystem (3) structure (3.1), process (3.2), and global distribution (3.3), and these changes ultimately affected climate. All biotic and abiotic changes inevitably also altered the supply of ecosystem services (Table 2).

Table 1. Stress classes, general stresses, and specific stresses of biological diversity induced by climate change at 3 different levels of biological organization.

1	Change at individual and population level
1.1	direct stresses to individuals and populations
1.1.1	change in physiology and behavior of individuals
1.1.1.1	change in morphology
1.1.1.2	change in metabolism and physiology
1.1.1.3	change in immune function
1.1.1.4	change in growth rate
1.1.1.5	change in photosynthetic rate
1.1.1.6	change in rate, timing, and frequency of life-cycle events
1.1.1.7	change in behavior[a]
1.1.1.8	immediate death due to extreme events
1.1.2	change in population dynamics
1.1.2.1	change in population growth rate
1.1.2.2	changes in sex determination and sex ratio
1.1.2.3	change in gene pool
1.1.2.4	change in dispersal, recruitment, and colonization
1.2	habitat-related stresses to individuals and populations
1.2.1	loss of habitat
1.2.1.1	reduction of local or global quantity of habitat due to elevational and latitudinal shifting of climatic space (includes barriers [mountains, coastlines] and poor connectivity between recent and potential future habitats)
1.2.1.2	mismatch of required climatic and nonclimatic habitat components
1.2.1.3	reduction of climatically suitable space
1.2.1.4	reduction due to sea-level rise and coastal erosion
1.2.1.5	physical surface conversion of formerly inhabited area[b]
1.2.1.6	melting of ice sheets
1.2.2	change in habitat quality
1.2.2.1	change in abiotic habitat components and factors (cf. 3.1)
1.2.2.2	change in biotic habitat components and interactions (cf. 2)
1.2.2.3	change in disturbance regimes (cf. 3.3.1, 3.3.3)
1.2.2.4	change in resource and food availability
2	Change at community level
2.1	change of synecological relations (trophic interactions, symbioses, competition)
2.1.1	loss or decoupling of synecological interactions and interdependencies
2.1.1.1	loss of interactions due to differential range shifting of interacting species
2.1.1.2	loss of interaction due to local extinction or abundance loss of a partner species
2.1.1.3	loss of interactions due to phenological mismatch
2.1.2	change in the character of existing interactions
2.1.2.1	change of interaction due to changed fitness or competitiveness of a partner (including pathogens and parasites)
2.1.2.2	changed interactions due to change in behavior of an interacting species
2.1.2.3	changes of interactions and resource availability or accessibility due to phenological mismatch
2.1.3	new species interactions
2.1.3.1	appearance of new competitors that affect species richness or abundance of individuals
2.1.3.2	appearance of new predators
2.1.3.3	appearance of new pathogens and parasites
2.1.3.4	appearance of new prey and host species
2.2	change in community structure
2.2.1	change of community composition
2.2.1.1	loss or disassembly of community
2.2.1.2	loss of species
2.2.1.3	appearance of new species
2.2.2	change of relative abundances
2.2.2.1	abundance change due to changed competitive relations between species at same trophic level
2.2.2.2	abundance change due to changed species interactions between trophic levels (e.g., predation, symbioses, disease)
3	Change at ecosystem level
3.1	change of abiotic conditions
3.1.1	(micro)climatic changes (average, variability, and seasonality)
3.1.1.1	change of interannual and long-term climatic variability[c]
3.1.1.2	change in annual average temperatures and temperature variability
3.1.1.3	change in amount, distribution, and form of precipitation
3.1.1.4	change of wind patterns and strengths
3.1.1.5	change in evaporation and humidity
3.1.1.6	change in cloud cover

continued

Table 1 (continued).

