Ecosystems and biodiversity have long been threatened by natural and anthropogenic stressors (MA 2005; Mooney et al. 2009). A stressor is an activity or phenomenon that induces an adverse effect and therefore degrades the condition and viability of a natural system (EPA 2008). The stressors that have most damaged natural systems fall into four general categories: (1) land-use and land-cover change ([LULCC], including habitat fragmentation and degradation, urbanization, and infrastructure development), (2) biological disruptions (introduction of non-native invasive species, diseases, and pests), (3) extractive activities (such as fishing, forestry, and water withdrawals), and (4) pollution (including chemicals, heavy metals, and nutrients). The combined impacts of these stressors are estimated to have altered more than 75% of Earth’s ice-free land (Ellis and Ramankutty 2008) and virtually all reaches of the world’s oceans (Halpern et al. 2008).

Climate change has emerged as a new and increasingly important threat to natural systems (Mooney et al. 2009). Climate change is a stressor in its own right, and it interacts with these other stressors in complex ways. Here we present a conceptual framework of climate interactions with other stressors, survey and categorize current knowledge about the intersection of climate change and these stressors, highlight potential interactions under future climate scenarios, and discuss the implications for developing effective response strategies.

In a nutshell:

- Climate change is projected to be an increasingly important source of stress for ecosystems, both directly and through complex interactions with other stressors.
- Ecosystems that are already stressed due to habitat loss, extraction of natural resources, biological disturbances, and pollution are likely to be affected more quickly and severely by climate change.
- Understanding the complex interactions between climate change and other stressors will be essential in designing effective strategies for adapting to climate change.
- Climate adaptation and mitigation strategies may create new and sometimes unforeseen stresses on ecosystems, as well as introducing novel interactions with existing stresses.

Ecosystems and biodiversity have long been threatened by land-use and land-cover change, extraction of natural resources, biological disturbances, and pollution. These environmental stressors have been the primary source of ecosystem degradation to date, and climate change is now exacerbating some of their effects. Ecosystems already under stress are likely to have more rapid and acute reactions to climate change; it is therefore useful to understand how multiple stresses will interact, especially as the magnitude of climate change increases. Understanding these interactions could be critically important in the design of climate adaptation strategies, especially because actions taken by other sectors (e.g., energy, agriculture, transportation) to address climate change may create new ecosystem stresses.

ecosystems. In natural systems that are relatively undisturbed by human activities, climate change may increase susceptibility to additional environmental stresses. Human responses to climate change may further complicate these relationships, presenting additional and novel sources of stress.

Figure 1a highlights four pathways illustrating how a single climatic change and a single stressor can affect species, populations, or ecosystems. Figure 1b illustrates these pathways in the example of native salmon populations affected by the climatic stressor of temperature increases and the existing stressor of non-native salmonid encroachment. The pathways are as follows:

(i) Climate change can directly affect species, populations, and ecosystems. In this example, climate-induced increases in stream temperature have a direct, negative impact on native salmon (Battin et al. 2007).

(ii) Climate change can affect a pre-existing stressor and therefore have an indirect impact on the species, populations, and ecosystems. For instance, projected increases in water temperatures may also favor non-native, more temperature-tolerant trout species (Wenger et al. 2011), thus indirectly increasing competitive pressures on native salmon.

(iii) Climate mitigation or adaptation actions may directly affect the ecosystem. For example, farmers may respond to higher temperatures by increasing irrigation, thereby decreasing streamflow and degrading fish habitat.

(iv) Climate mitigation or adaptation actions may indirectly affect the ecosystem. In this case, as increased irrigation depletes in-stream water, the remaining water will warm more rapidly, further favoring non-native salmonids.

Normally there will be multiple climatic changes and multiple additional environmental stressors, making it much more challenging to identify and categorize interaction pathways. Figure 2 illustrates more pathways for climate and other stressors to affect salmon in California’s Central Valley. However, even this figure is not inclusive of all the possible interactions; for example, each environmental stressor can interact with any of the other stressors, and there may be interactions involving multiple stressors.

