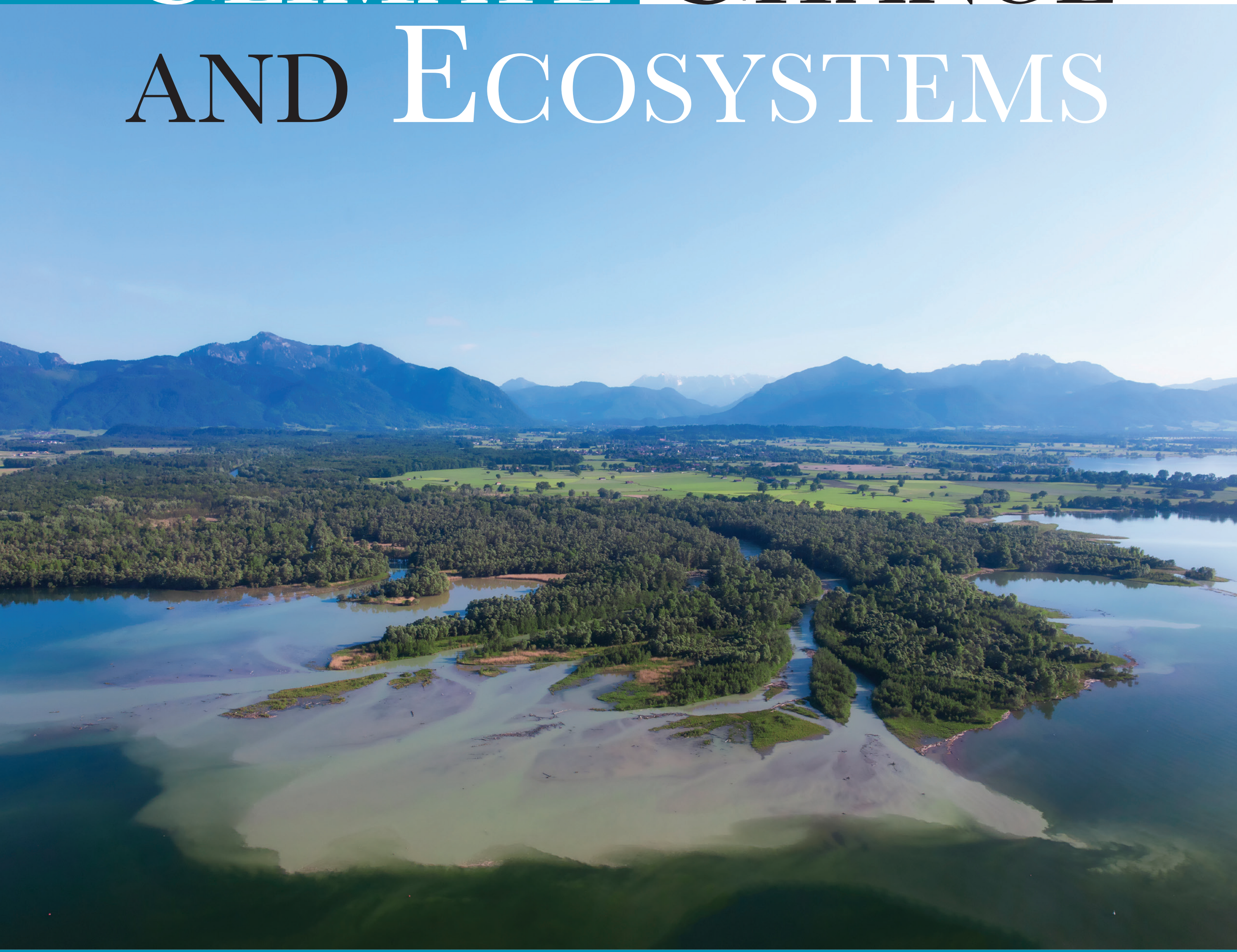
Climate Change and Ecosystems



NATIONAL ACADEMY OF SCIENCES

THE ROYAL SOCIETY

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Climate change is already having a dramatic effect on many ecosystems, leading to questions about what the future will bring. In recent years, plant and animal populations have changed much more quickly and drastically than anticipated, and there is evidence that the pace of change is accelerating. Researchers have grown increasingly concerned about the changes observed, especially in light of the many valuable services that ecosystems provide to human societies.

This state of heightened concern was the backdrop to the Sackler Forum on Climate Change and Ecosystems that was held in Washington, DC, on November 8-9, 2018. Jointly organized by the National Academy of Sciences and The Royal Society, the forum brought together leading scientists and practitioners in the fields of climate change, ecology, land use, and biodiversity who study terrestrial, marine, and freshwater ecosystems—research communities that do not commonly have opportunities to collaborate.

The forum had moments of both pessimism and optimism, and attendees recognized that the effects of climate change are context specific and could lead to negative, neutral, or positive outcomes. Climate change is posing widespread and complex challenges to species and to ecosystem function, as well as to associated services that natural systems provide to society. The forum highlighted current research frontiers such as the effects of climate extremes; interactions among climate and other stressors; the timing, sequence, and clustering of climate-related events; and tipping points for abrupt change. At the same time, society can adapt to altered conditions with the help of healthy ecosystems by using nature-based solutions to climate-related challenges. Greater understanding of ecosystems could reveal how they can best be managed to avoid the worst impacts of climate change. The forum highlighted that healthy, well-managed landscapes and seascapes have the potential to be part of the solution to the climate change challenge.

Although there is room for greater understanding, enough is known to take informed action now. Researchers at the forum demonstrated that they are reaching beyond their fields and taking responsibility for discussing, disseminating, and promoting their work to inform political and societal decisions. They are also going beyond identifying problems and are offering compelling solutions that can be widely implemented, with the potential to deliver broad societal benefits.

The Sackler Forum provides an opportunity for leading scientists, primarily from the United States and United Kingdom, to identify research opportunities, build multidisciplinary and international collaborations, and discuss how science can provide or inform solutions to pressing international problems. Few issues are as important for the future of human society and life on Earth as the past, current, and future interactions of climate change and ecosystems.

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ACKNOWLEDGMENTS

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This summary was developed based on the presentations and participant discussions at the 2018 Raymond and Beverly Sackler USA-UK Scientific Forum. It was prepared by Steve Olsson, April Melvin, and Sarah Giles, with assistance from Amanda Staudt and Emma Woods. The document was reviewed in draft form by the planning committee and underwent an external peer review by forum participants Nancy Grimm, Arizona State University, and Val Kapos, United Nations Environment World Conservation Monitoring Centre. Ruth DeFries, Columbia University, served as arbiter to oversee that external review comments were appropriately incorporated into the final version of this summary. Support for this activity was provided by the Raymond and Beverly Sackler Foundation.

NATIONAL ACADEMY OF SCIENCES

The National Academy of Sciences was established in 1863 by an Act of Congress, signed by President Lincoln, as a private, nongovernmental institution to advise the nation on issues related to science and technology. Members are elected by their peers for outstanding contributions to research.

THE ROYAL SOCIETY

The Royal Society is a self-governing Fellowship of many of the world's most distinguished scientists. Its members are drawn from all areas of science, engineering, and medicine. It is the national academy of science in the United Kingdom. The Society's fundamental purpose, reflected in its founding Charters of the 1660s, is to recognize, promote, and support excellence in science and to encourage the development of use of science for the benefit of humanity.

[1] National Academy of Sciences.

[2] Fellow of The Royal Society.

Ecosystems are composed of the plants, animals, people, and other living things that interact with the physical environment around us. We depend on ecosystems to provide food, clean water, air, and materials such as wood and fiber that are vital to everyday life. Ecosystems are also sources of human recreation, mental well-being and inspiration, and protection from natural hazards, while at the same time, support diverse sets of organisms. These many attributes make ecosystems a critical component of societal well-being and a healthy natural world. Currently, however, ecosystems are experiencing and responding to numerous human-induced stressors, with climate change among the primary concerns.

"The biosphere is a thin, living film on our planet that exists today only because living organisms that evolved on the planet play an active role in the Earth system."
—**Janet Franklin**, University of California, Riverside

Climate change is increasing air and water temperatures, altering precipitation patterns, intensifying many natural disturbances, affecting species distribution and survival, and changing ocean chemistry, among other impacts. These environmental changes are occurring concurrently with other pressures such as pollution, conversion of natural ecosystems to other land uses, transport and introduction of non-native species, and exploitation of natural resources. Together, these stressors threaten the contributions that species make to ecosystem functioning and the ability of ecosystems to sustain the many benefits—known as ecosystem services—that society has come to rely on.

