Biodiversity in a changing climate: a synthesis of current and projected trends in the US

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This paper provides a synthesis of the recent literature describing how global biodiversity is being affected by climate change and is projected to respond in the future. Current studies reinforce earlier findings of major climate-change-related impacts on biological systems and document new, more subtle after-effects. For example, many species are shifting their distributions and phenologies at faster rates than were recorded just a few years ago; however, responses are not uniform across species. Shifts have been idiosyncratic and in some cases counterintuitive, promoting new community compositions and altering biotic interactions. Although genetic diversity enhances species' potential to respond to variable conditions, climate change may outpace intrinsic adaptive capacities and increase the relative vulnerabilities of many organisms. Developing effective adaptation strategies for biodiversity conservation will not only require flexible decision-making and management approaches that account for uncertainties in climate projections and ecological responses but will also necessitate coordinated monitoring efforts.

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Within the past decade, the evidence has become unequivocal that global climate is changing and is having widespread effects on biodiversity (IPCC 2007; Bellard *et al.* 2012). Human understanding of the myriad ways that ecological systems are responding to this unprecedented change is improving, but because biological responses are complex and sometimes unexpected, the full range of possible outcomes remains highly uncertain. In this paper, we assess recent advances regarding the impacts of climate change on biodiversity in the US. By summarizing key messages of a technical input (Staudinger *et al.* 2012) to the 2014 National Climate Assessment (NCA), which were derived from an extensive literature review, we address (1) current and future effects of climate change on biodiversity, (2) vulnerabilities of and risks to biodiversity, and (3) challenges facing biodiversity conservation. Specifically, we evaluate temporal (eg phenology), spatial (eg range), and organismal (eg physiology) responses of biological systems to climate variables (Table 1), as documented in observational studies, field and laboratory experiments, and various modeling approaches published since the last NCA in 2009 (USGCRP 2009). Within this framework we consider aspects of terrestrial, aquatic, and marine biodiversity, at scales ranging from genes to populations, species, communities, and ecosystems. Finally, to inform natural resource managers and decision makers on biodiversity–climate-change issues, we also discuss critical knowledge gaps, research initiatives, and best management practices. The key findings of the workgroup are shown in italic at the beginning of each of the following sections.

In a nutshell:

- Species are responding to climate change in complex, variable, and often unexpected ways
- Shifts in ranges and phenologies are occurring at faster rates than were previously documented, promoting novel ecological communities and interactions
- Improved understanding of intrinsic adaptive capacity – evolutionary potential, phenotypic plasticity, and dispersal capabilities – will help to identify which species will be able to adjust and keep pace with the rate and magnitude of climate change
- We provide a synthesis of the current state of knowledge regarding climate adaptation strategies for biodiversity conservation and identify key uncertainties

Shifting phenologies and geographic ranges

Climate change is causing many species to shift their geographic ranges, distributions, and phenologies at faster rates than were documented in the last NCA; however, the timing, direction, and magnitude of these rates are not uniform across species or ecosystems.

In the Northern Hemisphere, numerous taxonomic groups have already shifted their geographic ranges in

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response to changes in climate (Figure 1, A–C); existing estimates suggest that for some species, rates of movement are two to three times greater than were reported previously (eg USGCRP 2009; Burrows *et al.* 2011; Chen *et al.* 2011). Habitats or regions that are structurally or topographically more complex (eg forests, montane systems) are more likely to retain microclimates, contain refugia, and exhibit slower rates of change (Loarie *et al.* 2009). Despite faster rates of warming on land, the most rapid shifts in ranges and phenologies have been documented in marine environments, and model projections suggest that a "reshuffling" of marine floras and faunas is likely throughout the world's oceans during this century (Figure 1D; Cheung *et al.* 2009; Burrows *et al.* 2011).

Previously, researchers suggested that species and populations with sufficient adaptive capacity would primarily respond to increased temperatures by shifting poleward, upward in elevation, or downward to greater depths in the oceans (IPCC 2007). However, recent research, particularly in terrestrial settings, shows that movements can be highly idiosyncratic and sometimes counterintuitive as organisms respond to complex climate drivers, such as the seasonal timing of energy (eg springtime minimum and maximum temperatures) and water availability (eg summer precipitation, soil moisture, evapotranspiration) that constrain growing season length and productivity (Figure 1, B and E; Dobrowski *et al.* 2013). As such, generalizations relative to the direction, magnitude, and timing of species responses to ongoing climate change may have limited applicability.