These pathways can be further organized by recognizing the different types of interactions among stressors. These interactions may be additive, such that the effect of multiple stressors equals the sum when each acts alone, or they may be nonlinear, so that the combined impacts have a different effect than the sum of the individual contributions (Brook et al. 2008). The existence of an additional stressor most often exacerbates the impact of a single stressor (i.e., synergistic), although there are some cases in which a stressor can be antagonistic and will ameliorate the effects of other stressors (Folt et al. 1999). Most studies do not specify whether particular interactions are additive, synergistic, or antagonistic.

Climate change can also affect the character of a separate environmental stressor, specifically by affecting the timing, spatial extent, or intensity of the effects of that stressor. In California’s Central Valley, for instance, increased incidence of drought may affect the timing of water withdrawals for irrigation, causing them to take place earlier in the season, for a longer duration, or with increased frequency (Figure 2; Fischer et al. 2007). In contrast, warmer stream temperatures are facilitating greater encroachment of non-native fishes, which threatens native frogs in the Sierra Nevada (Knapp et al. 2007); this is an example of an impact on the spatial extent of a stressor. If new climate conditions benefit an existing pest or invasive species, increasing the effects of competition or predation on native species, then this is a case of climate change affecting the intensity of a stressor.

\[ \text{Figure 1. (a) General conceptual diagram of the pathways by which a single climatic change and another environmental stressor may affect a species, population, or ecosystem. A climatic change can (i) have a direct effect as a stressor in its own right, (ii) interact with another environmental stressor to either increase or decrease the effect of that stressor, (iii) induce a climate mitigation or adaptation response that has a direct effect, or (iv) induce a climate mitigation or adaptation response that interacts with another environmental stressor. (b) Application of the conceptual diagram to a specific example for native salmon populations. This example considers the combined effects and interactions between climate warming and the environmental stressor of non-native salmonids.} \]
Interactions of climate change with specific stressors

Climate change is already interacting with other environmental stressors to affect biodiversity and ecosystems. While the literature on the direct effects of climate change on species, populations, and ecosystems (pathway [i] in Figure 1a) has grown extensively in recent years (Grimm et al. 2013; Staudinger et al. 2013), less attention has been devoted to understanding and quantifying the interactions among climatic changes and other environmental stressors (pathway [ii] in Figure 1a). In this section, we summarize the current state of knowledge about these interactions, focusing on the four major categories of environmental stressors identified above: LULCC, extraction of natural resources, biological disturbances, and pollution. Figure 3 illustrates examples of species affected by the interaction of climate change with each of these categories of stressor.

Land-use and land-cover change

Widespread LULCC in the US has affected the amount, configuration, and quality of habitat and has altered hydrological and climatic regimes (Tilman et al. 2001). Habitat loss, degradation, and fragmentation are leading causes of terrestrial biodiversity loss, impairment of ecosystem functioning, and associated declines in ecosystem services (IPCC 2007; Krauss et al. 2010).

Climate change is likely to interact with LULCC in ways that further exacerbate these detrimental effects. For example, a recent meta-analysis of empirical studies found that biodiversity was more likely to be negatively affected by habitat loss in areas where precipitation rates have changed (Mantyka-Pringle et al. 2012). One empirical study of butterflies in the Sierra Nevada of California showed that both habitat loss and climate change had likely contributed to declines in species richness (Forister et al. 2010). The rapid disappearance of the green salamander (Aneides aeneus) from the southern Appalachians of the US has been attributed to changes in temperature coupled with the salamander’s limited ability to disperse in landscapes modified by logging, resort development, and dams (Corser 2001).

Only a few studies have explicitly projected future effects on species and ecosystems caused by the interactions between LULCC and climate change. Jetz et al. (2007) projected substantial range shifts for ~4.5–10% and ~10–20% of 8750 land bird species by 2050 and 2100, respectively; climate change was the primary driver of range contractions in temperate regions, whereas LULCC was the primary driver in the tropics. Similarly, the combined effects of LULCC and climate change are projected to bring about a loss of 7–24% of vascular plant diversity relative to 1995 by 2050, with climate change becoming a more important driver in the second half of this century (Van Vuuren et al. 2006).