The rapidity of the changes that are now being observed has raised many questions about ecosystem vulnerability, what future ecosystems will look like, and their long-term ability to sustain the same (or similar) services they provide today. In response to these concerns, researchers are working to improve understanding of the effects of climate change and how ecosystems respond to them, as well as to identify opportunities to manage ecosystems so that they can persist in the face of climate change.

Despite the increasing impacts of climate change, many natural ecosystems have demonstrated a strong ability to withstand and recover from (or be resilient to) climate change and other pressures. Such resilience is more likely when an ecosystem is generally healthy and retains much of its original species diversity, and it can be facilitated through management and conservation measures that utilize both traditional and innovative methods. Collectively, these approaches provide many opportunities to promote restoration and continued ecosystem health, but they also require careful consideration of risks, feasibility, costs, and other tradeoffs that may be necessary when making management decisions.

Ecosystems can also provide nature-based solutions, both for climate change mitigation and for helping society adapt to climate change and reduce the impacts of climate-related disasters. Ecosystems mitigate climate change by removing the heat-trapping greenhouse gas carbon dioxide from the atmosphere and storing it in biomass and soils on land or in phytoplankton, algae, and sediments in the oceans. Societies also adapt to climate impacts via the many benefits they derive from ecosystems. For example, coastlines can be protected from sea level rise, erosion, and storm surges by the presence of mangrove swamps and wetlands, while inland, erosion can be reduced and flood control increased through the presence of forests.

Research efforts to improve knowledge of nature-based solutions, expand measurement networks, and link natural, physical, and social sciences will advance our understanding of climate change and ecosystem interactions, as well as the societal impact of those interactions. At the same time, ecosystem research has already advanced to a point where it can inform management and policy decisions across a range of anticipated future scenarios. Scientists are already working with diverse groups of stakeholders and decision makers to share and develop this knowledge. These efforts have the goal of facilitating the adoption of best practices that promote ecosystem health and the utilization of nature-based solutions, thereby benefiting the ecosystems themselves and the human communities they support.

DEFINITIONS OF KEY TERMS

1. **Climate adaptation:** Adjustment in natural and human systems in response to actual or expected climate stimuli or their effects, which moderates harm or exploits beneficial opportunities.[a]

2. **Ecosystem services:** The benefits people derive from ecosystems. Examples include services or goods such as food, wood, and other raw materials; essential regulating services such as pollination of crops, prevention of soil erosion, and water purification; and cultural services, such as recreation and a sense of place.[b]

3. **Nature-based solutions:** Actions to protect, sustainably manage, and restore natural or modified ecosystems that address societal challenges effectively and adaptively, simultaneously providing human well-being and biodiversity benefits.[c]

4. **Resilience:** A capability to anticipate, prepare for, respond to, and recover from significant multi-hazard threats with minimum damage to social well-being, the economy, and the environment.[d]

[a] IPCC (Intergovernmental Panel on Climate Change). 2014. Climate Change 2014: Impacts, Adaptation, and Vulnerability. Contribution of Working Group II to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change. C. B. Field, V. R. Barros, D. J. Dokken, K. J. Mach, M. D. Mastrandrea, T. E. Bilir, M. Chatterjee, K. L. Ebi, Y. O. Estrada, R. C. Genova, B. Girma, E. S. Kissel, A. N. Levy, S. MacCracken, P. R. Mastrandrea, and L. L. White, eds. Cambridge, United Kingdom, and New York, NY: Cambridge University Press.

[b] See https://www.iucn.org/commissions/commission-ecosystem-management/our-work/cems-thematic-groups/ecosystem-services.

[c] See https://www.iucn.org/commissions/commission-ecosystem-management/our-work/nature-based-solutions.

[d] NRC (National Research Council). 2010. Adapting to the Impacts of Climate Change. Washington, DC: The National Academies Press. DOI: https://doi.org/10.17226/12783.

1 | Ecosystems Are Rapidly Changing

Ecosystems around the globe are rapidly changing in response to climate change and other human-induced stressors. Average global temperature has increased by about 1 °C (1.8 °F) since the industrial revolution, with much of this increase taking place since the mid-1970s,[3,4] and further increases expected if emissions of heat-trapping greenhouse gases continue. In October 2018, the Intergovernmental Panel on Climate Change warned that allowing the planet to warm more than 1.5 °C (2.7 °F) could have long-lasting and in some cases irreversible consequences for ecosystems and that this threshold will be passed by 2030 if current rates of warming continue.[5] In addition to rising temperatures, researchers are observing changes in precipitation patterns, the occurrence and severity of extreme events, species' behaviors, and the chemistry of the ocean, among other effects. Concurrently, ecosystems are being modified by a multitude of human-induced stressors, including resource extraction, habitat degradation and conversion, invasive species, and pollution.

Climate change and other pressures affect the health and function of ecosystems as well as the wide variety of species that live in them.[6] Changes are being observed on land, in freshwater systems, and in the ocean. The climate could be pushed into a different state

[3] NAS (National Academy of Sciences). 2014. *Climate Change: Evidence & Causes.* Washington, DC: The National Academies Press.

[4] IPCC. 2018. Summary for Policymakers. In: *Global Warming of 1.5°C. An IPCC Special Report on the impacts of global warming of 1.5°C above pre-industrial levels and related global greenhouse gas emission pathways, in the context of strengthening the global response to the threat of climate change, sustainable development, and efforts to eradicate poverty.* V. Masson-Delmotte, P. Zhai, H.-O. Pörtner, D. Roberts, J. Skea, P. R. Shukla, A. Pirani, Moufouma-Okia, C. Péan, R. Pidcock, S. Connors, J. B. R. Matthews, Y. Chen, X. Zhou, M. I. Gomis, E. Lonnoy, Maycock, M. Tignor, and T. Waterfield, eds. Geneva, Switzerland: World Meteorological Organization.

[5] Ibid.

[6] IPBES (Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services). 2019. *Summary for policymakers of the global assessment report on biodiversity and ecosystem services of the Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services.* Bonn, Germany: IPBES Secretariat. https://www.ipbes.net/news/ipbes-global-assessment-summary-policy makers-pdf, accessed August 2, 2019.

"Within a few decades, either we will be committed to a substantially warmer climate or we will have taken major actions to avoid such a climate. Ecosystems will play a major part in dealing with both scenarios."
—YADVINDER MALHI,
University of Oxford

by numerous competing processes once a threshold has been surpassed. In addition, gradual climate changes can cross thresholds or tipping points in both natural systems and human systems, leading to abrupt change[7] (see Box 1). The extinction threat for marine and terrestrial species is an example of a tipping point under way today. According to the World Wildlife Fund for Nature's Living Planet Report, released shortly before the forum, populations of vertebrate animals—including mammals, birds, and fish—declined by an average of 60% between 1970 and 2014 due to overexploitation, agriculture, and other forms of land conversion. Climate change is a growing threat to these populations.[8] These declines occurred in all bioregions, with the largest impacts occurring in the tropics. Other recent reports have also suggested large-scale declines of invertebrates.[9]

[7] NRC. 2013. *Abrupt Impacts of Climate Change: Anticipating Surprises.* Washington, DC: The National Academies Press. DOI: https://doi.org/10.17226/18373.

[8] WWF (World Wildlife Fund). 2018. *Living Planet Report 2018: Aiming Higher.* Gland, Switzerland: WWF.

[9] Hallmann, C. A., M. Sorg, E. Jongejans, H. Siepel, N. Hofland, H. Schwan, W. Stenmans, A. Müller, H. Sumser, T. Hörren, D. Goulson, and H. de Kroon. 2017. More than 75 percent decline over 27 years in total flying insect biomass in protected areas. *PLOS ONE* 12(10):e0185809. DOI: 10.1371/journal.pone.0185809.

BOX 1. TIPPING POINTS IN CLIMATE AND BIOSPHERE FUNCTION

Tipping points may occur when ecosystems are degraded to a point where they can no longer recover, such as following fires, storms, and other major disturbances. Impacts may be of relatively small scale, with population-level effects, or much more expansive, with climate system changes and ecosystem effects that are at least subcontinental in extent. Examples of potential climate and ecosystem tipping points are shown in Figure A. Tipping points are more likely as global average temperatures increase further, and the occurrence of one tipping point would make others more likely.

A major challenge for the research community is determining where, when, and why tipping points are most likely to occur.

