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Climate change: helping nature survive the human response

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Abstract

Climate change poses profound, direct, and well-documented threats to biodiversity. A significant fraction of Earth's species is at risk of extinction due to changing precipitation and temperature regimes, rising and acidifying oceans, and other factors. There is also growing awareness of the diversity and magnitude of responses, both proactive and reactive, that people will undertake as lives and livelihoods are affected by climate change. Yet to date few studies have examined the relationship between these two powerful forces. The natural systems upon which people depend, already under direct assault from climate change, are further threatened by how we respond to climate change. Human history and recent studies suggest that our actions to cope with climate change (adaptation) or lessen its rate and magnitude (mitigation) could have impacts that match—and even exceed—the direct effects of climate change on ecosystems. If we are to successfully conserve biodiversity and maintain ecosystem services in a warming world, considerable effort is needed to predict and reduce the indirect risks created by climate change.

Introduction

Climate change threatens biodiversity and ecosystem services both directly and indirectly. The direct effects of climate change, including changing precipitation and temperature, rising and acidifying oceans, and climate-driven losses of habitat, threaten a significant fraction of Earth's species with extinction (Parmesan & Yohe 2003; Thomas *et al.* 2004; IPCC 2007). This topic has received considerable attention, with hundreds of studies focused on quantifying the impacts of current and projected climate change on species and ecosystems. On the other hand, the indirect effects, which stem from the ways in which people respond to climate change, have received comparatively little attention in policy deliberations and scientific research. Yet the indirect effects of climate change may affect biodiversity and ecosystem services as

much or more than the direct effects of climate change alone.

Indirect effects will result from efforts to both mitigate and adapt to climate change (Paterson *et al.* 2008). Mitigation includes proactive steps taken to reduce atmospheric greenhouse gas (GHG) concentrations, such as the adoption of new energy sources or the protection of natural carbon sinks. Adaptation encompasses the steps that people take to cope with the disruptive effects of climate change on their lives, from the proactive (e.g., building seawalls in response to rising oceans) to the reactive (e.g., evacuation from flooded areas). Several recent high-level policy documents have recognized the need to increase planning for indirect effects, and have identified in particular the unintended consequences of large-scale mitigation efforts (e.g., Campbell *et al.* 2009; Berry *et al.* 2008; Secretariat of the Convention on Biological

Diversity 2009). Unfortunately, these newly recognized policy and planning needs have thus far received relatively little attention from scientific researchers. Peer-reviewed articles on indirect threats to biodiversity have focused primarily on habitat loss due to mitigation efforts such as dams and other forms of alternative energy development (Paterson *et al.* 2008). However, as people adapt to climate change across multiple scales, ranging from local to national and international, a wide range of new risks to biodiversity will emerge. Here, we explore the diversity and magnitude of the potential biodiversity impacts of both mitigation and adaptation (with particular focus on the latter) over a range of biomes and socioeconomic contexts, and discuss the research that is needed to guide policy and planning that can help both biodiversity and humanity cope with a warming planet.

Indirect impacts of mitigation

Attempts to mitigate climate change pose serious threats to biodiversity through habitat loss or alteration across broad spatial areas (Paterson *et al.* 2008). Many mitigation activities are already taking place and, in some cases, impacts on biodiversity have been quantified (Campbell *et al.* 2009; Berry *et al.* 2008; Secretariat of the Convention on Biological Diversity 2009). Renewable energy, for example, is integral to virtually every national or international strategy for curbing emissions, including plans to promote biofuels. However, rising U.S. ethanol production has been linked to losses of grassland habitats in the Conservation Reserve Program (Wilson *et al.* 2008), while booming demand for palm oil, including for use as a biofuel, spurred the clearing of more than 28,000 km² of Malaysia and Indonesia's megadiverse forests from 1990 to 2005, causing substantial declines in biodiversity (Koh & Wilcove 2008). Although the notion that converting tropical forests and grasslands to biofuel crops will generally decrease net carbon emissions has been debunked (Gibbs *et al.* 2008), reducing GHG emissions remains an oft-invoked justification for expanding biofuel production into these habitats.