Although range shifts may raise the probability of persistence for some species and populations, the ability to disperse or migrate to new areas does not guarantee survival. Factors such as species interactions and anthropogenic activities (eg land use, exploitation) may act as barriers to movement and decrease the chances for successful establishment (Hoffmann and Sgrò 2011). Moreover, changes in phenologies often differ across species, regional populations, and systems (Figure 1, F–I), increasing the potential for disruption of interactions between dependent species (ie trophic mismatches/asynchronies) that affect population dynamics (Figure 1, J–K; Miller-Rushing *et al.* 2010; Yang and Rudolf 2010).

Species-specific differences in phenotypic plasticity, evolutionary potential, and nongenetic parental effects may allow some individuals and populations to respond in situ (Figure 1, L–O) and reduce the need for range shifts in the near term (Doak and Morris 2010; Bellard *et al.* 2012). Nonetheless, there is concern that projected rates of regional climate change may outpace many species' intrinsic abilities to adjust (Loarie *et al.* 2009; Dobrowski *et al.* 2013). As a result, organisms that are less able to respond to mounting environmental variability (eg through shifts in range, phenology, and/or physiology) may be at an elevated risk of local extirpation or extinction (Bellard *et al.* 2012). On the other hand, climate change is likely to benefit some organisms by relaxing environmental constraints that currently limit species' distributions and promote range expansion in more favorable environments (eg Hare *et al.* 2010). Positive effects of climate change, for instance, have been observed in environments where warmer temperatures and/or longer breeding seasons improve reproductive success and survival or expand the availability of suitable habitat (Schmidt *et al.* 2011). These climate-mediated fluctuations in population distribution and abundance have the potential to further alter community dynamics in new and unanticipated ways.

■ Novel ecological communities and interactions

Increasing evidence suggests that range shifts and novel climates will result in new ecological communities, new associa-

Table 1. Overview of physical changes associated with climate change and examples of potential impacts associated with these changes

Observed or projected physical change	*Examples of potential impacts on biodiversity*
Increased ambient temperature	Species and population range shifts and/or changes in phenology leading to alteration or loss of biotic interactions
Changes in annual and seasonal precipitation	Changes in community composition and structure
Increased frequency of extreme events	Damage or mortality resulting from flooding after storms, drought events, deep freezes, heat waves, and disease outbreaks
Changes to hydrologic regimes	Changes in stream flow affecting population persistence and community composition
Changes to fire regimes	Changes in community composition and structure
Elevated CO_2 levels	Increased photosynthesis and plant growth; chemosensory, auditory, and neurological effects that impair behavioral activities in marine organisms
Ocean acidification	Change in water chemistry affecting calcification rates of marine organisms
Sea-level rise	Habitat loss and fragmentation affecting population persistence
Increases in ocean stratification	Reduced productivity of pelagic ecosystems
Changes in coastal upwelling	Changes in productivity of coastal ecosystems and fisheries

tions among species, and promote interactions that have not existed in the past.

The disappearance of some existing climatic conditions and the advent of new ones (ie novel climates) will alter interspecific interactions, reshuffle communities, and foster new combinations of species (Figure 1P; Urban *et al.* 2012). Changing environmental conditions have already produced shifts in patterns of species dominance and community composition in various ecosystems (Figure 1, Q–T). In some cases, these shifts are bringing together organisms that have rarely or never encountered one another in the past and are expected to generate strong new interactions (Lurgi *et al.* 2012; Smith *et al.* 2012).