Advanced warning of abrupt changes can be found in many complex systems. These warnings may manifest as a slower recovery from the same perturbation or disturbance as the ecosystem gets closer to a tipping point, such as in the case of corals that undergo repeated bleaching events. In other cases, impending tipping points may manifest as increasing fluctuations. For example, oceanic circulation models have been used to experimentally collapse the Atlantic Meridional Overturning Circulation (which includes the Gulf Stream), showing that fluctuations in the circulation slow down as collapse nears.[a]

Another major research challenge for understanding potential abrupt changes in ecosystems is to address the complexity introduced by multiple interacting drivers and disturbances, where spatial variation can dampen, amplify, or synchronize changes.

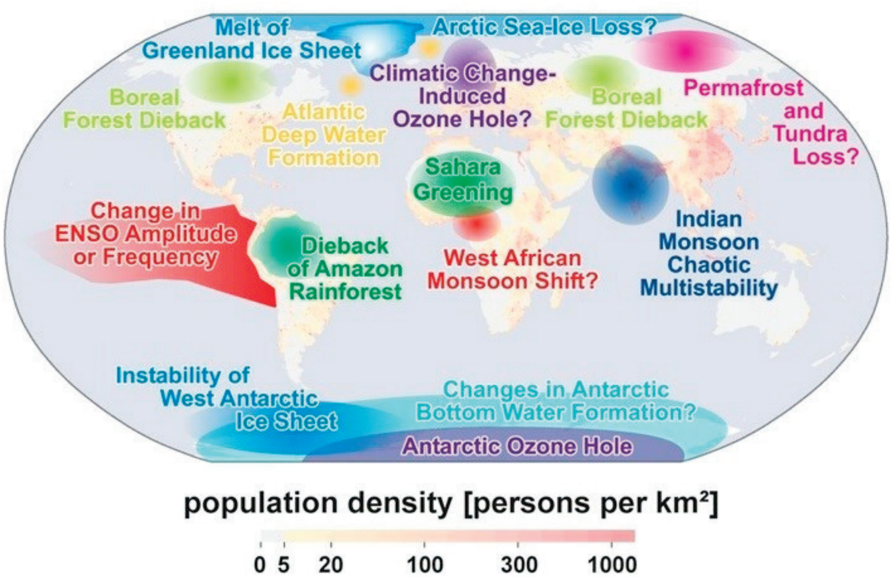

FIGURE A. Potential 21st-century climate and ecosystem tipping points linked to climate change. Question marks indicate systems where the existence of tipping points is especially uncertain. SOURCE: Potsdam Institute for Climate Research, https://www.pik-potsdam.de/services/infodesk/tipping-elements, accessed September 10, 2019.

[a] Boulton, C.A., L. C. Allison, and T. M. Lenton. 2014. Early warning signals of Atlantic Meridional Overturning Circulation collapse in a fully coupled climate model. *Nature Communications* 5:5752.

> *"We are seeing increases in observations of abrupt change in many ecosystems … these are big changes that are fast in time … they often surprise us … and this is a major challenge in contemporary ecology, but especially as we think about the effects of climate change."*
> —Monica Turner, University of Wisconsin–Madison

Changes to Terrestrial Ecosystems

Terrestrial ecosystems include areas of natural or semi-natural vegetation cover as well as areas that are more intensely managed, such as forest plantations, agricultural croplands, and urban and suburban areas. All of these ecosystems are vulnerable to impacts of climate change and other stressors, but they may vary in how they are affected due to the complex interactions among species, disturbances, and other factors. Human pressures such as landscape fragmentation can result in animal and plant species existing in more patchy environments than in the past, often in small populations. Such landscape fragmentation reduces species' capacity to migrate in response to climate change and other stressors.

Many terrestrial ecosystems are well adapted to long standing patterns of natural disturbances such as fires, storms, or periods of drought. However, increases in the frequency and intensity of these disturbances, as well as interactions with other factors such as climate variability, mean that events may recur before the system has a chance to recover from a previous disturbance. Furthermore, the effects of multiple events become synergistic and cause more stress than in the past. This can lead to abrupt loss of some of the ecological memory or adaptive capacity of the ecosystem, resulting in a rapid transition to a new ecosystem type or a mixture of species that differs from the pre-disturbance state. For example, in Yellowstone National Park,

fires are occurring more frequently and burning more severely such that fewer seeds remain to establish a new forest; seeds can be unable to reach all burned areas if a fire is large.[10] The present conditions under which the forest will regenerate also differ from their previous state because of climate change.

Complex relationships between climate change and species ranges have also been identified in the absence of major disturbances. For instance, many species have shifted northward and upslope as temperatures have increased. Recent research also shows that some species are shifting downslope and to the west or east in response to precipitation changes associated with climate change.[11] This new understanding suggests climate change has had a larger impact on species ranges than previously estimated and that future warming is likely to cause even greater effects.

Managed terrestrial ecosystems are also influenced by climate change and other stressors in complex ways. A globally predominant managed ecosystem type is agricultural land; about 11% of Earth's ice-free land surface was recently estimated to be cropland and about 22% pasture.[12] In general, agriculture is becoming more efficient, which should mean that less land is needed to produce the same yield. However, adoption of more efficient agriculture is not happening quickly enough to outpace the combined effects on demand of increases in human population and per-capita food consumption, so further conversion of natural ecosystems to agricultural land is occurring. Concurrently, climate change is threatening yields (see Figure 1), which could cause cropland expansion—primarily by converting natural ecosystems to agricultural production—with negative consequences for ecosystem services, such as reduced water quality, air quality, and biodiversity.[13] Nutrient loading or scarcity is an additional compounding factor in global agricultural patterns.

The linkage between climate change and agriculture is further complicated by the role that agriculture itself plays in driving further climate change. As a sector, agriculture (including soil and nutrient management and emissions from livestock), combined with

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[10] Turner, M. G., K. H. Braziunas, W. D. Hansen, and B. J. Harvey. 2019. Short-interval severe fire erodes the resilience of subalpine lodgepole pine forests. *Proceedings of the National Academy of Sciences of the United States of America.* DOI: 10.1073/pnas.1902841116.

[11] Fei, S., J. M. Desprez, K. M. Potter, I. Jo, J. A. Knott, and C. M. Oswalt. 2017. Divergence of species responses to climate change. *Science Advances* 3(5):e1603055. DOI: 10.1126/sciadv.1603055.

[12] Ramankutty, N., A. T. Evan, C. Monfreda, and J. A. Foley. 2008. Farming the planet: 1. Geographic distribution of global agricultural lands in the year 2000. *Global Biogeochemical Cycles* 22(1). DOI: 10.1029/2007gb002952.

[13] Molotoks, A., E. Stehfest, J. Doelman, F. Albanito, N. Fitton, T. P. Dawson, and P. Smith. 2018. Global projections of future cropland expansion to 2050 and direct impacts on biodiversity and carbon storage. *Global Change Biology* 24(12):5895-5908.

forestry and other land uses (e.g., wetland conversions and other managed lands), accounts for 24% of global greenhouse gas emissions,[14] meaning that these practices directly contribute to climate change, while also being impacted by it. At the same time, agricultural ecosystems can take up carbon dioxide from the atmosphere, which helps to mitigate climate change, and there is potential to increase this uptake (see Chapter 3).