3.1.2	change in marine water characteristics
3.1.2.1	change in water temperature regime
3.1.2.2	change in water chemistry (including salinity, pH)
3.1.2.3	change in currents and upwelling
3.1.2.4	change in wave and spray patterns
3.1.3	change in freshwater hydrological regimes (wetlands)
3.1.3.1	permanent change of water levels
3.1.3.2	change in water-level variability in wetlands
3.1.3.3	change in groundwater tables
3.1.3.4	change in flood occurrence, frequency, intensity, and area flooded (including hydroperiod)
3.1.3.5	change in runoff and river flow
3.1.3.6	change in water temperatures
3.1.3.7	change in chemical water characteristics
3.1.3.8	change in evaporation
3.1.4	change in snow or ice regimes
3.1.4.1	change in snow pack
3.1.4.2	change in snow loads
3.1.4.3	change in snow cover period
3.1.4.4	change in thickness of permanent ice sheets and melting of glaciers and permanent snow cover
3.1.4.5	change in duration and thickness of seasonal ice sheets and freezing of water bodies
3.1.4.6	melting of permafrost soils
3.1.5	change in abiotic soil conditions
3.1.5.1	change in soil moisture
3.1.5.2	change in soil temperature
3.1.5.3	change in physical soil composition[d]
3.1.5.4	change in chemical characteristics
3.2	change in ecosystem structure
3.2.1	change in the abiotic structure
3.2.1.1	change in surface structure and terrain
3.2.1.2	sea-level rise, fluctuation, and coastal impacts
3.2.2	change in the biotic structure
3.2.2.1	change in basic biotic structural elements (e.g., structure-constituting species such as trees or corals)
3.2.2.2	change in synecological interactions (cf. 2.1)
3.2.2.3	change in community composition and structure (cf. 2.2)
3.3	change in ecosystem processes and dynamics
3.3.1	change in geophysical and disturbance processes
3.3.1.1	change in evapotranspiration and cloud formation
3.3.1.2	change in type, frequency, intensity or length of climatic extreme events (e.g., droughts, hurricanes)
3.3.1.3	change in flood frequency, intensity and area flooded (e.g., potamic flooding, tsunamis, storm floods)
3.3.1.4	change in surface movements (avalanches, erosion, landslides)
3.3.1.5	change in seismic and volcanic processes
3.3.1.6	change in fire frequency, intensity, or extent
3.3.2	change in energy flow and nutrient or matter cycle-related ecosystem processes
3.3.2.1	change in decomposition rates
3.3.2.2	change in nutrient availability
3.3.2.3	change in primary production
3.3.2.4	change in oxygen cycle
3.3.2.5	change in carbon cycle
3.3.2.6	change in nitrogen cycle
3.3.2.7	change in phosphorous cycle
3.3.2.8	change in accumulation of non-nutrient elements, pollutants and heavy metals
3.3.3	change in succession processes and ecosystem development
3.3.3.1	change in short-term succession processes (seasonal, small-scale disturbances, individual and species turnover)
3.3.3.2	change in long-term succession and ecosystem development
3.4	change in ecosystem presence and global distribution
3.4.1	change in global distribution of ecosystems
3.4.1.1	spatial extent of individual ecosystems
3.4.1.2	spatial distribution of ecosystem types
3.4.2	change in diversity of ecosystems
3.4.2.1	loss or dissolving of known ecosystems
3.4.2.2	emergence of formerly unknown ecosystems[e]

[a] *Behavioral adaptation to new environmental conditions (e.g., changes in temporal and spatial movement pattern).*
[b] *For example, by erosion, landslides, avalanches, and other extreme events.*
[c] *Climatic variability between years or over longer periods.*
[d] *Texture, structure, aggregation, density, drainage, and water-holding capacity.*
[e] *Includes novel ecosystems.*

Table 2. Overview of effects of climate change on ecosystem services[a].

1	Change in provisioning services
1.1	availability of and access to food
1.2	availability of and access to fiber
1.3	availability of and access to genetic resources
1.4	availability of and access to biochemicals, natural medicines, and pharmaceuticals
1.5	availability of and access to ornamental resources
1.6	availability of and access to fresh water
2	Change in supporting services
2.1	soil formation
2.2	photosynthesis
2.3	primary production
2.4	nutrient cycling
2.5	water cycling
3	Change in regulating services
3.1	air-quality regulation
3.2	local, regional, or global climate regulation
3.3	regulation of atmospheric gases[b]
3.4	water regulation
3.5	water purification and waste treatment
3.6	erosion regulation
3.7	disease regulation
3.8	pest regulation
3.9	pollination
3.10	seed dispersal[c]
3.11	natural-hazard regulation
4	Change in cultural services
4.1	cultural diversity
4.2	spiritual and religious values
4.3	knowledge systems
4.4	educational values
4.5	inspiration
4.6	aesthetic values
4.7	social relations
4.8	sense of place
4.9	cultural heritage values
4.10	recreational and tourism values

[a]*Slightly adapted from the Millennium Ecosystem Assessment (MA 2005).*
[b]*Category added to Millennium Ecosystem Assessment classification; carbon sequestration and regulation of atmospheric elements and compounds including carbon dioxide, oxygen, and ozone (Costanza 1997; Groot et al. 2002; Wallace 2007).*
[c]*Category added to the Millennium Ecosystem Assessment classification (from Wallace 2007).*

Discussion

We designed our classification to inform detailed analyses of climate-changed-induced stresses at specific sites and to specific conservation targets. It can be used to help determine whether observed changes in conservation targets might result from climate change. The classification may also provide a basis for models of climate change effects on particular ecological systems or protected areas.