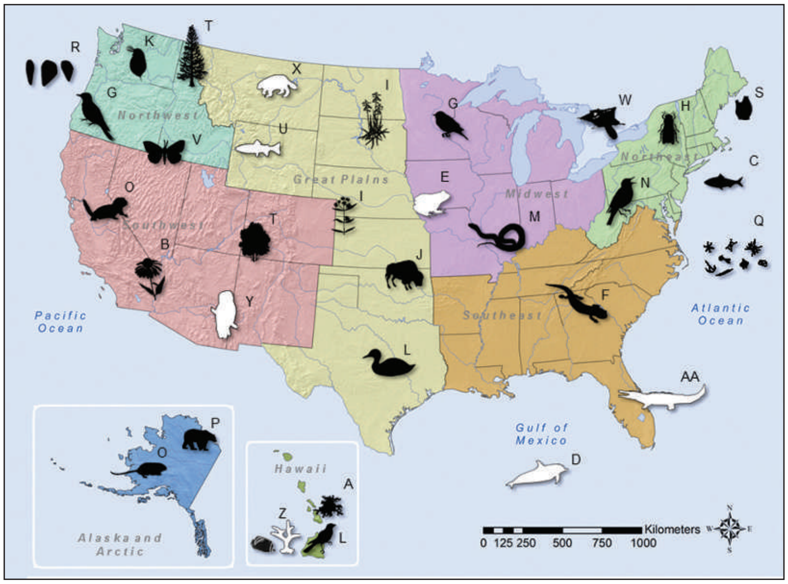

Figure 1. *A selection of recent studies demonstrating the diverse array of observed (black icons) and projected (white icons) biological responses to climate change across the US. Shifts in range and distribution were observed in (A) epiphytic communities, (B) flowering plants, and (C) marine fish species; distributional shifts are projected globally for (D) marine mammals and (E) amphibians. Phenological shifts were observed in seasonal migrations of (F) salamanders, (G) birds, and (H) insects, as well as (I) first flowering dates in meadow plants. Trophic mismatch and asynchronies are occurring as changes in (J) the availability and quality of food resources for bison and (K) algal–herbivore interactions in lake systems. Organismal responses have been observed as behavioral changes in (L) birds and (M) reptiles, and in body size in (N) birds and (O) small mammals. Novel and shifting species interactions were observed in (P) arctic, (Q) pelagic, (R) rocky intertidal, (S) subtidal communities, and (T) conifer and quaking aspen-dominated forests, and (U) are projected in fish assemblages of coldwater streams and rivers. Local adaptations have been shown to result in (V) decreased fitness in butterflies and interspecific hybridization in (W) flying squirrels. Climate-induced loss of habitat is leading to increased risk of extinction in (X) wolverines, (Y) spotted owls, (Z) coral reefs, and (AA) the American alligator. Expanded descriptions of these case studies and relevant bibliographic information can be found in WebTable 1 and in the WebReferences, respectively. All icons were obtained from the University of Maryland Center for Environmental Science (www.ian.umces.edu/imagelibrary/).*

Modeling studies have projected climate-mediated turnover in species composition resulting from the combination of local species losses and invasions from other regions. Estimates of species turnover range from 25–38% across the Western Hemisphere by the end of the century for terrestrial vertebrates (Lawler *et al.* 2009) to as high as 55% by 2050 for global marine animals, with invasions concentrated at high latitudes (Cheung *et al.* 2009). For example, in California, novel bird communities are projected across 70% of the state by 2070 (Stralberg *et al.* 2009).

Observed and predicted changes in community composition have important implications for how organisms interact to affect ecosystem structure and functioning (Smith *et al.* 2012), particularly because extinctions and invasions are often biased toward species with particular functional traits, such as those related to life history and trophic level (Miller-Rushing *et al.* 2010). Although many non-native invasive species are hypothesized to respond more positively to climate change than native species – due in part to relatively strong dispersal abilities and tolerance of disturbance – the body of experimental work on the subject has only recently been synthesized (Sorte *et al.* 2013). The cumulative evidence indicates that invasive species will likely have an advantage over natives, particularly in aquatic systems. Thus aquatic systems already threatened by invasive species will likely face escalating pressure as climate continues to change.

The broader ecological impacts of climate change on biotic interactions at the community level have received less attention than studies of direct physiological responses to abiotic change, in part because indirect effects are more difficult to quantify and predict. Efforts to model the effects of climate change on species interactions are growing and will be necessary for understanding and predicting how invasions or losses of particular species or populations will affect communities and ecosystem processes. Such efforts will help to identify species that may better adjust and successfully compete under scenarios of future environmental change as well as those that may be at a greater risk of decline (Figure 1U).

■ Adaptive capacity and the rate of climate change

The potential for biodiversity to respond to climate change over short (eg ecological) and long (eg evolutionary) timescales is enhanced by increased genetic diversity; however, the rate of climate change may outpace species' capacity to adjust.

Genetic diversity is the basic building block of biodiversity and enables species to persist through environmental change. Yet, current understanding of the capacity of species and populations to tolerate and ultimately adapt to climate change is limited (Reed *et al.* 2011). Under strong selection pressure such as rapid climate change, populations are at risk of going extinct before beneficial genes have a chance to enhance population fitness (Hoffmann and Sgrò 2011). However, evolutionary responses to novel conditions can occur rapidly with sufficient genetic diversity and when potential beneficial genes are already present in the population (Hoffmann and Sgrò 2011; Kovach *et al.* 2012).