PROJECTED IMPACT OF CLIMATE CHANGE ON AGRICULTURAL YIELDS

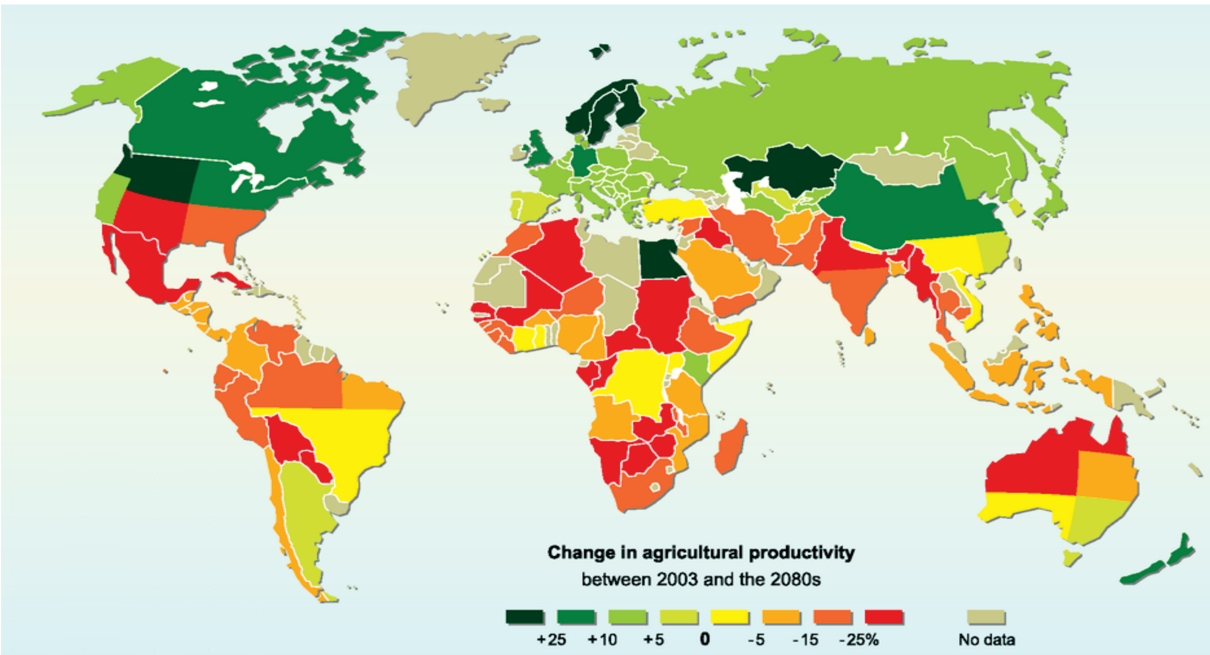

FIGURE 1. Projected impact of climate change on agricultural yields globally by the 2080s compared to 2003. This map includes consideration of carbon dioxide fertilization, whereby the elevated atmospheric carbon dioxide concentration enhances photosynthesis in some plants, including wheat, rice, and soybeans. Areas closer to the equator may see decreases in agricultural productivity because in general, temperatures there are already close to crop tolerance levels. Areas farther from the equator and those at higher elevations may see some increases in agricultural productivity.

SOURCE: Cline, W. 2007. *Global Warming and Agriculture: Impact Estimates by Country*. Washington, DC: Peterson Institute.

[14] Smith, P., M. Bustamante, H. Ahammad, H. Clark, H. Dong, E. A. Elsiddig, H. Haberl, R. Harper, J. House, M. Jafari, O. Masera, C. Mbow, N. H. Ravindranath, C. W. Rice, C. Robledo Abad, A. Romanovskaya, F. Sperling, and F. Tubiello. 2014. Agriculture, Forestry and Other Land Use (AFOLU). In: *Climate Change 2014: Mitigation of Climate Change. Contribution of Working Group III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change.* O. Edenhofer, R. Pichs-Madruga, Y. Sokona, E. Farahani, S. Kadner, K. Seyboth, A. Adler, I. Baum, S. Brunner, P. Eickemeier, B. Kriemann, J. Savolainen, S. Schlömer, C. von Stechow, T. Zwickel and J. C. Minx, eds. Cambridge, United Kingdom, and New York, NY: Cambridge University Press.

Changes to Freshwater and Marine Ecosystems

Water covers about 70% of Earth's surface and houses a range of saltwater (marine) and freshwater ecosystems. Only about 2.5% of this water is fresh, and most of that is in the form of ice, leaving a relatively small amount available for freshwater ecosystems. However, this small fraction of liquid freshwater harbors about 10% of the planet's known animal species[15] and supports critical ecosystem services, such as the production of a sustained clean drinking water supply. Both freshwater and marine systems are sources of food, transport, waste disposal, energy production, and protection for shorelines and coastal communities.

Freshwater Ecosystems

Abrupt and irreversible changes in the makeup and function of freshwater ecosystems are increasingly likely with climate change.[16] Many freshwater species have shifted their ranges,

[15] Dudgeon, D. 2014. Threats to Freshwater Biodiversity in a Changing World. In: *Global Environmental Change. Handbook of Global Environmental Pollution, vol 1*. B. Freedman, ed. Dordrecht, the Netherlands: Springer.

[16] IPCC. 2014. Summary for Policymakers. In: *Climate Change 2014: Impacts, Adaptation, and Vulnerability. Part A: Global and Sectoral Aspects. Contribution of Working Group II to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change.* C. B. Field, V. R. Barros, D. J. Dokken, K. J. Mach, M. D. Mastrandrea, T. E. Bilir, M. Chatterjee, K. L. Ebi, Y. O. Estrada, R. C. Genova, B. Girma, E. S. Kissel, A. N. Levy, S. MacCracken, P. R. Mastrandrea, and L. L. White, eds. Cambridge, United Kingdom, and New York, NY: Cambridge University Press.

> *"A lot is happening in the ocean, even in places that used to be so far away from us that we couldn't imagine having any impacts at all."*
> **—Nancy Knowlton,** Smithsonian Institution

behaviors, and interactions with other species. At the same time, climate change effects on temperature and precipitation can result in droughts that reduce connectivity across systems and heavy rain events that produce damaging floods. Freshwater systems also face many other threats, including pollution, dams, fishing, watershed modification, and invasive species. Even seemingly isolated riverine ecosystems, such as portions of Amazonia, are being affected by mining, deforestation, and the construction of dams.[17] Meanwhile, 4 billion people already face severe water scarcity, which may be further exacerbated by climate change.[18]

Marine Ecosystems

Marine ecosystems also face many threats from climate change. The number of heatwave days has increased dramatically in recent decades as the ocean has warmed, which has severely stressed organisms.[19] The ocean's oxygen content has also declined in many areas, creating inhospitable conditions for many species. In the open ocean, this oxygen decline is due to warming, whereas along coastlines it is caused by nutrient pollution from land sources that leads to eutrophication.[20] Increasing absorption of atmospheric carbon dioxide into the ocean is also causing acidification, which affects the ability of organisms to produce shells and hard skeletons. Along low-lying coastal areas, rising sea levels are causing extensive flooding that affects local ecosystems as well as communities living in these areas.

Among marine ecosystems, coral reefs have been and will continue to be particularly affected by warming temperatures and the growing risk of ocean acidification.[21] Coral bleaching events (in which corals expel the photosynthetic algae that live inside their tissues and become white in appearance) have become increasingly common, largely because of temperature extremes. Even if coral reefs do not die from a single bleaching,

[17] Castello, L., and M. N. Macedo. 2016. Large-scale degradation of Amazonian freshwater ecosystems. *Global Change Biology* 22(3):990-1007.

[18] Mekonnen, M. M., and A. Y. Hoekstra. 2016. Four billion people facing severe water scarcity. *Science Advances* 2(2):e1500323.

[19] Oliver, E. C. J., M. G. Donat, M. T. Burrows, P. J. Moore, D. A. Smale, L. V. Alexander, J. A. Benthuysen, M. Feng, A. S. Gupta, A. J. Hobday, N. J. Holbrook, S. E. Perkins- Kirkpatrick, H. A. Scannell, S. C. Straub, and T. Wernberg. 2018. Longer and more frequent marine heatwaves over the past century. *Nature Communications* 9:1324.

[20] Breitburg, D., L. A. Levin, A. Oschlies, M. Grégoire, F. P. Chavez, D. J. Conley, V. Garçon, D. Gilbert, D. Gutiérrez, K. Isensee, G. S. Jacinto, K. E. Limburg, I. Montes, S. W. A. Naqvi, G. C. Pitcher, N. N. Rabalais, M. R. Roman, K. A. Rose, B. A. Seibel, M. Telszewski, M. Yasuhara, and J. Zhang. 2018. Declining oxygen in the global ocean and coastal waters. *Science* 359(6371):eaam7240. DOI: 10.1126/science.aam7240.

[21] NASEM (National Academies of Sciences, Engineering, and Medicine). 2018. *A Research Review of Interventions to Increase the Persistence and Resilience of Coral Reefs.* Washington, DC: The National Academies Press. DOI: https://doi.org/10.17226/25279.

degraded reefs are more susceptible to subsequent disturbances compared to reefs that have not previously bleached.[22]

Marine ecosystems are also facing a large number of other threats. Since 1970, populations of more than 1,000 marine species have undergone declines of approximately 50%,[23] and considerable habitat losses have been observed in key ecosystems including mangroves, seagrasses, and coral reefs. Fisheries are unmanaged or poorly managed across much of the world, and declines in these systems continue in most regions. Marine ecosystems are also much more intensively used today than in the past for purposes beyond fishing, including energy generation, transport, mining, and waste disposal. Even the deepest regions of the ocean are now becoming at risk from human activities.[24]

[22] Hughes, T. P., K. D. Anderson, S. R. Connolly, S. F. Heron, J. T. Kerry, J. M. Lough, A. H. Baird, J. K. Baum, M. L. Berumen, T. C. Bridge, D. C. Claar, C. M. Eakin, J. P. Gilmour, N. A. J. Graham, H. Harrison, J.-P. A. Hobbs, A. S. Hoey, M. Hoogenboom, R. J. Lowe, M. T. McCulloch, J. M. Pandolfi, M. Pratchett, V. Schoepf, G. Torda, and S. K. Wilson. 2018. Spatial and temporal patterns of mass bleaching of corals in the Anthropocene. Science 359(6371):80-83. DOI: 10.1126/science.aan8048.