We think the analysis of climate-changed-induced stresses should be part of a holistic, systemic situation analysis as conducted in the Open Standards. In contrast to the threats analysis in the Open Standards, which does not necessarily include a stress analysis (CMP 2007), other threat-analysis systems, such as The Nature Conservancy's Conservation Action Planning Framework (TNC 2007), differentiate between the sources of stresses and stresses themselves. We consider a stress-based threat analysis of climate change indispensable. For example, climate change as a threat can increase tree mortality in a forest. The specific impact mechanism (stress) could, for instance, be extreme climatic events, such as droughts and storms that immediately kill trees (Schlyter et al. 2006) or increases in herbivory by bark beetles that arise because climate change has induced changes in the beetle's life cycle (Jönsson et al. 2007; Jönsson et al. 2009). In many cases, there will be a synergy of effects: forests stressed by extreme events can be more susceptible to pathogens and pests (Schlyter et al. 2006).

Climate change can have cascading effects. For example, changes in sea water temperature (3.1.2.1) may stress certain marine species, such as sea turtles (Hawkes et al. 2009). Climate change also changes the chemical characteristics of seawater (3.1.2.2) and may modify ocean currents and upwelling (3.1.2.3). These stresses may then negatively affect marine species that would not have been stressed by a change in water temperature itself (Harley et al. 2006). Conservation targets may be stressed by effects of climate change that are geographically distant. For instance, a change in seawater temperature (3.1.2.1) mainly affects marine species and processes (Edwards 2009) and does not directly stress terrestrial ecosystems. Nevertheless, changes in water temperatures may affect, for example, the El Niño and La Niña oscillations and cyclones. Thus, a forest ecosystem may be severely affected by changes in precipitation (3.1.1.3) that threaten, for instance, the viability of species with low drought tolerance (Williamson et al. 2000; Fredriksson et al. 2007).

Although the classification is in list format for ease of use (Salafsky et al. 2008), one must keep in mind the underlying nonlinearity of climate change-induced stresses. It is crucial to account for connections among stresses. Most stresses may induce more stresses on other components and levels of biological diversity and could in turn be caused by a range of other stresses. It would be helpful to create a conceptual model of those connections when applying the classification to a situation analysis, as in the Open Standards framework.

Here, we illustrate how to apply our classification in an analysis of climate-change-induced stresses to an element of biological diversity. We base our example on documented interactions between fire and climate in a forest ecosystem (e.g., Cochrane et al. 1999; Laurance 2004; Nepstad et al. 2008). Fire increasingly is a stress, and its occurrence is affected by climate change.

Fire may affect single species or ecosystem processes. Our target in this case is a forest ecosystem in which an increase in fire frequency (Table 1, 3.3.1.6) may increase tree mortality. The stress of fire affects levels of biological diversity other than the ecosystem. The cause of increased fire frequency could be a change in abiotic elements (3.1) such as temperature (3.1.1.2), precipitation (3.1.1.3), or the frequency of climatic extremes, such as droughts (3.3.1.2). Because fire changes habitat quality (change of disturbance regime 1.2.2.3) for certain species (e.g., birds that nest in live specimens of a particular tree species [1.1.1.8]), an increase in tree mortality changes the structure of the ecosystem and community. When the abundances (2.2.2) of species associated with the ecosystem under consideration change, interactions among those species will change, and abundances of other species, often grasses or forbs in this case, may increase (due to increased competitiveness [2.1.2.1] or new invasion [2.2.1.3]). An increase in abundance of grasses may increase fire risk. The structure of (3.2) and processes occurring in (3.3) the original forest are changed over the long term, and the forest could develop into a new ecosystem (e.g., 3.4.2.1; 3.4.2.2). Such changes will also affect provision of ecosystem services by the forest (Table 2).

The characteristics and magnitude of a stress, especially one associated with changes in abiotic factors (3.1), differ depending on locality. For instance, an increase in mean annual temperature (3.1.1.2) may have a stronger effect on land masses and higher northern latitudes, such as the continental interior of Asia and northwestern North America, than on the southern Oceans and the North Atlantic (Meehl et al. 2007; Trenberth et al. 2007). In some regions mean annual temperature might even periodically decrease (Trenberth et al. 2007). Similarly, changes in type, frequency, intensity, or duration of extreme events (3.3.1.2) are applicable to any kind of extreme event, such as droughts, storms, or flooding, and will vary among locations.