It is often unknown which genes or combinations of genes are responsible for population persistence and evolutionary adaptation to climate change. Laboratory methods that measure gene expression have the potential to identify which transcripts and proteins are most likely to be affected when climatic conditions change (Buckely and Somero 2009), but more work is needed to determine the extent of genetic diversity underlying those changes. Modeling studies have demonstrated that local adaptations can impact the dynamics of species' range shifts under future climate change, sometimes resulting in counterintuitive patterns (Atkins and Travis 2010). Species with large ranges, for example, can experience population declines under climate change if local adaptation is common across the range and warm-adapted alleles have difficulty dispersing and establishing in regions historically dominated by cool-adapted phenotypes (Figure 1V). When locally adapted species compete with one another under climate change, the rate at which ranges shift also appears to slow down (Bocedi *et al.* 2013). These results emphasize the need to measure the distribution of genetic diversity within and among species and maximize the preservation of diversity so that adaptive traits have a chance to occur in locations where they may be most beneficial. Interspecific hybridization may also influence species persistence under climate change, and genetic mixing among related species may become more prevalent as new species assemblages develop across spatial and temporal scales (Figure 1, P and W).

Changes in climate can also indirectly affect gene flow and other processes that sustain genetic diversity (Figure 1X). For example, because planktonic larval duration is temperature dependent and correlated with dispersal distance, marine species may disperse over shorter distances in a warming climate, potentially reducing connectivity of gene flow among populations (O'Connor *et al.* 2007). Modeling studies suggest that genetic diversity will be affected by both the type of range change (eg range contraction or shift) and the rate of change in ways that have not been anticipated (Arenas *et al.* 2012). For instance, rapid range contractions may be better at preserving genetic diversity than slow range contractions; in addition, a rapid range shift may lead to lower diversity compared to a slow range shift. Natural resource managers will be challenged to find ways to promote diversity in newly established or founding populations, maintain population viability in historical regions where range contractions have occurred, and sustain gene flow between new and historical populations. Recent research provides insights into ways to address these problems, but much remains to be learned about the factors that promote evolution as environmental conditions change (Hoffmann and Sgrò 2011).

■ Vulnerability and risk to climate change

Differences in how organisms respond to climate change determine relative vulnerabilities of species or populations; specifically, those that will benefit, and those that will decline and may go locally or globally extinct.

Climate-change vulnerability is defined as a function of a species' or ecosystem's exposure to climatic changes, its sensitivity to that exposure, and its adaptive capacity, or ability to cope with and adjust to those changes (IPCC 2007; Glick *et al.* 2011a). Understanding what traits make some species vulnerable and others resilient to such changes will improve the ability to predict differential species responses. Although there are few documented cases of extinction due to climate change (Monzón *et al.* 2011), the majority of studies are finding evidence for and forecasting negative impacts of climate change on biodiversity (Bellard *et al.* 2012). In general, vulnerabilities are expected to be higher among ecological specialists, species with long generation times or low fecundity, and populations living near the extremes of their physiological climatic tolerances. Also likely to be at an elevated risk are species and populations with restricted ranges, those dependent on habitats expected to undergo major changes (Figure 1, X–AA), or those that exhibit little phenotypic plasticity, low genetic variability, or poor dispersal capabilities (Both *et al.* 2009). In contrast, species favored by changing climate tend to be habitat and dietary generalists, have high phenotypic plasticity, adjust quickly, thrive in disturbed and rapidly changing environments, and are good dispersers and competitors (Lurgi *et al.* 2012).

Climate change also interacts with other environmental and anthropogenic stressors – including land-use change, exploitation (eg fishing or hunting pressure), pollution, non-native invasive species, and disease – to affect native species and ecosystems (for an in-depth discussion, see Staudt *et al.* 2013). In many cases, these other stressors have been, or are currently, the primary drivers of biodiversity loss (Master *et al.* 2009) and will interact with climate change to affect the vulnerability of species and populations (Barnosky *et al.* 2011; Mantyka-Pringle *et al.* 2011). Threats from climate change have recently begun to play a prominent role in the US endangered species listing process (eg polar bears, arctic seals, corals) and are being incorporated in the criteria for assessing threatened species under the International Union for Conservation of Nature (IUCN) Red List process (Figure 2; IUCN 2012). Because it is often difficult to disentangle the direct and indirect climate-change impacts from other co-occurring stressors, improved characterization and understanding of the cumulative impacts and synergistic interactions on species' vulnerabilities is a priority for research and will be critical to conducting conservation assessments and setting management priorities.