Renewable energy development also focuses heavily on hydropower, which has the potential to avert 0.87 Gt of CO₂-equivalent GHG emissions by 2030 (IPCC 2007), but severely damages habitats within the vicinity of, and often far downstream of, dams (Totten *et al.* 2003; Paterson *et al.* 2008). Although China's Three Gorges Dam can produce over 22,000 MW of electricity, its 600-km² reservoir eliminated or fragmented habitats in the bio-diverse mountains of central China. The dam threatens at least 37 endemic plant taxa and 44 endemic fish species, and has displaced over 1 million people, creating fur-

ther pressure on biodiversity as new areas are transformed to support displaced agriculture (López-Pujol & Ren 2009). Elsewhere in Asia, the hundreds of dams being planned in Himalayan portions of Pakistan, India, Nepal, and Bhutan—a region long known as a biodiversity hotspot (Mittermeier *et al.* 2004)—will submerge natural ecosystems, damage fisheries, displace residents, and disrupt the timing, volume, and quality of river flows. A similar suite of impacts will likely follow in other areas important for biodiversity around the world.

Indirect impacts of adaptation

Historical examples of indirect impacts

The effects of climate change are not yet pronounced enough to have prompted an adaptation response in many parts of the world; thus, few substantive adaptation measures have been implemented to date (Campbell *et al.* 2009). However, throughout history, human responses to gradual and extreme environmental change have had a wide range of indirect impacts on biodiversity that may inform projections of future risk. For example, in the 8th–10th centuries, multiyear droughts likely forced the Mayan population to disperse away from major ceremonial centers, bringing agricultural expansion and forest clearing to a broader swath of Mesoamerica (Orlove 2005). The severe drought and “Dust Bowl” in the American Great Plains during the 1930s forced millions of people to resettle thousands of kilometers away. This large-scale population shift supported later agricultural expansion in California frontiers, while those who remained in the Great Plains responded by intensifying their agricultural practices, further exacerbating environmental degradation (Hansen & Libecap 2004). More recently, frequent droughts and high rainfall variability were significant factors in human migration into southern and western Burkina Faso in the late 20th century, as shown by one of the few quantitative investigations of the influence of climate and related environmental factors on migration (Henry *et al.* 2003). This population shift fueled a provincial-scale agricultural expansion that converted 13% of existing forests and savannas to croplands, with some localities recording natural vegetation losses of 50% (Paré *et al.* 2008).

History shows that adverse circumstances leading to scarcities of noncultivated resources can also harm biodiversity as people turn to alternatives. In Ghana, reductions in fish supply may have led to compensatory increases in the bushmeat trade (Brashares *et al.* 2004), a known driver of wildlife declines in Africa and other parts of the world. If important fisheries are diminished

by climatic change—as studies in West African fisheries suggest can happen (Zeeberg *et al.* 2008)—it may lead to analogous impacts on other terrestrial or marine species as struggling residents seek alternative protein sources.

Past and current human responses to water scarcity provide clues as to how people are likely to respond to climate-related impacts in the future. For example, in the American Southwest, decreasing water supplies coupled with rising populations have spurred efforts to transfer groundwater from riparian valleys in eastern Nevada to Las Vegas. The proposed infrastructure would involve over 100 wells, 500 km of pipeline, and substantial consequences for rare species and ecosystems (SNWA 2008). In Australia, the ongoing drought has prompted proposals for water pipelines that conflict with policies to maintain the ecological health of river systems (Bond *et al.* 2008). As changing climate alters freshwater availability around the world, governments and communities will divert water, build new dams, expand and intensify agriculture, or move settlements from water-stressed regions to less-developed areas, all actions that are likely to alter substantially the habitats and ecological processes on which biodiversity depends.

Examples of rapid environmental impacts may be most pronounced in human responses to sudden extreme events. Such events may prompt increased exploitation of natural sources of food, fuel, fiber, and other needs during emergency responses and reconstruction, as has happened during past natural disasters. Reconstruction from the Indian Ocean tsunami of December 2004, for example, damaged ecosystems in Indonesia's Aceh province in multiple ways: uncoordinated sand and gravel extraction from river channels altered freshwater flows and habitats, an unnecessary emphasis on burnt clay bricks as building material increased logging of forests for fuelwood, and siting of new housing without regard to environmental sensitivity threatened the biodiverse habitats of the Leuser-Ulu Masen area (UNEP 2007). As climate change increases the intensity of some types of extreme events (e.g., potentially droughts, cyclones, floods, fires in some regions; IPCC 2007), biodiversity is likely to be affected by both sudden and gradual human responses.