In adaptive management in general and the Open Standards in particular, the identification of specific conservation targets and their threats is best done through conceptual models, which can be the basis for strategy building. Only with a holistic understanding of the system under study, the conservation targets, and their threats can planning be effective. Effective planning identifies the need for action and where in the system action can be taken. Generally, conservation strategies aim to abate threats or enhance viability of targets (i.e., restoration of key ecological attributes). Strategic actions needed to mitigate the effects of climate change are less easily identified than most actions needed to mitigate conventional threats. Abatement of direct threats of climate change is seldom feasible within in the management framework of most conservation sites. Hence, strategic actions to mitigate the effects of climate change must center on targets and enhance their viability through abatement of conventional threats or through direct intervention. It may also be necessary to reconsider the choice of conservation targets or the goals of the conservation plan.

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Supporting Information

A list of the conservation sites and associated projects used as sources of information for the development of the classification (Appendix S1) and a list of references for specific stresses in the stresses classification (Appendix S2) are available online. The authors are solely responsible for the content and functionality of this material. Queries (other than the absence of the material) should be directed to the corresponding author.

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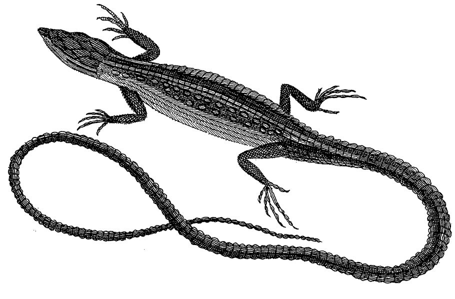

Appendix S1: Conservation sites and connected projects/conservation planning exercises used as sources of data for the development of classification of climate change-induced stresses to biodiversity

Conservation Site	Project	Project period	Local expert(s)	Institution
Danube Floodplain National Park (Austria)	Thesis project Martin Bienek (BSc, supervisor P.L. Ibisch, S. Kreft): Climate change in the Danube Floodplain National Park – risks and options, Eberswalde University of Applied Sciences	2007-2008	Christian Fraissl, Christian Baumgartner	National Park administration
"Río Grande-Valles Cruceños" Natural Area of Integrated Management (Bolivia)	Management planning "Área Natural de Manejo Integrado Río Grande Valles Cruceños", among others part of PhD project Veronica Chavez	2009	Maria Teresa Vargas, Israel Vargas, Huascar Azurduy, Nigel Asquith, Steffen Reichle	
Ilha Grande State Park (Brazil)	Thesis project Maja Noack (BSc, supervisor P.L. Ibisch): Planejamento Padrões Abertos para a prática de Conservação. Open Standards for the Practice of Conservation com a ferramenta MIRADI de apoio à implementação do Plano de Manejo do Parque Estadual da Ilha Grande /RJ, Brasil, [Open Standards for the Practice of Conservation with the tool MIRADI as support for the implementation of the management plan of the Ilha Grande State Park (Rio de Janeiro, Brazil)]. Eberswalde University for Sustainable Development	2007-2010	João Emílio, Rafael Cuellar, Gilberto Terra, Juliana Correia	Parque Estadual da Ilha Grande

Conservation Site	Project	Project period	Local expert(s)	Institution
Valdivian Coastal Reserve (Chile)	Thesis project Felix Cybulla (BSc, supervisor P.L. Ibisch, D. Kramm): Adapting to climate change. An analysis of the applicability of the methodology "Proactive Conservation Action Planning", Eberswalde University for Sustainable Development	2008-2009	Alfredo Almonacid	Reserva Costera Valdiviana
Biosphere Reserve Spreewald (Germany)	Thesis project Nicole Linke (BSc, supervisor: P.L. Ibisch, S. Kreft): The UNESCO Biosphere Reserve Spreewald under climate change. Options of action for its management.	2007-2008	Michael Petschick	Biosphere Reserve administration
Lower Oder Valley National Park (Germany)	Thesis project Nicole Linke (MSc, supervisor: P.L. Ibisch, S. Kreft): Climate change and its impacts on the viability of the forest habitat types of the habitat’s directive in the Lower Odra Valley National Park, Eberswalde University of Applied Sciences	2007-2008	Dirk Treichel, Michael Tautenhahn	Nationa Park administration
Natura 2000 (SAC) site “Falkenseer Kuhlaake” (DE 3444-306, Germany)	Thesis project Franziska Tucci (BSc, supervisor: P.L. Ibisch, S. Kreft): Exemplary management plan for the Natura 2000 (SAC) site “Falkenseer Kuhlaake” in Brandenburg (DE 3444-306). Climatic risk assessment and adaptation strategies for its management to climate change, Eberswalde University of Applied Sciences	2007-2008	Thomas Peters	Local forestry administration Falkensee