Developing effective adaptation strategies and management responses

Understanding sources of vulnerability and how species are likely to respond to climate change is critical to developing effective climate adaptation strategies and management responses; biodiversity conservation efforts will increasingly need to focus on managing for change.

As the effects of climate change grow and interact with other stressors, the success of traditional biodiversity conservation efforts will increasingly be compromised. Protected areas may no longer contain the range of climate and habitat conditions necessary to support the species that these refuges were designed to protect (eg Monzón *et al.* 2011). For this reason, climate-change adaptation – initiatives and strategies to prepare for and cope with climate impacts – is becoming a major focus of biodiversity conservation efforts (Stein *et al.* 2013). Until recently, the dominant paradigm for this field has been preservation of existing conditions or restoration to a past state regarded as ecologically "more desirable". In light of the rapid changes in climate currently underway, conservation goals and strategies must consider not only historical benchmarks but also projections of future climatic and ecological conditions (Glick *et al.* 2011b).

Key to determining whether and how conservation goals and associated actions may need to be revised is an understanding of projected climate-change impacts and the sources of vulnerability of ecological resources. Projected changes in physical conditions, species distributions, species interactions, phenologies, genetics, and ecological processes have important consequences for determining what conservation actions are required to meet particular conservation goals. Conservation planning will not be successful in the face of climate change if it evaluates only where species, habitats, or ecosystems currently exist in the landscape and ignores where those entities are most likely to move and persist as conditions change (Monzón *et al.* 2011).

Vulnerability assessment tools and approaches are progressively being used to identify species and habitats at greatest risk from climate change, articulate why species and habitats are vulnerable, and inform conservation strategies designed to reduce those vulnerabilities (Glick *et al.* 2011a). Reductions in vulnerability can be achieved by reducing exposure to climatic changes (direct or indirect), decreasing the organism's or system's sensitivity to those changes, or enhancing the adaptive capacity of the target species or ecosystem (Figure 3; Dawson *et al.* 2011; Rowland *et al.* 2011; Stein and Shaw 2013). Although valuable for informing conservation priorities, vulnerability information alone does not determine those priorities. Depending on the values and objectives of relevant stakeholders, priorities may range from maintaining the most vulnerable species and ecosystems to investing in those most resilient to change and therefore most likely to persist.

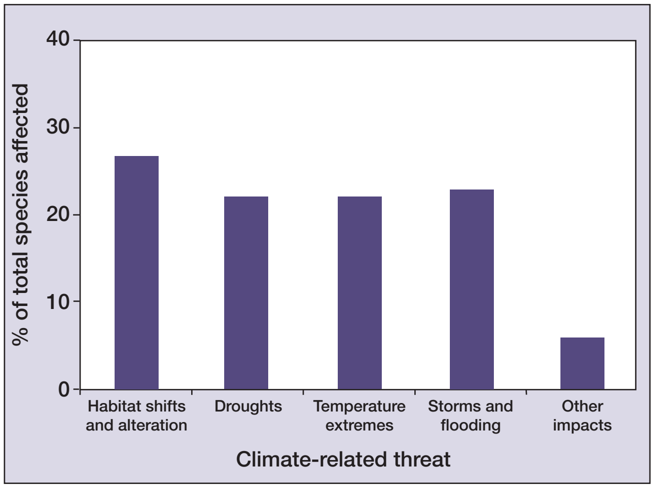

Figure 2. *Distribution of climate-related threats for 6030 terrestrial and aquatic species evaluated globally under the IUCN Red List of Threatened Species. There may be overlaps in threat categories, and this evaluation does not represent cumulative and synergistic impacts of other environmental and anthropogenic stressors; therefore, results should be interpreted with caution (IUCN 2012).*

Given the rate and magnitude of changes already underway, adaptation for biodiversity conservation will increasingly need to focus on managing – rather than resisting – change, and sustaining ecological and evolutionary functions as opposed to maintaining historical patterns of species assemblages (West *et al.* 2009; Stein and Shaw 2013). There is also growing recognition of the requisite not only to adjust management strategies in light of climate change but also to reconsider and, as appropriate, modify underlying conservation goals. Stein *et al.* (2013) provide a review of the emerging field of climate adaptation with respect to biodiversity and ecosystem conservation. Adopting adaptive management approaches will be particularly important given the uncertainties associated with future climate scenarios, as well as the ecological and human responses to these changes. Managers will similarly be faced with addressing near-term conservation challenges, but doing so in ways that are consistent with longer term climate adaptation strategies.