[23] WWF. 2015. *Living Blue Planet Report: Species, Habitats and Human Well-Being.* Gland, Switzerland: WWF.

[24] Danovaro, R., J. Aguzzi, E. Fanelli, D. Billett, K. Gjerde, A. Jamieson, E. Ramirez-Llodra, C. R. Smith, P. V. Snelgrove, L. Thomsen, and C. L. Dover. 2017. An ecosystem-based deep-ocean strategy. *Science* 355(6324):452-454.

2 Sustaining Ecosystems in the Face of Climate Change

Numerous approaches are being considered for sustaining ecosystems in the face of climate change. One option is to strengthen the natural ability of ecosystems to withstand or recover from (or be resilient to) pressures, or to adjust to new environmental conditions. For example, intact, extensive, and connected ecosystems have better prospects for resilience than do degraded ecosystems. Ecosystems that are generally healthy, with high (or intact) species diversity, are better able to naturally adapt to changes in their environment. For these reasons, many efforts to address current or anticipated climate impacts on ecosystems focus initially on traditional approaches to ecosystem conservation and restoration.

Increasingly, however, ecosystems' natural resiliencies are insufficient. The climate is changing more quickly than the ecosystems can. This situation is exacerbated when ecosystems are already degraded, in which case their natural adaptive capacity is compromised. In these cases, novel conservation measures are being considered to augment traditional approaches.[25] Many factors must be considered in determining the best strategy for sustaining ecosystems. Likewise, a diverse set of decision makers and stakeholders (e.g., ecosystem managers; local, state, federal, and international policy makers; and scientists) must be involved in the implementation of conservation practices.

Role of Established Conservation Practices in Climate Adaptation

The primary conservation strategies used to date have been in situ, meaning that actions are taken where the ecosystem is located. These approaches include ecosystem protection, establishment of reserves, and managing populations of target species within their existing ranges.

[25] Bennett, E. M., M. Solan, R. Biggs, T. McPhearson, A. V Norström, P. Olsson, L. Pereira, G. D. Peterson, C. Raudsepp-Hearne, F. Biermann, S. R. Carpenter, E. C. Ellis, T. Hichert, V. Galaz, M. Lahsen, M. Milkoreit, B. Martin-López, K. A. Nicholas, R. Preiser, G. Vince, J. M. Vervoort, and J. Xu. 2016. Bright spots: seeds of a good Anthropocene. *Frontiers in Ecology and the Environment* 14(8):441-448.

Studies have shown that implementing conservation on large scales is most effective. Greater ecosystem resilience to climate change is often conferred by large areas of intact and high-quality habitat, large species populations, high levels of reproduction, and connections among populations, which make in situ approaches an effective strategy in many instances. For marine ecosystems, one study suggested that protection of 30-50% of the ocean is needed to achieve biodiversity conservation, ecosystem connectivity, support for fisheries adjacent to protected areas, and other objectives.[26] Protected areas can also be a particularly powerful tool to rebuild depleted populations and to retain and repair habitats that have been degraded by climate change. In addition, designing a network of wildlife areas across a fragmented landscape could allow for easier movement of individuals, thereby helping them expand their range to accommodate changing climate conditions. For example, in California, the Quino checkerspot butterfly has exhibited resilience to climate change,[27] which is likely due to the protection of undeveloped land within both the traditional and expanding ranges of the butterflies. Such protection provided the butterflies several options for adjusting naturally to climate change.

"An immediate challenge is to characterize and separate the response of species and communities to periodic, stochastic, and/or cyclical natural variations from change imposed by long-term climatic forcing."
—**Martin Solan,** University of Southampton

Andrew Fisher, USFWS

[26] O'Leary, B. C., M. Winther-Janson, J. M. Bainbridge, J. Aitken, J. P. Hawkins, and C. M. Roberts. 2016. Effective coverage targets for ocean protection. *Conservation Letters* 9(6):398-404.

[27] Parmesan, C., A. Williams-Anderson, M. Moskwik, A. S. Mikheyev, and M. C. Singer. 2015. Endangered Quino checkerspot butterfly and climate change: Short-term success but long-term vulnerability? *Journal of Insect Conservation* 19(2):185-204. DOI: 10.1007/s10841-014-9743-4.

Some forum participants noted that other conservation strategies being used with increased frequency to address climate stresses on ecosystems include those that are ex situ and trans situ. Ex situ involves preserving biodiversity outside the naturally occurring ecosystem, for example in zoos, botanical gardens, and gene or seed banks. Trans situ includes the facilitated movement of species to new locations through such means as stepping stones, corridors, or physically moving organisms from one location to another. Ex situ and trans situ approaches are often used in concert with in situ approaches, as part of a holistic strategy to conserve a particular ecosystem or species.

Although conservation ethics and policies have largely discouraged facilitating movement of species to new location, these sorts of strategies may become increasingly important under a changing climate. For example, sustaining particular ecosystem services in a particular location may require plant or animal species with specific functional traits. If the species endemic to the area are severely endangered by changing local climate conditions, it may make sense to consider introducing exotic species with similar functional traits

into the ecosystem. One specific example is the case of several species of small-range water beetles whose distribution falls outside protected areas in the Iberian Peninsula.[28] Because water beetles are good surrogates of inland water biodiversity, managers might consider moving them to similar habitats in other areas of Europe (e.g., Pyrenees Mountains, Wales). However, such a strategy has not been implemented. Policy makers tend to view this as an issue for Spain to address given that these particular species of water beetles are endemic to the Iberian Peninsula.

Role of Genetics in Climate Adaptation

Adaptation occurs naturally within ecosystems when a species or interacting community of species can change sufficiently in response to an environmental change to cope with it. It can involve change within individuals and species, or changes in the composition of the community that still result in essential ecosystem attributes remaining intact. In general, the capacity to adapt is higher in healthy and intact ecosystems when compared to degraded or fragmented ones. Functional trait diversity—defined as the value, range, distribution, and relative abundance of the functional traits collectively present among organisms in a given ecosystem—can also facilitate adaptation when new recruits into an ecosystem (even if a different species) have similar functional traits to those that may be declining or lost.[29]

Some scientists are beginning to explore options for genetically modifying organisms to be more resistant to climate change impacts (see Box 2 for potential examples for coral reef ecosystems) or hybridizing native and invasive species. These approaches could promote the adaptive capacity of species that are under significant stress.

[28] Sánchez-Fernández, D., D. T. Bilton, P. Abellán, I. Ribera, J. Velasco, and A. Millán. 2008. Are the endemic water beetles of the Iberian Peninsula and the Balearic Islands effectively protected? *Biological Conservation* 141(6):1612-1627. DOI: 10.1016/j.biocon.2008.04.005.

[29] Díaz, S., S. Lavorel, F. de Bello, F. Quétier, K. Grigulis, and T. M. Robson. 2007. Incorporating plant functional diversity effects in ecosystem service assessments. *Proceedings of the National Academy of Sciences of the United States of America* 104(52):20684-20689. DOI: 10.1073/pnas.0704716104.

BOX 2. CORAL REEFS: AN EXAMPLE OF MANAGEMENT IN DYNAMIC ECOSYSTEMS

Coral reef ecosystems face climate change threats primarily from increasing water temperatures and ocean acidification.[a] To address these threats, ecosystem managers are exploring a range of conventional and novel management practices and considering the challenges associated with each.

Asexual propagation, where coral fragments are grown elsewhere and introduced onto reefs, is a commonly used practice designed to increase the number of corals on a reef to improve biodiversity, fish presence, and reef biomass, among other benefits. Research advancements in promoting sexual reproduction on reefs are being explored as well to increase coral populations. Methods for assisted evolution are also being tested, whereby researchers work to help corals adapt to climate change impacts by genetically increasing their resistance to stresses such as temperature and acidity.[b]

Efforts to reduce ocean acidity in reef ecosystems and increase reef growth are being evaluated at the local scale using seagrasses and other marine plants, as well as chemical remediation. Field studies have shown that cultivation of seagrasses can increase carbon uptake by the plants through photosynthesis, thereby reducing acidity,[c] while chemical remediation can reduce acidity through the introduction of chemicals such as calcium carbonate or sodium hydroxide that neutralize carbonic acid (the acid formed through the interaction of carbon dioxide and water).