Conservation Site	Project	Project period	Local expert(s)	Institution
Natura 2000 (SAC) site “Trauf der südlichen Frankenalb” (DE 6833-371, Germany)	Thesis project Lena Strixner (BSc, supervisor P.L. Ibisch, S. Kreft): Evaluation of the current management and suggestions for possible adaptation to climate change using the example of the Natura 2000 (SAC) site “Trauf der südlichen Frankenalb” (DE 6833-371), Eberswalde University for Sustainable Development	2007-2008	Peter Sammler Claus Rammler Andreas Regehr	Amt für Landwirtschaft und Forsten Weißenburg/Bayern District administration Mittelfranken Natura 2000 Team Mittelfranken
Carpathian Biosphere Reserve (Ukraine)	Project funded by the German Environment Foundation (DBU): Fundamentals for a modern management concept for the Carpathian Biosphere Reserve (Transcarpathia, Ukraine).	2009-2010	Fedir Hamor Victoria Gubko Vasyl Pokynchereda Yaroslav Dovhanych Ivan Kruhlov Andriy Hamor	Biosphere Reserve administration Lviv University University of Uzhgorod
Cape Cod National Seashore, Fire Island National Seashore, Gateway National Recreation Area, Assateague Island National Seashore, Colonial National Historical Park, Sagamore Hill National Historic Site, George Washington Birthplace National Monument, Acadia National Park, Boston Harbor Islands National Recreation Area, Saugus Iron Works National Historic Site, Roosevelt-Vanderbilt National Historic Sites, George Washington Memorial Parkway and National Capital Parks-East (USA)	Strategy for Monitoring Climate Change Impacts on NPS Coastal Resources in the North Atlantic	2010	Brian Mitchell, Sara Stevens, Pat Campbell	US National Park Service

Appendix S2. Reference list for the classification of climate change-induced stresses of biodiversity

Stress classification		*References*
1	**Change at individual and population level**	
1.1	Direct stresses to individuals and populations	
1.1.1	*Change in physiology and behavior of individuals*	
1.1.1.1	Change in morphology	*Babin-Fenske et al. 2008; Meiri et al. 2009*
1.1.1.2	Change in metabolism and physiology	*Gillooly et al. 2001; Burek et al. 2008*
1.1.1.3	Change in immune function	*Raffel et al. 2006; Burek et al. 2008*
1.1.1.4	Change in growth rate	*Broadmeadow et al. 2005; Morecroft et al. 2008; Piovesan et al. 2008*
1.1.1.5	Change in photosynthetic rate	*Niu et al. 2008; Zavalloni et al. 2009*
1.1.1.6	Change in rate, timing, and frequency of life-cycle events	*Bradley et al. 1999; Stenseth & Mysterud 2002; Jenni & Kery 2003; Ahola et al. 2004; Gaston et al. 2005; Barbraud & Weimerskirch 2006; Dingemanse & Kalkman 2008; Doi & Takahashi 2008; Gordo & Sanz 2010*
1.1.1.7	Change in behavior	*Post et al. 1999; Kearney et al. 2009*
1.1.1.8	Immediate death due to extreme events	*Thibault & Brown 2008; Welbergen et al. 2008*
1.1.2	*Change in population dynamics*	
1.1.2.1	Change in population growth rate	*Moss et al. 2001; Both et al. 2006; Saba et al. 2007*
1.1.2.2	Change in sex determination and sex ratio	*Janzen 1994; Godley et al. 2002; Hawkes et al. 2007; Mitchell et al. 2010*
1.1.2.3	Change in gene pool	*Bawa & Dayanandan 1998; Umina et al. 2005; Balanya et al. 2006; Franks & Weis 2009; Pelini et al. 2009*
1.1.2.4	Change in dispersal, recruitment and colonization	*Gaston et al. 2005; Brooker et al. 2007; Ibanez et al. 2007; Chaloupka et al. 2008*
1.2	Habitat-related stresses to individuals and populations	
1.2.1	*Loss of habitat*	
1.2.1.1	Reduction of local or global quantity of habitat due to elevational and latitudinal shifting of climatic space (includes barriers [mountains, coastlines] and poor connectivity between recent and potential future habitats)	*Berry et al. 2002; Peterson 2003; Thomas et al. 2004; Colwell et al. 2008; Moritz et al. 2008; Virkkala et al. 2008*
1.2.1.2	Mismatch of required climatic and non-climatic habitat components	*Hill et al. 1999; Berry et al. 2003; Virkkala et al. 2008*
1.2.1.3	Reduction of climatically suitable space	*Berry et al. 2002; Berry et al. 2003; Moritz et al. 2008*
1.2.1.4	Reduction due to sea level rise and coastal erosion	*Fish et al. 2005; Baker et al. 2006; Fish et al. 2008*
1.2.1.5	Physical surface conversion of formerly inhabited area	*Gillooly et al. 2001; Goldenberg et al. 2001*