Coordinated monitoring to support research and policy

Broader and more coordinated monitoring efforts across all institutions are necessary to support biodiversity research, management, assessment, and policy.

More and more, resource managers require tools that project the impacts of climate change on biodiversity. Yet, a lack of biological time series observations across genetic,

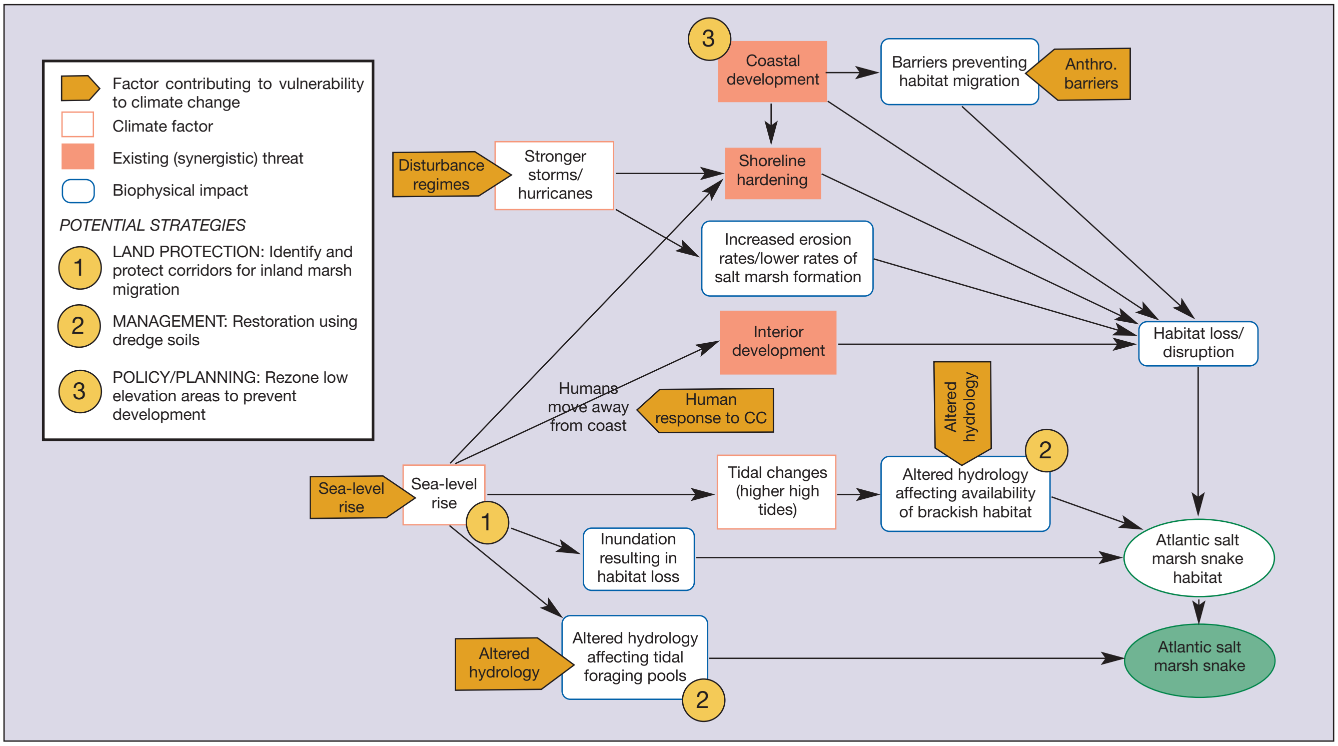

Figure 3. *Conceptual model illustrating how climate-change vulnerability assessments can be used to inform potential conservation strategies for priority species. Understanding how different factors relate to anticipated changes in climate and other conservation threats affecting viability provides a basis for linking conservation strategies to climate-related impacts on the species. The conceptual model shows a limited set of factors that were identified by species experts for the Atlantic salt marsh snake (*Nerodia clarkii taeniata*) in Florida (Dubois* et al. *2011).*

organismal, and ecosystem scales undermines new techniques using modeling frameworks to forecast ecological change. Currently, climate observations and other environmental time series greatly outnumber commensurate biological observations, though a few notable datasets have augmented our understanding of how biodiversity is responding to climate-change impacts (eg North American Breeding Bird Survey, USA National Phenology Network, the US Forest Service Forest Inventory and Analysis Program; see WebTable 2 for additional information).