To date, all of these approaches have only been tested at small scales; they would need to be implemented at much larger scales to be broadly effective, a challenging prospect in many cases. Additional research is needed to determine how these management strategies could be implemented more widely, what the costs and safety issues would be, and what interactions these approaches may have with other aspects of the ecosystems, including how well they cope with other stressors.[d]

[a] NASEM. 2018. A *Research Review of Interventions to Increase the Persistence and Resilience of Coral Reefs*. Washington, DC: The National Academies Press. DOI:https://doi.org/10.17226/25279.

[b] van Oppen, M. J. H., J. K. Oliver, H. M. Putnam, and R. D. Gates. 2015. Building coral reef resilience through assisted evolution. *Proceedings of the National Academy of Sciences of the United States of America* 112(8):2307-2313. DOI:10.1073/pnas.1422301112.

[c] Mongin, M., M. E. Baird, S. Hadley, and A. Lenton. 2016. Optimising reef-scale CO2 removal by seaweed to buffer ocean acidification. *Environmental Research Letters* 11(3):034023.

[d] NASEM. 2018. A *Research Review of Interventions to Increase the Persistence and Resilience of Coral Reefs*. Washington, DC: The National Academies Press. DOI:https://doi.org/10.17226/25279.

New Conservation Challenges in a Changing Climate

As ecosystems are increasingly stressed by climate change, ecosystem managers are facing new challenges in designing conservation strategies. For example, the primary objectives of a management plan could focus on individual species or the ecosystem a as a whole. If the primary objective is to keep the building blocks of biodiversity intact, it may be necessary to concentrate on species that are globally endangered rather than trying to maintain populations of organisms that could be significant locally but are not globally threatened. For climate adaptation, there are also outstanding research questions related to how scientists can identify species that may be unlikely to adapt naturally and whether trying to conserve them should be a priority, while recognizing their importance under other contexts.

Where particular ecosystems provide valuable ecosystem services, it might be advantageous to allow ecosystem change through shifts in species ranges, species composition, and even evolution. Alternatively, assisted transformation of species—for example, through genetic engineering or hybridization between native and invasive species—may allow ecosystems or species to be retained where they might otherwise be degraded or lost as a result of climate change. These types of actions can be controversial, however. For example, if a forest is drying out, should ecosystem managers allow species of dry forest trees to invade at the expense of established native species? Or should the forest be allowed to shift toward a more open, savanna-like biome? Additionally, if ecosystem managers and policy makers deem range expansion an appropriate management strategy, then cooperation across national or other borders may be needed, which could prove challenging if different groups or nations have differing objectives or priorities. This becomes more complicated in the oceans, where ranges can include international waters or cross transition zones (e.g., land to sea) where multiple authorities can have jurisdiction.

Finally, given that climate change is a global threat and many ecosystem types cover vast areas, the feasibility of implementing climate adaptation and conservation efforts at scales that can maximize ecosystem health and services is challenging, and risks associated with these practices at scale are understudied. At the same time, costs of implementation can be very high, even at small scales, and the objectives of one intervention in one part of an ecosystem may conflict with the objectives of another intervention in another part of the ecosystem. As such, it is important for the science community and decision makers to evaluate the balance between ecosystems services provided relative to the costs of management to make informed decisions about implementation.

3 Ecosystems as a Climate Solution

Nature-based solutions are actions to protect, sustainably manage, and restore natural or modified ecosystems. Such actions address societal challenges effectively and adaptively, simultaneously providing human well-being and biodiversity benefits.[30] These solutions can result in climate-related benefits such as increases in carbon storage or the avoidance of greenhouse gas emissions. Examples of nature-based solutions that provide climate benefits include reforestation, avoided deforestation, coastal wetland restoration, and agricultural soil management. As the importance of ecosystems in addressing the drivers and impacts of climate change has become better recognized, there has been increased attention to nature-based solutions and how they can be implemented to benefit society.

Ecosystems and Climate Change Mitigation

Ecosystems mitigate climate change by removing the greenhouse gas carbon dioxide from the atmosphere. In recent years, roughly a quarter of the carbon dioxide emitted by human activities (due largely to fossil fuel burning and land use change) has been taken up and stored in the plants and soils of terrestrial ecosystems.[31] In this way, ecosystems act as carbon "sinks." As greenhouse gas concentrations continue to rise in the atmosphere, some researchers are exploring ways to manage ecosystems to enhance these carbon sinks beyond the capacity they have exhibited in the past.

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[30] See https://www.iucn.org/commissions/commission-ecosystem-management/our-work-nature-based-solutions, (accessed September 11, 2019).

[31] Le Quéré, C., R. M. Andrew, P. Friedlingstein, S. Sitch, J. Hauck, J. Pongratz, P. A. Pickers, J. I. Korsbakken, G. P. Peters, J. G. Canadell, A. Arneth, V. K. Arora, L. Barbero, A. Bastos, L. Bopp, F. Chevallier, L. P. Chini, P. Ciais, S. C. Doney, T. Gkritzalis, D. S. Goll, I. Harris, V. Haverd, F. M. Hoffman, M. Hoppema, R. A. Houghton, G. Hurtt, T. Ilyina, A. K. Jain, T. Johannessen, C. D. Jones, E. Kato, R. F. Keeling, K. K. Goldewijk, P. Landschützer, N. Lefèvre, S. Lienert, Z. Liu, D. Lombardozzi, N. Metzl, D. R. Munro, J. E. M. S. Nabel, S. I. Nakaoka, C. Neill, A. Olsen, T. Ono, P. Patra, A. Peregon, W. Peters, P. Peylin, B. Pfeil, D. Pierrot, B. Poulter, G. Rehder, L. Resplandy, E. Robertson, M. Rocher, C. Rödenbeck, U. Schuster, J. Schwinger, R. Séférian, I. Skjelvan, T. Steinhoff, A. Sutton, P. P. Tans, H. Tian, B. Tilbrook, F. N. Tubiello, I. T. van der Laan-Luijkx, G. R. van der Werf, N. Viovy, A. P. Walker, A. J. Wiltshire, R. Wright, S. Zaehle, and B. Zheng. 2018. Global carbon budget 2018. *Earth System Science Data* 10(4):2141-2194. DOI:10.5194/essd-10-2141-2018.

Enhanced mitigation potential of many ecosystem types can be achieved through management practices that promote greater carbon uptake and storage. Recent efforts have explored this potential, along with the costs and risks associated with management across a wide range of ecosystem types, to determine feasibility of implementation at scales likely to have a measurable impact on climate change.[32,33]

Ecosystem management alone is not enough to address the challenge of rising carbon emissions, but it can play a significant role.[34] Research on carbon uptake

[32] NASEM. 2019. *Negative Emissions Technologies and Reliable Sequestration: A Research Agenda.* Washington, DC: The National Academies Press. DOI: https://doi.org/10.17226/25259.

[33] The Royal Society. 2018. *Greenhouse Gas Removal. London, United Kingdom: Royal Society.* https://royalsociety.org/-/media/policy/projects/greenhouse-gas-removal/royal-society-greenhouse-gas-removal-report-2018.pdf, accessed May 22, 2019.

[34] Anderson, C. M., R. S. DeFries, R. Litterman, P. A. Matson, D. C. Nepstad, S. Pacala, W. H. Schlesinger, M. R. Shaw, P. Smith, C. Weber, and C. B. Field. 2019. Natural climate solutions are not enough. *Science* 363(6430):933-934. DOI: 10.1126/science.aaw2741.

and mitigation presented at the forum suggested that a wide range of ecosystem types have the potential to increase carbon storage and/or avoid greenhouse gas emissions with conservation, restoration, and/or improved land management actions (see Figure 2).[35] Ecosystem management in this study includes reforesting areas where trees have been cut down, avoiding the conversion of forests to other land uses, and better management of natural forests. Increased carbon storage can also occur in agricultural systems, where better nutrient management may be the most cost-effective approach, and other practices (such as the addition of biochar) may have the greatest potential to improve carbon uptake and storage. In wetlands, protecting and restoring peatlands and coastal restoration may also provide improved, cost-effective carbon uptake. Coastal ecosystems such as seagrass beds, mangrove swamps, and salt marshes also act as significant carbon sinks, and ocean organisms act as a biological pump transferring carbon from surface waters into the deep ocean carbon sink.[36]

Throughout the forum, participants discussed the tradeoffs when making decisions to manage ecosystems for mitigation purposes. For instance, the production and use of biofuels with carbon capture and storage can have a negative impact on biodiversity and occupy large areas of land needed to grow food. The challenges of implementation at different scales and the influence of how those scales affect social issues (e.g., equity and jobs), political decisions, and institutional questions were also discussed. Key questions moving forward include "how can barriers be identified and overcome?" For further discussion, see Chapter 4.