1.2.1.6	Melting of ice sheets	*Stirling et al. 1999; Croxall et al. 2002; Burek et al. 2008*
1.2.2	*Change in habitat quality*	
1.2.2.1	Change in abiotic habitat components and factors (cf. 3.1)	*Beaugrand et al. 2002; Berry et al. 2002; Chaloupka et al. 2008*
1.2.2.2	Change in biotic habitat components and interactions (cf. 2)	*Roy et al. 2004; Schweiger et al. 2008*
1.2.2.3	Change in disturbance regimes (cf. 3.3.3)	*Malevsky-Malevich et al. 2008; Lindner et al. 2010*
1.2.2.4	Change in resource and food availability	*Durant et al. 2007; Schweiger et al. 2008*

2 Change on community level

2.1 Change in synecological relations (trophic interactions, symbioses, competition)

2.1.1	*Loss or decoupling of synecological interactions and interdependencies*	
2.1.1.1	Loss of interactions due to differential range shifting of interacting species	*McLaughlin et al. 2002; Memmott et al. 2007; Preston et al. 2008; Pelini et al. 2009*
2.1.1.2	Loss of interaction due to local extinction or abundance loss of a partner species	*Memmott et al. 2007; Pelini et al. 2009*
2.1.1.3	Loss of interactions due to phenological mismatch	*Stenseth & Mysterud 2002; van Nouhuys & Lei 2004; Durant et al. 2007; Memmott et al. 2007; Both & et al. 2009*
2.1.2	*Change in the character of existing interactions*	
2.1.2.1	Change of interaction due to changed fitness or competitiveness of a partner (including pathogens and parasites)	*Harvell et al. 2002; Jiang & Morin 2004; Roy et al. 2004*
2.1.2.2	Changed interactions due to change in behavior of an interacting species	*Post et al. 1999; Ahola et al. 2004; Burek et al. 2008; DeLucia et al. 2008*
2.1.2.3	Changes of interactions and resource availability or accessibility due to phenological mismatch	*Stenseth & Mysterud 2002; Durant et al. 2007; Memmott et al. 2007; Both & et al. 2009*
2.1.3	*New species interactions*	
2.1.3.1	Appearance of new competitors that affect species richness or abundance of individuals	*Svensson et al. 2005; Jepsen et al. 2008*
2.1.3.2	Appearance of new predators	*Roy et al. 2004; Jepsen et al. 2008*
2.1.3.3	Appearance of new pathogens and parasites	*Harvell et al. 2002; Burek et al. 2008; Jepsen et al. 2008; Garrett et al. 2009*
2.1.3.4	Appearance of new prey and host species	*Roy et al. 2004; Burek et al. 2008*

2.2 Change in community structure

2.2.1	*Change in community composition*	
2.2.1.1	Loss or disassembly of community	*Beaugrand et al. 2002; Root et al. 2003; Brooker et al. 2007; Morecroft et al. 2008; Moritz et al. 2008*
2.2.1.2	Loss of species	*Berry et al. 2002; Schiel et al. 2004; Gritti et al. 2006; Moritz et al. 2008*
2.2.1.3	Appearance of new species	*Dukes & Mooney 1999; Gritti et al. 2006; Walther et al. 2009*

2.2.2 Change in relative abundances

2.2.2.1	Abundance change due to changed competitive relations between species at same trophic level	*Ahola et al. 2004; Jiang & Morin 2004; Schiel et al. 2004; Svensson et al. 2005; Pauli et al. 2007*
2.2.2.2	Abundance change due to changed species interactions between trophic levels (e.g., predation, symbioses, disease)	*Ims & Fuglei 2005; MacLeod et al. 2007*

3 Change on ecosystem level

3.1 Change of abiotic conditions

3.1.1 (Micro)climatic changes (average, variability and seasonality)