New technologies and approaches, ranging from genetic techniques to the airborne and satellite remote sensing of entire ecosystems or biomes, are becoming more prevalent. These tools have improved scientists' ability to detect, observe, and forecast biological and evolutionary responses to climate change across a range of spatial and temporal scales, and also provide new insights into how past climate change has affected modern biogeography (Sandel *et al.* 2011; Swatantran *et al.* 2012). These new genetic and remote-sensing techniques reinforce the importance of historical biological datasets. For example, information on previous conditions is crucial for comparisons with the two to three decades of remotely sensed environmental information now available (eg in Earth Observing System Data and Information System; also see WebTable 2). While these new approaches are gradually being adopted by natural resource managers, many techniques still need to be made user-friendly to be incorporated into their daily operations (Danner *et al.* 2012).

The integration of physical climate models with ecological, habitat, and population responses is urgently required, particularly by natural resource managers who are tasked with assessing vulnerability, gauging adaptation strategies, or attributing changes in biodiversity to climate or other stressors (Jones *et al.* 2010; Dawson *et al.* 2011). Assembling temporally rich datasets requires databases and data networks that organize, make accessible, and archive observations. Furthermore, these networks should foster the development of standardized data collection and analysis protocols as well as the use of key metrics and indices of biodiversity status. There are numerous federal, state, and other (eg municipal, nongovernmental, and private-sector) efforts within the US that monitor biodiversity across different scales (eg genes, species, communities), and a growing number of facilities offer various types of biodiversity information (Figure 4). Nonetheless, gaps in coverage remain, and there is no coordinated nationwide monitoring program within the US that addresses the wide-reaching impacts of climate, or any other driver of change, on biodiversity. These limitations affect our ability to track the impacts of climate change on biodiversity and understand how biodiversity is/is not responding to change across different scales.

Ongoing efforts to address the coordination of biodiversity observations globally include the Group on Earth

Observations Biodiversity Observation Network, which aims to integrate regionally and taxonomically focused biodiversity networks around the world and to promote the management and accessibility of biodiversity data (Scholes *et al.* 2012). In addition, the Intergovernmental Platform on Biodiversity and Ecosystem Services seeks to establish an international policy framework and assessment regime for biodiversity and ecosystem services between the scientific community and policy makers (Perrings *et al.* 2011). Although these new international efforts are encouraging, a review of current systems, preferably conducted by natural resource managers, is still necessary to identify gaps and key indicators so that monitoring systems can help to protect and manage biodiversity in a rapidly changing climate.

■ Conclusions

The key messages presented here and in Staudinger *et al.* (2012) are consistent with those from previous assessments (eg USGCRP 2009); however, the amount of evidence and the level of expert consensus has grown considerably over the past few years, thereby providing a more comprehensive view of the ways that biodiversity has responded to climate change, and is expected to respond in the coming decades. Assessments provide an overview of the current state of knowledge and guide strategies to resolve risk and uncertainty within the discipline. Therefore, to help guide conservation practitioners and policy makers, we conclude with an overview of key knowledge gaps and future research needs.

Ecologists have long recognized that biodiversity plays an important role in ecosystem function, persistence, and services, but the specific functional or interactive roles of particular species or groups are often poorly understood. As a result, our ability to predict responses to the synergistic impacts of climate change and other stressors, as well as consequences to the societal benefits that biodiversity supports, remains limited (Cardinale *et al.* 2012; Mace *et al.* 2012). The degree to which organisms will tolerate new conditions imposed by climate change will vary widely, and scientists cannot yet predict the extent to which phenotypic plasticity, evolutionary adaptation, and nongenetic parental effects will facilitate adaptive responses. Basic and applied research that advances the understanding of physiological, behavioral, and ecological mechanisms that produce differential responses among species, regions, and systems is essential; these data are critical to informing monitoring priorities, improving modeling approaches, and assisting strategic decision making by natural resource managers seeking to identify vulnerable species and to reduce biodiversity loss.