[35] Griscom, B. W., J. Adams, P. W. Ellis, R. A. Houghton, G. Lomax, D. A. Miteva, W. H. Schlesinger, D. Shoch, J. V. Siikamäki, P. Smith, P. Woodbury, C. Zganjar, A. Blackman, J. Campari, R. T. Conant, C. Delgado, P. Elias, T. Gopalakrishna, M. R. Hamsik, M. Herrero, J. Kiesecker, E. Landis, L. Laestadius, S. M. Leavitt, S. Minnemeyer, S. Polasky, P. Potapov, F. E. Putz, J. Sanderman, M. Silvius, E. Wollenberg, and J. Fargione. 2017. Natural climate solutions. *Proceedings of the National Academy of Sciences of the United States of America* 114(44):11645-11650. DOI: 10.1073/pnas.1710465114.

[36] Boyd, P. W., H. Claustre, M. Levy, D. A. Siegel, and T. Weber. 2019. Multi-faceted particle pumps drive carbon sequestration in the ocean. *Nature* 568(7752):327-335. DOI:10.1038/s41586-019-1098-2.

CLIMATE MITIGATION POTENTIAL IN 2030 (PgCO^{2}eyr^{1})

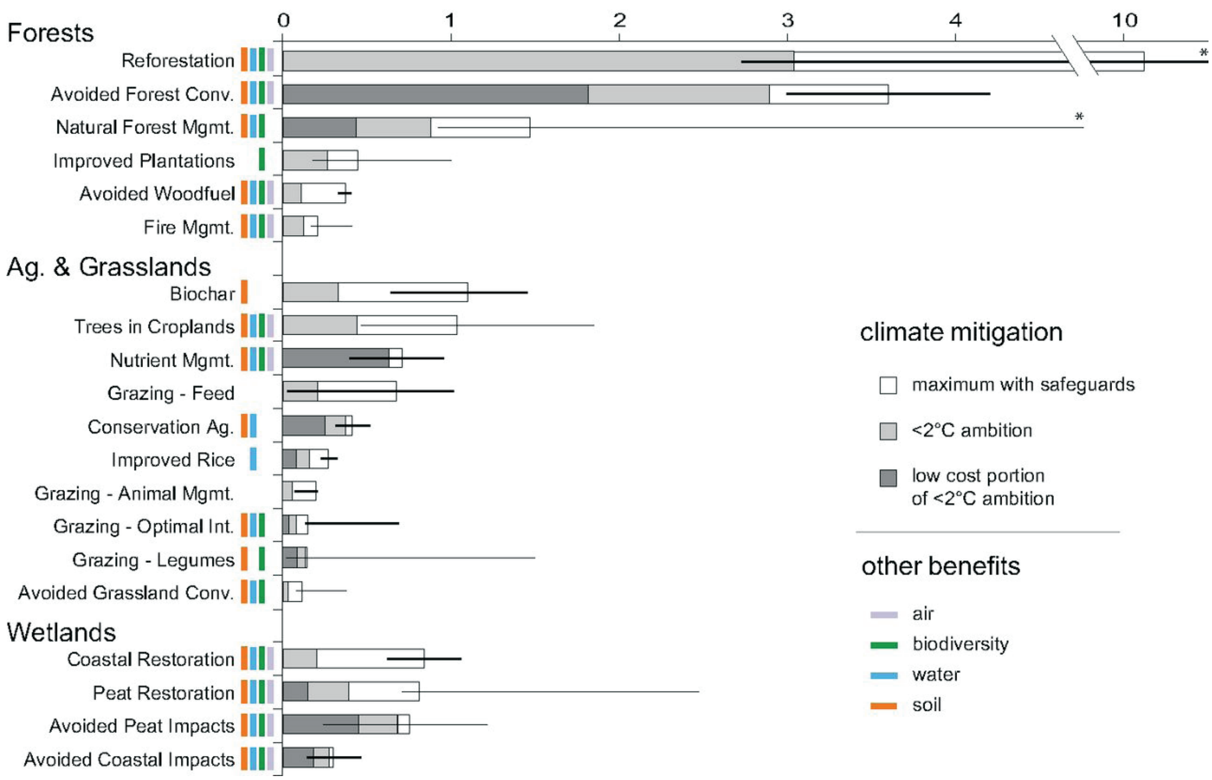
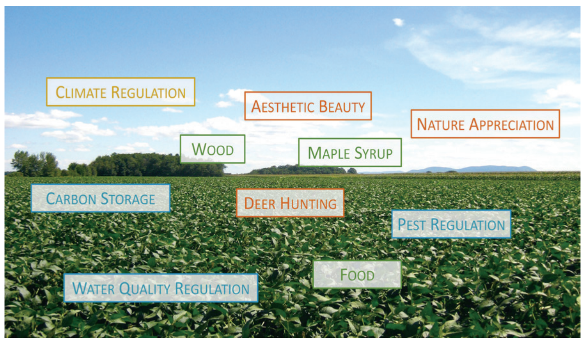


FIGURE 2. The maximum additional mitigation potential for natural pathways in the year 2030 considering differing degrees of climate mitigation (illustrated with gray shading). Ecosystem service benefits (listed as "other benefits") linked with each pathway are indicated by colored bars listed with each category on the left side of the figure.

SOURCE: Griscom, B. W., J. Adams, P. W. Ellis, R. A. Houghton, G. Lomax, D. A. Miteva, W. H. Schlesinger, D. Shoch, J. V. Siikamäki, P. Smith, P. Woodbury, C. Zganjar, A. Blackman, J. Campari, R. T. Conant, C. Delgado, P. Elias, T. Gopalakrishna, M. R. Hamsik, M. Herrero, J. Kiesecker, E. Landis, L. Laestadius, S. M. Leavitt, S. Minnemeyer, S. Polasky, P. Potapov, F. E. Putz, J. Sanderman, M. Silvius, E. Wollenberg, and J. Fargione. 2017. Natural climate solutions. *Proceedings of the National Academy of Sciences of the United States of America* 114(44): 11645-11650. DOI: 10.1073/pnas.1710465114.

Ecosystems and Societal Adaptation to Climate Change

Sustaining or expanding critical ecosystem services that foster human well-being can help society adapt to climate change. These nature-based solutions have often been considered at relatively small scales with unique goals in mind based on the services needed at a given location and the specific local climate change impacts.



Coastal and marine ecosystems are located at the frontlines of climate change effects related to sea level rise and shoreline impacts from increases in extreme weather. Healthy wetlands and coral reefs may be able to keep pace with sea level rise, providing low-cost coastal protection that is self-repairing (by maintaining a positive net accretion) while also supporting fisheries that can sustain human livelihoods. Coastal ecosystems can reduce wave energy, stabilize shorelines, reduce erosion, trap debris, and protect the productivity of inland areas. Coral reefs, kelp forests, seagrass beds, and mangrove swamps contribute to erosion control and storm protection, with additional benefits of preservation of cultural heritage, education, food production, and tourism.[37]

Working terrestrial landscapes can also be managed to provide multiple benefits. For example, in Monteregie, a suburbanizing agricultural region just outside Montreal, Canada, a multi-stakeholder partnership is working to prioritize and plan for future land uses and ecosystem service needs.[38] Benefits being considered include climate regulation, carbon storage, aesthetic beauty and nature appreciation, fuel wood, maple syrup production, deer hunting, pest regulation, water quality regulation, and food production. By understanding community needs and service options, planners can maximize benefits, understand the tradeoffs of the decisions they make, and ensure that resilience to future climate change can be incorporated into land use decisions.

Nature-based solutions that provide a biodiversity- based bio-economy are also being explored. In the Amazon, efforts are under way to provide viable value chains for products

[37] Gattuso, J.-P., A. K. Magnan, L. Bopp, W. W. L. Cheung, C. M. Duarte, J. Hinkel, E. Mcleod, F. Micheli, A. Oschlies, P. Williamson, R. Billé, V. I. Chalastani, R. D. Gates, J.-O. Irisson, J. J. Middelburg, H.-O. Pörtner, and G. H. Rau. 2018. Ocean solutions to address climate change and its effects on marine ecosystems. *Frontiers in Marine Science* 5(337). DOI:10.3389/fmars.2018.00337.