Yet in contrast to the earlier examples, recent history suggests that some indirect effects of adaptation can also be positive. One example involves the northern Sahel, where an observed vegetation recovery following the severe droughts that ended in the 1990s may be partially attributed to emigration (Olsson *et al.* 2005) spurred, in part, by the experienced climatic instability (Henry *et al.* 2003; Paré *et al.* 2008). Similarly, rural to urban migration in mega-diverse Latin America, caused by both economic and climatic events (e.g. Hurricane Mitch in Honduras), is allowing ecosystems (particularly montane forests) to

recover and native species to reestablish (Aide & Grau 2004).

Projecting future indirect impacts

Climate change is likely to spur the increasing deployment of adaptation measures within most, if not all, sectors of human endeavor, resulting in a range of potential impacts for biodiversity (e.g., Berry *et al.* 2008). Adaptation within the agricultural sector is likely to result in particularly pronounced consequences. According to climate models, regions that already host large undernourished populations, particularly South Asia and southern Africa, may experience substantial declines in staple crop productivity within two decades (Lobell *et al.* 2008). In southern Africa, for example, wheat and maize crop yields are projected to diminish 15%–28%. Long-term projections (through 2080) suggest that up to 60% of southern Africa's and 25% of China and India's currently cultivated land could experience declines in cereal production potential of 35% or more (Fischer *et al.* 2005). Biodiversity may suffer as humans adapt to declining food production and livelihood opportunities by appropriating natural habitats and water for crop cultivation and livestock production (e.g., Paré *et al.* 2008). If overall yield is reduced or curtailed due to climate change, priority areas for biodiversity conservation in and near agricultural landscapes may face increased risk of conversion to crops. We illustrate this scenario in Figure 1 using an empirical model to approximate future changes in an important South African wheat-growing region.

Climate change will produce increases as well as decreases in agricultural productivity. Important biodiversity areas that increase in suitability for agriculture due to climate change will likely face additional risk of conversion to cropland. Globally, nearly 7 million km²—an area almost the size of the world's remaining boreal forests—is projected to become newly suitable for agriculture by 2080 under a “business as usual” emissions scenario (Ramanakutty *et al.* 2002). For example, increasing winter temperatures could support cultivation of winter cereals in landscapes where frost risk was previously too high, such as alpine environments and parts of northern Europe or western Russia (IPCC 2007). Maize yield potential is projected to increase in high-elevation areas in East Africa (Thornton *et al.* 2009), overlapping substantially with an important biodiversity hotspot (Mittermeier *et al.* 2004).

More gradual effects of ongoing sea level rise—inundation, erosion, and soil and groundwater salinization—will threaten both human settlements and natural ecosystems in coastal areas. These threats are particularly acute in developing countries, where research