Land surfaces are major reservoirs of carbon (C), so LULCC could be a major driver of climate change if associated activities lead to more greenhouse-gas releases; alternatively, it could help mitigate future climate change if such activities help store or return C to the land surface (IPCC 2007). Actions such as clear-cutting or replanting major tracts of forests can also affect local weather patterns and the resulting potential capacity for biomass storage of C (Dale et al. 2011). As such, modifications to land use and land cover intended to address climate mitigation or climate adaptation may in turn interact with existing stressors or might directly affect species, populations, and ecosystems (via pathways [iii] and [iv] in Figure 1a).

Extraction of natural resources

Natural resources can be important ecosystem goods. However, their extraction can cause severe stress to species and ecosystems. Climate change can exacerbate these stresses, particularly if it further reduces the supply of a harvested resource. For example, a sufficient population growth rate in targeted fish species is one factor relevant to limiting fishery overexploitation. However, changes to the physical environment, such as water temperature, can affect individual growth, survival, and reproduction rates, and thereby rates of population replacement (Jonsson and Jonsson 2009). Likewise, water withdrawals combined with climate change are projected to have major effects on freshwater fish; for instance, Xenopoulos et al. (2005) projected that 25% of rivers

![Figure 2. Conceptual diagram of the combined effects of and interactions among multiple climatic changes, climate adaptation actions, and other environmental stressors on native salmon in California's Central Valley. The colors correspond to those used in Figure 1.](image-url)
could lose more than 22% of fish species by 2070 due to the combined effects of increased water withdrawal and climate change. For three out of the four rivers examined in the US, the combined effects of climate change and water withdrawal were notably greater than the effect of climate change alone (Xenopoulos et al. 2005).

Resource extraction may also make ecosystems more vulnerable to climate change. The overharvesting of forests, for example, has the dual effect of causing local environmental damage that can decrease the resilience of an ecosystem to climate change and potentially compounding the magnitude of climate change itself by releasing stored C into the atmosphere (Hansen and Hoffman 2011). Furthermore, deforestation can lead to local warming and reductions in rainfall that can exacerbate climate impacts (Lawrence and Chase 2010). Despite the predominantly negative interactions between natural resource extraction and climate change, some interactions could have a positive impact or might make new resources available; for example, retraction of ice cover and earlier thaw in spring may result in new fishing grounds in arctic regions. In some cases, forest harvest can result in localized cooling, countering climate-induced increases in air temperature (Gibbard et al. 2005). One study found higher levels of butterfly diversity adjacent to irrigated fields, suggesting that irrigation may mitigate the water-limitation effects of climate change in ecosystems adjacent to agricultural fields (González-Estébanez et al. 2011).

**Biological disturbance**

Biological disturbances include invasion by non-native species that have a competitive advantage, allowing them to spread rapidly; emergence of pest species that have expanded their range or are better able to survive milder winters; and disease outbreaks, whether novel, reoccurring, or introduced. Climate change will likely affect the severity, timing, and location of biological disturbances, as well as limiting the ability of the ecosystem to recover following such an event.
Climate change is expected to exacerbate the impacts of many introduced plant and animal species. Evidence suggests that some of these species have already responded to recent changes in the atmosphere and to climate (Walther et al. 2009), and future changes are likely to increase the ranges of several invasive plant species across the US (Bradley et al. 2010), potentially expanding their impact. In particular, changes in fire regimes will affect interactions among native and non-native species (Keith et al. 2008). Extreme climatic events that stress or kill native species are thought to temporarily increase communities’ susceptibility to invasion (Díez et al. 2012); these events are projected to become more frequent with climate change. Although climatic changes may have strong effects on species ranges in the future, changes in the extent of different habitat types within a region have the potential to exert as much or more influence over the abundance of some invasive plant species (Ibáñez et al. 2009).