3.1.1.1	Change in interannual and long-term variability	*Timmermann et al. 1999; Schar et al. 2004; van Oldenborgh 2007*
3.1.1.2	Change in annual average temperatures and temperature variability	*Root et al. 2005; Trenberth et al. 2007; Walther et al. 2007; Welbergen et al. 2008*
3.1.1.3	Change in amount, distribution and form of precipitation	*Burlando & Rosso 2002a; Fowler & Kilsby 2003; Trenberth et al. 2007; Shongwe et al. 2009*
3.1.1.4	Change in wind patterns and strengths	*Goldenberg et al. 2001; van Oldenborgh & van Ulden 2003; McInnes et al. 2005; Reichler 2009*
3.1.1.5	Change in evaporation and humidity	*Pounds et al. 1999; Sperling et al. 2004; Tejeda-Martinez et al. 2008; Uhlmann et al. 2009*
3.1.1.6	Change in cloud cover	*Croke et al. 1999; Pounds & Puschendorf 2004; Sperling et al. 2004; Zhu et al. 2007*

3.1.2 Change in marine water characteristics

3.1.2.1	Change in water temperature regime	*Levitus et al. 2000; Barnett et al. 2001; Beaugrand et al. 2002; Attrill 2009*
3.1.2.2	Change in water chemistry (including salinity, pH)	*Harley et al. 2006; Bindoff et al. 2007; Portner & Knust 2007; Turley & Findlay 2009*
3.1.2.3	Change in sea currents and upwelling	*Bakun & Weeks 2004; Schmittner 2005; Bindoff et al. 2007; McGregor et al. 2007; Kanzow & Visbeck 2009*
3.1.2.4	Change in wave and spray patterns	*Vikebo et al. 2003; Gulev & Grigorieva 2004*

3.1.3 Change in freshwater hydrological regimes (wetlands)

3.1.3.1	Permanent change in water levels	*Magnuson et al. 1997; Lofgren et al. 2002; Schwartz et al. 2004*
3.1.3.2	Change in water level variability in wetlands	*Wedgbrow et al. 2002; Singh & Bengtsson 2004; Gibson et al. 2005; Andersen et al. 2006*
3.1.3.3	Change in groundwater tables	*Eckhardt & Ulbrich 2003; Herrera-Pantoja & Hiscock 2008*
3.1.3.4	Change in flood occurrence, frequency, intensity and area flooded (including hydroperiod)	*Knowles & Cayan 2002; Cunderlik & Simonovic 2005; Dankers & Feyen 2008; Jones 2008; Wilby et al. 2008; Allamano et al. 2009*

3.1.3.5	Change in run-off and river flow	*Burlando & Rosso 2002b; Barnett et al. 2005; Gibson et al. 2005; Liu et al. 2010*
3.1.3.6	Change in water temperatures	*Magnuson et al. 1997; Sharma et al. 2007; Mooij et al. 2008*
3.1.3.7	Change in chemical water characteristics	*Yan et al. 1996; Gibson et al. 2005*
3.1.3.8	Change in evaporation	*Li & Molders 2008; Liu et al. 2010*
3.1.4	*Change in snow or ice regimes*	
3.1.4.1	Change in snow pack	*Beniston et al. 2003; Barnett et al. 2005; Lemke et al. 2007; Stewart 2009; Wipf et al. 2009*
3.1.4.2	Change in snow loads	*Laternser & Schneebeli 2003; Wipf et al. 2009*
3.1.4.3	Change in snow cover period	*Barnett et al. 2001; Beniston et al. 2003; Laternser & Schneebeli 2003; Wipf et al. 2009*
3.1.4.4	Change in thickness of permanent ice sheets and melting of glaciers and permanent snow cover	*Haeberli & Beniston 1998; Singh & Bengtsson 2004; Lemke et al. 2007; Vaughan 2009*
3.1.4.5	Change in duration and thickness of seasonal ice sheets and freezing of water bodies	*Lemke et al. 2007; Beltaos & Prowse 2009*
3.1.4.6	Melting of permafrost soils	*Haeberli & Beniston 1998; Lemke et al. 2007; McGuire et al. 2009*
3.1.5	*Change in abiotic soil conditions*	
3.1.5.1	Change in soil moisture	*Huszar et al. 1999; Jasper et al. 2006; Holsten et al. 2009*
3.1.5.2	Change in soil temperature	*Zhang et al. 2004; Hirota et al. 2006; Mellander et al. 2007; Ooi et al. 2009*
3.1.5.3	Change in physical soil composition	*Garcia-Fayos & Bochet 2009*
3.1.5.4	Change in chemical characteristics	*Schofield & Kirkby 2003; Keller et al. 2004; Verburg 2005*