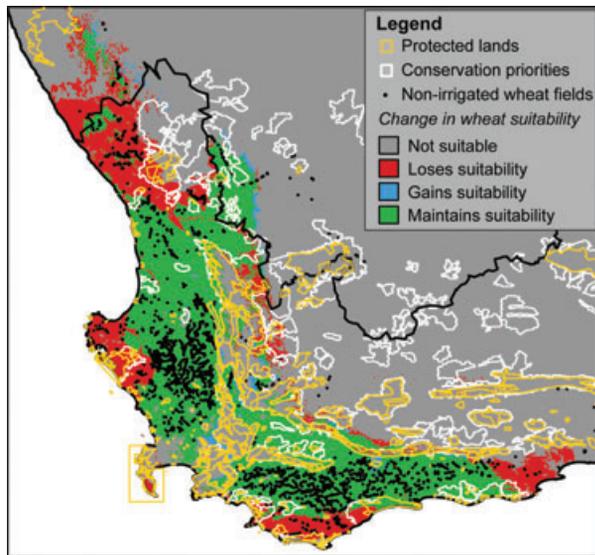


Figure 1 Projections of winter wheat yields in southwestern South Africa indicate challenges faced by biodiversity conservation as climate change alters crop suitability. Yields are projected to decline in much of the region (red). Maintenance of food production and livelihoods may increase pressure on protected areas (yellow) and conservation priorities identified within the conservation assessment for the National Protected Areas Expansion Strategy (white; S. Holness, unpublished data), particularly in areas that maintain (green) or gain (blue) suitability for wheat, and especially if projected declines in overall production create regional or national food crises. On the other hand, conservation and restoration opportunities may increase in the areas losing suitability. Black dots are wheat in cultivation in 2007–2008. Projected suitability is estimated from bioclimatic envelope models using Maximum Entropy and based on median 2050 projection of 10 general circulation models (IPCC 2007) under the B1 emissions scenario. Urban areas, mines, industrial land use, and topographically inappropriate or inaccessible areas are excluded. The median change affecting wheat is a 10% decrease in precipitation and 1.9 °C temperature rise. The model does not factor in the potential effects of elevated CO₂ on plant productivity.

needed to inform planning is scarce (Dasgupta *et al.* 2009). With inadequate planning, if just a fraction of the world's one billion coastal residents moved inland and began to clear land for agriculture, gather fuelwood, and hunt, the result would likely be substantial losses of biodiversity. A fifth of Earth's remaining tropical forests lie within a few days' walk (50 km) of human populations that could be inundated by a 1 m rise in sea level (Figure 2). Moreover, nearly half (259 of 524) of Alliance for Zero Extinction sites—forests and other habitats harboring the sole remaining population of one or more species (Ricketts *et al.* 2005)—lie within this zone. As risks to coastal communities mount, proactive attempts to reduce coastal threats, including construction of protective seawalls or other engineered projects,

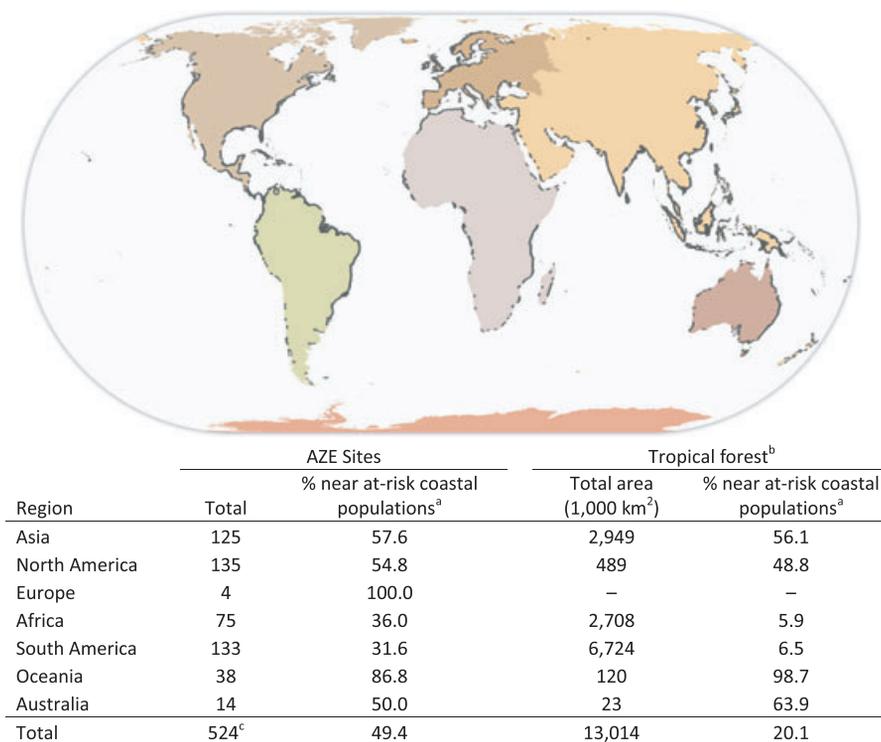
could themselves damage coastal ecosystems without appropriate planning (Dugan *et al.* 2008).

At the same time, positive results for biodiversity and conservation opportunities should also be expected and supported. As the aforementioned historical examples suggest, human adaptation to unfavorable climatic conditions will result in some land abandonment, creating opportunities for restoration and conservation of native habitat (e.g., red areas in Figure 1). Restoration opportunities may also arise from movement or retreat of non-native invasive species (Bradley *et al.* 2009). Reforestation with diverse indigenous species for purposes such as creating buffers from hurricanes and coastal erosion, or increasing carbon sequestration in the tropics, are likely to benefit biodiversity conservation (e.g., Campbell *et al.* 2009; Cowan *et al.* 2010).