Climate change is also affecting the geographic ranges and virulence of many pests, pathogens, parasites, and disease vectors, and enhancing their ability to spread. For example, climate-induced habitat change has expanded the range of fungal pathogens that cause amphibian mortality (Pounds et al. 2006). The near-epidemic spread of pine bark beetles in western US states (Bentz et al. 2010) and the northward expansion of the oyster diseases “MSX” and “dermo” to Nova Scotia (Ford and Smolowitz et al. 2010) and the northward expansion of the oyster diseases “MSX” and “dermo” to Nova Scotia (Ford and Smolowitz et al. 2010) may also be linked to climate. On the basis of an assumption of a 2°C warming and changes in precipitation, Benning et al. (2002) found that extant Hawaiian honeycreepers may be driven to extinction through the combined effects of climate change, introduced avian malaria (spread by introduced mosquitoes), and historical land-use changes. As warming continues, hemlock woolly adelgids (Adelges tsugae), insect pests that have killed many eastern hemlocks (Tsuga canadensis) in recent years, are likely to expand their ranges northward (Dukes et al. 2009). Climate-change impacts on pests may have cascading effects: projected increases in temperature could increase the frequency and severity of insect outbreaks, and the resulting increase in tree mortality may in turn promote wildfires.

Forecasting changes in impacts from pests, pathogens, or invasive plant species is often fraught with uncertainties beyond those associated with forecasting climate change alone; often, too little is known about the climatic tolerances or responses of the species of concern to make confident projections under a given scenario (Dukes et al. 2009). Indeed, climate change may not always increase the net impact of introduced species, and some have argued it could be associated with the decline of pathogens, vectors, and hosts (Lafferty 2009). In areas that become climatically suitable for a new pest, pathogen, or host, other factors – such as competition, physical barriers, or predation – may still limit its range. Furthermore, climate change may reduce climatic suitability for a species or induce other habitat changes that are less favorable to its spread (Slenning 2010).

Pollution

Climate change may magnify the adverse environmental effects of pollutants, including metals, pesticides, organic material, nutrients, endocrine disruptors, and atmospheric ozone (O₃; Hansen and Hoffman 2011). It also alters temperature, pH, dilution rates, salinity, and other environmental conditions that modify the availability of pollutants, the exposure and sensitivity of species to pollutants, and the transport patterns, uptake, and toxicity of pollutants (Noyes et al. 2009).

Climate change is affecting where and when pollutants are found in the environment. For example, changes in transport patterns, such as currents, wind, and river flows, may enable environmental pollutants to accumulate in new places, exposing biota to risk in different habitats. Some contaminants thought to be diminishing in concern, such as polychlorinated biphenyls, are being remobilized in the environment as a result of climate change. Persistent organic pollutants, deposited in glaciers during the period of heavy use in the mid-20th century, are now being released due to climate-induced ice melt (Blais et al. 2001). Adélie penguins (Pygoscelis adeliae) in western Antarctica, for example, have continued to bioaccumulate DDT over the past 30 years, most likely via DDT release from melting glaciers (Geisz et al. 2008). Altered pH can make heavy metals more biologically available in aquatic systems, thereby increasing their impact on the environment.

Climate change is also intensifying the effects of some pollutants. Rising temperatures, for instance, can enhance exposure to metals by increasing the respiration rates of fish (Ficke et al. 2007). Higher temperatures resulted in greater mortality rates in metal-exposed ectotherms in 80% of the cases examined, largely associated with increased biological uptake and accumulation of metals (Sokolova and Lannig 2008). Higher temperatures can also exacerbate hypoxic conditions because warmer water holds less dissolved oxygen than cooler water and accelerates the bacterial decay of organic matter, which in turn consumes more oxygen (Rabalais et al. 2009). More frequent extreme rainfall events can further exacerbate hypoxia by increasing the runoff of nitrogen and phosphorus (P) into waterways.