3.2 Change in ecosystem structure

3.2.1	*Change in the abiotic structure*	
3.2.1.1	Change in surface structure and terrain	*Capra 2006; Jungerius 2008; Macia & Robinson 2005*
3.2.1.2	Sea-level rise, fluctuation, and coastal impacts	*Galbraith et al. 2002; Bindoff et al. 2007; Nicholls et al. 2009*
3.2.2	*Change in the biotic structure*	
3.2.2.1	Change in basic biotic structural elements (e.g. structure-constituting species such as trees or corals)	*Phillips et al. 2002; Phillips et al. 2008*
3.2.2.2	Change in synecological interactions (cf. 2.1)	*Both & et al. 2009; Pelini et al. 2009*
3.2.2.3	Change in community composition and structure (cf. 2.2)	*Williams & Jackson 2007; Phillips et al. 2008*

3.3 Change in ecosystem processes and dynamics

3.3.1	*Change in geophysical and disturbance processes*	
3.3.1.1	Change in evapotranspiration and cloud formation	*Huntington 2004; Calanca et al. 2006*

3.3.1.2	Change in type, frequency, intensity and/or length of climatic extreme events (e.g., droughts, hurricanes)	*Easterling et al. 2000; Parmesan et al. 2000; Goldenberg et al. 2001; Schar et al. 2004; Trenberth et al. 2007; Welbergen et al. 2008*
3.3.1.3	Change in flood frequency, intensity and area flooded (e.g., potamic flooding, tsunamis, stormfloods)	*Fowler & Kilsby 2003; Cunderlik & Simonovic 2005; Dankers & Feyen 2008; Wilby et al. 2008; Allamano et al. 2009*
3.3.1.4	Change in surface movements (avalanches, erosion, landslides)	*Nearing et al. 2004; Jakob & Lambert 2009; Wei et al. 2009*
3.3.1.5	Change in seismic and volcanic processes	*McGuire et al. 1997; Huybers & Langmuir 2009*
3.3.1.6	Change in fire frequency, intensity, or extent	*McKenzie et al. 2004; Westerling et al. 2006; Robinson 2009*
3.3.2	*Change in energy flow and nutrient or matter cycle-related ecosystem processes*	
3.3.2.1	Change in decomposition rates	*Aerts 2006; Lensing & Wise 2007; Perez-Harguindeguy et al. 2007; Risch et al. 2007*
3.3.2.2	Change in nutrient availability	*Bouraoui et al. 2004; Lensing & Wise 2007*
3.3.2.3	Change in primary production	*Baptist & Choler 2008; Piovesan et al. 2008*
3.3.2.4	Change in oxygen cycle	
3.3.2.5	Change in carbon cycle	*Falloon et al. 2007; Chapin III et al. 2009; Lu & Cheng 2009; McGuire et al. 2009*
3.3.2.6	Change in nitrogen cycle	*Keller et al. 2004; Verburg 2005; Andersen et al. 2006*
3.3.2.7	Change in phosphorous cycle	*Malmaeus et al. 2006; Pant 2007; Jennings et al. 2009*
3.3.2.8	Change in accumulation of non-nutrient elements, pollutants and heavy metals	*Lynch & St.Clair 2004; Burek et al. 2008*
3.3.3	*Change in succession processes and ecosystem development*	
3.3.3.1	Change in short-term succession processes (seasonal, small-scale disturbances, individual and species turnover)	*Agenbag et al. 2008; Phillips et al. 2008; Hillebrand et al. 2010*
3.3.3.2	Change in long-term succession and ecosystem development	*Chapin III & Starfield 1997*
3.4	Change in ecosystem presence and global distribution	
3.4.1	*Change in global distribution of ecosystems*	
3.4.1.1	Spatial extent of individual ecosystems	*Beaugrand et al. 2002; Berry et al. 2002; Colwell et al. 2008*
3.4.1.2	Spatial distribution of ecosystem types	*Beaugrand et al. 2002; Berry et al. 2002*
3.4.2	*Change in diversity of ecosystems*	
3.4.2.1	Loss or dissolving of known ecosystems	*Beaugrand et al. 2002; Berry et al. 2002*
3.4.2.2	Emergence of formerly unknown ecosystems	*Chapin III & Starfield 1997; Hobbs et al. 2006; Williams & Jackson 2007; Hobbs et al. 2009*

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