Complex interactions

In today's connected world, human adaptation to climate change will have far-reaching effects, ricocheting between different biomes and affecting biodiversity through globally connected economies and markets. In 1972, an El Niño-induced collapse of the Peruvian anchovy fishery contributed to a boom in soybean production as a replacement livestock feed, resulting in substantial forest loss in Brazil (Brown 2005). Mitigation efforts such as expansion of biofuels can affect riparian and marine ecosystems far downstream. For example, fertilizer applied to corn grown for ethanol production in the American Midwest is increasing the nitrogen load of the Mississippi River. This nitrogen export, in turn, elevates the likelihood and extent of hypoxic events in the Gulf of Mexico, causing mortality in benthic marine communities and decline of fisheries (Donner & Kucharik 2008). Indirect harm can even arise from climate phenomena that appear beneficial to human interests. Declines in Arctic sea ice are permitting new shipping lanes and expanded oil and gas exploration, potentially resulting in an expansion of energy infrastructure, increased oil spill risk, and other impacts that could transform Arctic ecosystems and adversely affect marine mammals (Ragen *et al.* 2008).

Overall, historical accounts combined with current analyses and future projections suggest that biodiversity is likely to be undermined by a broad and complex array of human responses to climate change, absent the adoption of ecologically based approaches. Figure 3 presents a broad overview of these impacts based on our current understanding. These impacts derive from both proactive (Figure 3A and B) and reactive (Figure 3C–E) responses to climate change; attempts to mitigate climate change (Figure 3A) or adapt to its effects (Figure 3B, D



^aLying within 50 km of human population (>10 person/km²) that would be inundated by a 1 m rise in sea level.

^bAll forest land cover types within the tropics in a recent 500-m MODIS-based global land cover map (Friedl *et al.* 2010).

^cAlliance for Zero Extinction site boundaries have not been completely delineated. Those not delineated already were cross-referenced to existing polygon layers (e.g., protected areas, Important Bird Areas; F. Larsen, unpublished data). The total number of AZE polygons (524) differs from the original 595 sites (Ricketts *et al.* 2005) because some polygons contain more than one AZE site.

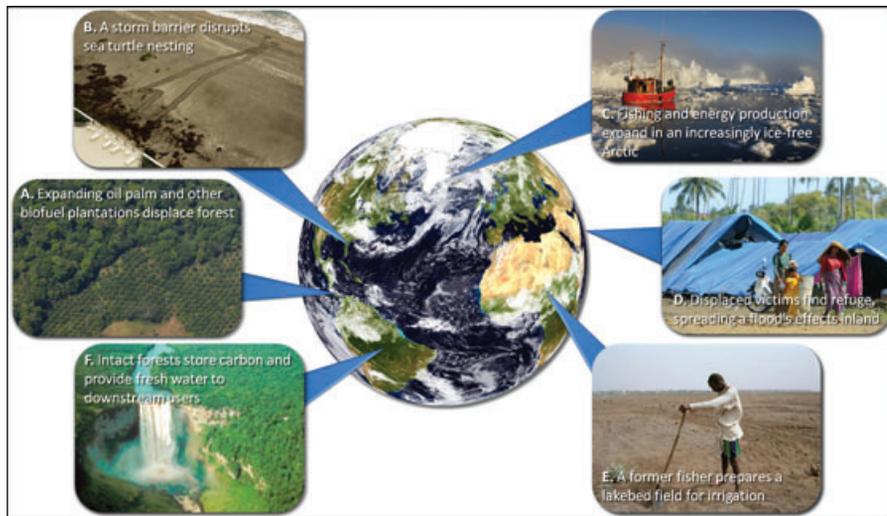
Figure 2 Sea level rise will stress human populations in close proximity to biodiversity. Roughly half of Alliance for Zero Extinction (AZE) sites and one-fifth of all tropical forest lie within 50 km (black area on map) of human populations that would be inundated by a one-meter rise in sea level.

and E); and responses to lost opportunities (Figure 3E) or to newly created opportunities (Figure 3C). Potential impacts can be greatly expanded based on location, type of change, and expected responses (Paterson *et al.* 2008; Berry *et al.* 2008; Secretariat of the Convention on Biological Diversity 2009). Collectively, projecting the nature and magnitude of indirect impacts will require substantial new research and monitoring.