Finally, climate change may cause increases in some pollutants, most notably ground-level O₃. Many regions of the world are projected to have higher O₃ concentrations by the end of the 21st century (Sitch et al. 2007). Few studies have examined the potential consequences of O₃ pollution for biodiversity, and predictions are confounded by interactions across trophic levels. However, reductions in wild plant productivity as a result of O₃ exposure suggest that climate-induced enhancement of O₃ concentrations could affect biodiversity (Wittig et al. 2009). Furthermore, ground-level O₃ damage will likely offset some productivity gains in plants due to rising
Implications for conservation, natural resource management, and research

Consideration of the multifaceted context in which biodiversity and ecosystems are being stressed will be critical for informing and prioritizing conservation strategies and natural resource management as climate change progresses. A failure to account for interactions may result in the implementation of climate adaptation strategies that are at best inefficient and at worst harmful. Fortunately, natural resource managers have considerable training and experience in addressing interacting environmental stressors; this institutional knowledge can be applied to climate adaptation strategies as well.

Reducing the impact of other stressors and increasing the connectivity of fragmented landscapes are already important components of most climate-change adaptation strategies (Stein et al. 2013). However, existing conservation actions to address non-climate stressors may no longer be sufficient to achieve desired outcomes (Hansen and Hoffman 2011), particularly if they do not address interactions among stressors and among potential response strategies. In many cases, available tools for responding to a particular stressor will need to be modified to incorporate the effects of climate change, as illustrated in Table 1. For example, there have been many suggestions regarding how to locate, design, and connect terrestrial reserves to accommodate new climatic conditions (Lawler 2009). Likewise, the regulations or policies that limit plant and animal harvest rates will probably need to be adjusted to reflect changes in distribution and abundance resulting from changing climates. In other

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<th>Table 1. Examples of how climate change interacts with other ecosystem stressors and options for modifying conservation and management strategies to facilitate climate-change adaptation</th>
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<td>Stress</td>
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<td>Disease</td>
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atmospheric carbon dioxide levels, thus reducing C storage on land and possibly contributing further to climate change (Sitch et al. 2007).

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cases, new management approaches might be required. For instance, past practices that typically allowed pine beetle (Dendroctonus spp) infestations to run their course have proven ineffective in recent years; the beetles propagated unchecked when the cold-weather conditions that typically regulate outbreaks failed to occur (Bentz et al. 2010).

The potential for maladaptive management strategies that address one stressor but exacerbate another is an additional factor in the effective stewardship of biodiversity and ecosystems in the context of climate change. As portrayed in our conceptual framework (Figures 1 and 2), climate adaptation strategies – for the benefit of either human or natural systems – can become new stressors themselves. Many of the tools used to control pests and disease outbreaks (eg pesticides), for instance, can have other adverse effects that may be compounded by climate change. Research is still needed to clarify how best to identify possible unintended consequences and reconcile different objectives.

A better understanding of the interactions between climate change and multiple environmental stressors will be essential for developing management strategies. There is only a nascent understanding regarding the precise pathways, types, and character of interactions. Yet, combinations of stressors will shape the ecosystems of the future. In particular, the presence of multiple interacting stressors increases the likelihood of broaching thresholds or tipping points that cause a system to rapidly shift to a new state. Future research should prioritize the development of analytical frameworks and tools to screen ecosystems for vulnerability, to model and identify critical thresholds, and to study interactions among climate and other stressors explicitly.

A critical barrier to investigating how multiple stressors interact is the lack of national networks that combine climate, biological, and stressor information, including explicit data on population structure and abundance for invasive, rare, imperiled, and other key species. Such networks would allow researchers to combine information on projected climate changes with species biological data to understand possible future range shifts, to consider how other environmental stressors would influence future species distributions, and to better attribute different impacts to climate change or other stressors. This more detailed understanding will be essential for developing effective natural resource management strategies that will mitigate the effects of a changing climate.

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