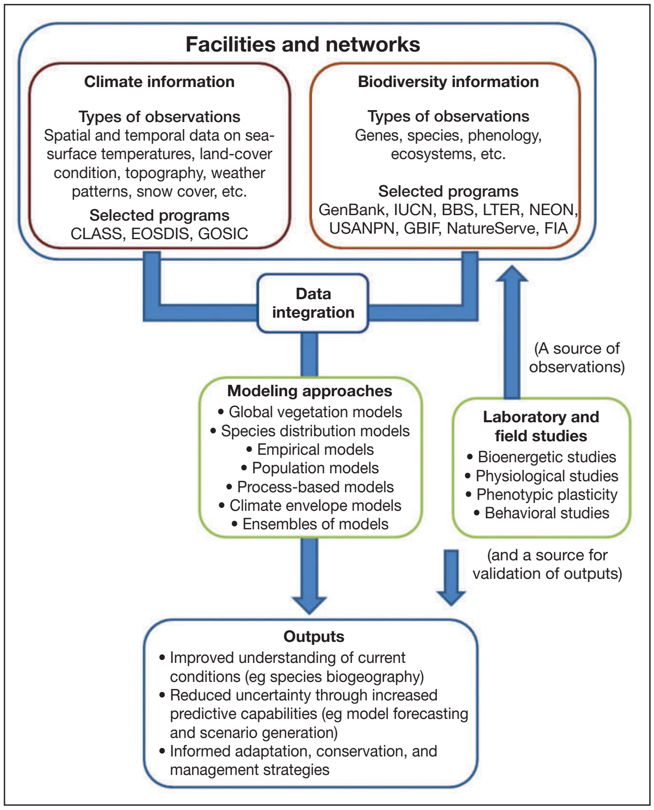

Figure 4. *Conceptual diagram showing how existing facilities and networks that organize and archive climate, land-cover (eg from airborne and satellite remote sensing), and biodiversity (in situ sensors such as camera traps, bioacoustic recorders, and animal tracking devices) observations need to be integrated to inform regional- and global-scale questions on how climate change is impacting ecological systems. See WebTable 2 for additional information.*

Models are central to forecasting future biological responses and vulnerabilities to climate change but are currently limited in their treatment of many biotic interactions (eg competition), dispersal abilities, and evolutionary processes (McMahon *et al.* 2011). These shortcomings can lead to over- or underestimations regarding the ability of species to track climatic changes (Schloss *et al.* 2012) and thus generate inaccurate estimates of potential extinction rates (Maclean and Wilson 2011; Urban *et al.* 2012). New modeling efforts are progressively incorporating variables that previously were unaccounted for (Cheung *et al.* 2009; Kearney and Porter 2009; Stock *et al.* 2011).

Without better observational and empirical data regarding which environmental drivers and biological responses influence shifts in biodiversity and alter ecological interactions, improvements to model performance is limited. For instance, there is strong agreement among researchers that trophic mismatches (ie disruptions in interactions between dependent species) have negative implications for ecosystem processes, ecosystem services, and the capacity for climate-change adaptation (Miller-Rushing *et al.* 2010; Thackeray *et al.* 2010; Yang and Rudolf 2010); however, time series of most observational data and empirical studies are insufficient to attribute and predict changes in species relationships and the emergence of novel interactions or community assemblages. Detecting and tracking changes in biological responses requires additional baseline data to evaluate trends, as well as better coordination among landscape-level monitoring programs to support decision making.

To effectively respond to the impacts of climate change on biodiversity, natural resource managers and policy makers must embrace approaches that are flexible and can account for multiple uncertainties stemming from variability in climate projections (eg precipitation patterns), impacts and responses across regions and ecosystems, and unknowns associated with the relative vulnerabilities and resiliencies of populations and habitats (Pereira *et al.* 2010; He and Hubbell 2011). There is also an increased demand for collaboration between scientists and managers to ensure that science adequately meets the needs of managers. Scientists should engage managers during the planning phase of research projects and develop final results (eg reports, articles) that present key findings with clear links to recommended conservation actions. Finally, examples of effectively implemented climate-change adaptation strategies (Stein *et al.* 2013) that successfully reduce vulnerabilities, improve resilience, and facilitate change across all aspects of biodiversity, associated ecosystems, and services should be documented in real time and shared across institutions.

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