Anticipating and avoiding indirect impacts

Climate change mitigation and adaptation are essential and inevitable; we must, however, ensure that these responses do not compromise the biodiversity and ecosystem services upon which societies ultimately depend. This will require coordinated, interdisciplinary research, and the implementation of ambitious new policies and actions

designed to prevent both the short- and long-term loss of biodiversity. Planners and policy makers will face difficult trade-offs between mitigation and adaptation efforts and biodiversity conservation (Paterson *et al.* 2008). Some actions, such as dams, may support adaptation and mitigation at a cost to biodiversity. Other actions could produce win-win scenarios, such as forest conservation measures supported by Reducing Emissions from Deforestation and Degradation (REDD). However, if inappropriately implemented, the same policies could create incentives that harm biodiversity, such as the promotion of afforestation of savannas and other lower carbon habitat through incentives that may eventually be provided by REDD (Putz & Redford 2009). The challenge is to integrate appropriate research into planning exercises so that negative indirect impacts can be anticipated, providing guidance toward a mix of approaches and places for mitigation and adaptation measures with less net harm to people and ecosystems.



Human response to climate change		Examples and biodiversity impacts
Mitigation	Hydropower	Dam construction floods upstream habitat and alters downstream sediments, temperature, flow regimes
	Biofuels	Expanded biofuel feedstock production displaces food crops, spurs forest clearing (A), promotes marine hypoxic 'dead' zones via nutrient runoff
	Geoengineering	Ocean fertilization disrupts marine food webs
	Afforestation	Naturally non-forest ecosystems converted to forest; diverse forests replaced with reduced-diversity tree plantations
Reactive adaptation	Coping with food shortage	Declines in crop, grazing, or fisheries productivity (E) lead to unplanned agricultural intensification, unsustainable groundwater extraction, exploitation of ecosystems for alternative macronutrient sources (e.g., bushmeat) or livelihoods (e.g., charcoal)
	Migration	Increasing natural disasters (e.g., droughts, flooding, storms) spur temporary or long-term settlement of human populations in new areas (D), unplanned use of habitats for timber, fuel, food, water
	Conflict	Competition for scarce resources (water, arable land) prompts migration, depletes supporting ecosystem services (e.g., freshwater water flows)
Proactive adaptation	Coastal defenses	Seawalls and other engineered barriers against storm surges, flooding, and coastal erosion alter or destroy coastal habitats and disrupt ecological processes (e.g., animal breeding, larval or adult dispersal; B)
New opportunities	New agricultural suitability	Increased crop suitability in some biodiverse areas promotes agricultural expansion and loss of natural habitats
	Arctic exploration and shipping	Decrease in extent and permanence of sea ice promotes increased exploration, shipping, and energy extraction in Arctic, disrupting marine ecosystems (C)
Ecosystem-based adaptation	Harnessing habitats as storm and flood buffers	As storm events increase in frequency or intensity, maintained or restored coastal habitats (e.g., mangrove forests, coral reefs) reduce storm surge impacts; inland habitats (e.g., forests, grasslands, wetlands) slow peak flows and reduce landslides under certain conditions
	Use of crop wild relatives	Conserved wildlands retain wild relatives of existing crops and novel cultivars, facilitating agricultural adaptation when changing temperature, precipitation patterns test physiological limits of current crops
	Maintaining freshwater flows	Maintenance and restoration of certain natural ecosystems help sustain clean and consistent freshwater flows that support downstream ecosystems and human communities
Ecosystem-based mitigation	Greenhouse gas storage/avoided emissions	Protection of carbon-rich ecosystems (e.g., forests, peatlands) prevent anthropogenic greenhouse gas emissions from habitat clearing or degradation (F)
	Greenhouse gas sequestration	Restoration of carbon-storing ecosystems (e.g., reforestation on degraded lands) or maintenance of high-sequestration habitats (e.g., seagrasses) remove atmospheric greenhouse gases

Figure 3 Diverse human responses to climate change, diverse impacts to biodiversity. Biodiversity may be harmed by a broad array of human responses to climate change, or it may be used to facilitate climate change mitigation and adaptation. (A) Rhett A. Butler/mongabay.com[©]. (B) Im-

age Quest Marine[©]. (C) Istockphoto[©]. (D) 3777190317/Shutterstock[©]. (E) Cédric Faimali / www.collectifargos.com[©]. (F) Conservation International[©]. We have acquired permissions for all images for this article.

For adaptation, given that land use change, primarily driven by agriculture, will likely continue to be the major driver of global habitat loss, models for projecting climate-induced changes to crop productivity will need to be refined, for example by filling gaps in our understanding of CO₂ fertilization effects (Tubiello *et al.* 2007). Understanding the extent to which local declines in water supply or food production can be offset (and consequent migration of resource-deprived people avoided) via efficient water use, fertilizers, genetically modified crops, drought-resistant cultivars, and other in situ actions is also essential, bearing in mind that many of these measures can themselves have environmental consequences if improperly implemented. If the biophysical models needed for this work are still inadequate, our understanding of socioeconomic dimensions lags even farther behind. Planning will also be aided by improving our ability to anticipate when, where, and why people move or change livelihoods in response to climate change, and better understanding of how these types of decisions are influenced by governance, land tenure, markets, and other factors. Meanwhile, evaluation of the threshold behaviors and complex interactions that are likely to emerge as the impacts of climate change cascade across coupled human and natural systems will require that increasingly sophisticated planning and predictive tools be developed, if we are to improve the resilience of these systems.

Climate change will be especially harmful to people in less-developed nations that lack the financial resources to devise and implement adaptation strategies. Further, human populations in developing nations are more directly dependent on local natural resources and ecosystem services, exacerbating their vulnerability in the face of environmental degradation driven by indirect effects. Assisting these countries and communities to minimize the negative environmental impacts of adaptation is a burden that should be shared among all nations. This burden could be lightened if calls to adopt ecosystem-based approaches, which integrate ecological goals with other development goals, are heeded (World Bank 2009; Cowan *et al.* 2010). Response plans for extreme weather events and refugee crises can ensure that crucial short-term efforts to secure human lives and livelihoods do not erode the biodiversity and ecosystem services upon which these same people ultimately depend for their wellbeing. As part of the solution, existing community-based and other adaptation efforts with minimal environmental impact could be supported, monitored, and, as needed, improved.

Climate is already changing, and governments and people are already implementing measures to mitigate emissions and, to a minor extent, to adapt to a new and

different world, with more of both in the offing. Appropriate guidance can minimize the impacts of these actions on biodiversity. On the policy side, parties to the UN Framework Convention on Climate Change (UNFCCC) can incorporate, in ongoing negotiations under the Ad Hoc Working Group on Long-term Cooperative Action (AWG-LCA), substantive text on how to plan for and avoid unintended consequences of climate change mitigation and adaptation. For example, UNFCCC parties widely supported a REDD+ mechanism designed to realize the mitigation benefits of REDD while reducing unintended impacts on biodiversity. REDD+ would include conservation safeguards to prevent conversion of natural forest habitat to plantation forestry. However, more work remains, including extending safeguards to nonforest habitat, before REDD+ is implemented. Similar guidelines and safeguards will be needed elsewhere if myriad other mitigation and adaptation activities are to avoid compromising biodiversity.

Way forward

The conservation of biodiversity and the amelioration of dangerous climate change are not inherently antithetical. Mitigation and adaptation policies that couple sustainable natural resource management with human development may offer the best possibility for positive ecological and societal outcomes (Ahmad 2009; World Bank 2009). These outcomes depend on considerably more guidance from, and research funding to, the scientific community. Fortunately, maintaining natural habitats, both in parks and working landscapes, is one of the most cost-effective and readily available approaches for mitigating climate change and facilitating human adaptation (Turner *et al.* 2009; Figure 3): intact marine and forest ecosystems sequester and store carbon and play critical roles in climate regulation; healthy mangroves and reefs dramatically reduce the impact of storm surges on coastal communities; forests, wetlands, and grasslands contribute to ample, clean, consistent water supplies for downstream communities and crops; and wildlands harbor untapped resources, such as the genetic diversity among wild relatives of crops, that can facilitate adaptation to a changing climate. Limiting the losses of biodiversity from climate change mitigation and adaptation actions will be critical to maintaining the ecological services upon which we and all other species depend. Increased research focus on the indirect effects of climate change, coupled with expanded support for biodiversity conservation, will ultimately lead to better policies and programs dealing with global climate change.

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