[38] Bennett, E. M., C. Albert, A. Ball, J. Cardille, K. Dancose, S. Delmotte, A. Gonzalez, H. Hui-Huang, M. Lechowicz, K. Liss, R. Kipp, D. Maguire, S. Mahajan, M. Mitchell, K. Teixeira-Martins, C. Raudsepp-Hearne, D. Renard, J. Rhemtulla, L. Taliana, M. Terrado, and C. Ziter. The Montérégie Connection: Understanding How Ecosystems Can Provide Resilience to the Risk of Ecosystem Service Change. *In Atlas of Ecosystem Services.* M. Schröter, A. Bonn, S. Klotz, R. Seppelt, and C. Baessler, eds. Cham, Switzerland: Springer.

derived from ecosystems such as food, nutraceuticals, cosmetics, fragrances, pharmaceuticals, and industrial oils. These efforts have a goal of creating a new sustainable development paradigm for tropical forests where the value of the ecosystems and attention to management may help to reduce ecosystem changes linked to climate change and human activities such as deforestation, mining, and dam construction.

"Solutions are going to have to be things that both improve human well-being and are good climate solutions." —Elena Bennett, McGill University

The utilization of nature-based solutions in cities plays an important role in societal adaptation to climate change. Some climate change impacts (e.g., hotter daily average and night-time temperatures, as well as extended heat waves, droughts, and flooding) are exacerbated in cities due to particular attributes of urban systems, such as the high impervious cover of cities, concentrations of waste heat and pollution, interdependent infrastructure, the concentration of people and infrastructure, and socioeconomic disparities. Nature-based solutions in cities include increased tree canopy cover, protection or restoration of streams, development of urban stormwater management structures, construction of green roofs and walls, increased area devoted to parks and open spaces, and restored coastal ecosystems to serve as protection.[39] In addition to the climate benefits of nature-based solutions in cities, these efforts can promote biodiversity, improved human mental and physical health, and other social benefits such as reduced crime and increased social cohesion.[40]

Because nature-based solutions can provide a range of different benefits based on selected management strategies, prioritization decisions will need to be made to maximize the most favorable services for the given situation or location. This could result in tradeoffs whereby some services cannot be met or other concessions need to be made. For example, vegetation can provide a variety of ecosystem services, but in some areas it can place demands on scarce water supplies. In some cases, climatic and other stressors, including extreme events, could eventually overpower nature-based solutions. This possibility will require that combinations of nature-based and engineered solutions—so called green-gray or hybrid approaches—be considered and implemented.

[39] Ziter, C. D., E. J. Pedersen, C. J. Kucharik, and M. G. Turner. 2019. Scale-dependent interactions between tree canopy cover and impervious surfaces reduce daytime urban heat during summer. *Proceedings of the National Academy of Sciences of the United States of America* 116(15):7575-7580. DOI:10.1073/pnas.1817561116.

[40] Engemann, K., C. B. Pedersen, L. Arge, C. Tsirogiannis, P. B. Mortensen, and J.-C. Svenning. 2019. Residential green space in childhood is associated with lower risk of psychiatric disorders from adolescence into adulthood. *Proceedings of the National Academy of Sciences of the United States of America* 116(11):5188-5193. DOI:10.1073/pnas.1807504116.

4 Advancing the Science While Moving to Action

Alongside continued research, it is already clear that enough scientific evidence is available now to support decisions and actions that promote ecosystem health, adaptive capacity, and mitigation potential and that augment options for societal adaptation to climate change.

Forum participants identified four strategies for advancing the science while moving into action:

- Research to advance understanding about the response of ecosystems to climate change and their potential role in mitigation and adaptation
- Communication of current knowledge to diverse audiences
- Development of interdisciplinary networks, particularly to incorporate financial drivers
- Translation of science to action

Research Priorities to Advance the Science

There is still much to be learned about how ecosystems will respond and adapt as climate change progresses, what optimal management and conservation practices will best facilitate resilience, and how to scale up nature-based solutions to climate change and other global challenges. Forum participants discussed the need to support interdisciplinary, sustained research and knowledge exchange networks, focusing on research questions related to the interconnections between climate, ecosystems, and human societies. Priority areas could include

- Understanding how complexity enhances ecosystem resilience
- Understanding how societal adaptation can be supported and enhanced
- Identifying the point at which restoration of an ecosystem is likely to fail as the climate warms
- Identifying early warning metrics and measurements
- Modeling complex socio-ecological systems
- Identifying the benefits and tradeoffs associated with ecosystem management

Expanded and modified data collection could also be undertaken. This could include increased measurements across different spatial and temporal scales that could help to tease apart dynamic processes that may not be captured with more limited or sporadic collection. Simplified but robust parameters to evaluate ecosystem health and change would also be useful and would form the basis of metrics for policy makers.

Communication to Diverse Audiences

Many researchers are motivated and excited to translate and communicate existing knowledge about ecosystems and climate change to diverse audiences of policy and decision makers, as well as other stakeholders. Understanding the makeup of stakeholder groups, their priorities, and considerations such as the economics underlying potential options may allow for constructive discussions that can inform actions. It may be appropriate to engage a range of stakeholders, including policy makers, business leaders, the media, communities, indigenous and migrant populations, and scientific groups. Boundary and communications organizations that provide expertise in sharing knowledge across diverse stakeholder audiences can also serve an important role in facilitating discussion and progress. Engagement will necessarily be iterative, as data and knowledge are communicated across disciplines and sectors, with recognition and balance given to the needs of this generation with those of the next.

"The climate challenge is about finding an accelerator pedal for action rather than transitioning from doing nothing to doing something."
—Chris Field,
Stanford University

Interdisciplinary Networks

Setting up an interdisciplinary network could include merging questions between different disciplines and/or applying multiple approaches to address a set of common questions. Broad inclusion of a range of perspectives—including those who benefit from the status quo, those who benefit from healthy ecosystems, and those who make decisions—could inform research questions and priority areas to help ensure that new knowledge can inform both short- and long-term goals and actions. Additionally, identifying and analyzing the financial agents and forces involved in ecosystem degradation, protection, and use could inform how to translate the science to action. For example, researchers could study how reputational rewards and other incentives related to ecosystems and climate can change behaviors. Research could also evaluate how ideas propagate through social systems to bend actions in desirable directions.

Translation of Science to Action

Many researchers in the ecosystem science community are actively working to translate and disseminate scientific knowledge to decision makers and other stakeholders in constructive, useful ways that can inform actions. As highlighted throughout this report, efforts to maintain and manage ecosystems can help mitigate the impacts of climate change while also sustaining or creating many other services that benefit communities around the globe. Therefore, conveying this information such that it can be used to implement environmentally sound decisions and policies is of great importance to scientists.

However, communication between scientists and decision makers can be challenging. In addition to translating information about ecosystem value and opportunities, other considerations should be kept in mind in order to facilitate productive conversations and knowledge exchange. For example, discussing the economics of ecosystem services and nature-based solutions is key to explaining tradeoffs, costs of management actions, and the importance of systems providing multiple benefits. The cost of nature-based solutions at scale will often be large (although some may be less costly than many engineered solutions), and the people and entities who can afford to pay tend to be those who profit from the current system. Economic considerations also lead to political questions, such as who receives the benefits and bears the costs of an option and how those that do not gain (or lose) direct benefits will be compensated. A lack of political will, regulatory authority, and public empowerment can also affect progress toward ecosystem management and implementation of nature-based solutions. Further, management actions not intended specifically for ecosystem services are often not aligned with long-term sustainability or the global good and may not be advantageous to local communities.

Additional barriers to action include the difficulty of undertaking efforts at larger scales and at times across national borders, the need to think and act on long-term problems, institutional and governmental inertia, and aversion to thinking about topics where some outstanding science questions remain, as is the case with ecosystem science.

Concluding Thoughts

Climate change is here, and within the next few decades, societies and ecosystems will either be committed to a substantially warmer world or major actions will be taken to limit warming to moderate levels. Ecosystems play a major part in both of these future scenarios. The complex responses to climate change can act as a buffer to major change in many cases through the presence of extensive and connected ecosystems, species diversity, habitat heterogeneity, and genetic variability.

Improved communication of the value of ecosystem services is needed to inform decisions at local to international levels. Nature-based solutions such as ecosystem management can play a major role in climate change mitigation and societal adaptation, but they will provide the greatest benefit when used concurrently with actions to reduce fossil fuel emissions and change behavior. Benefits of these solutions can be particularly useful when ecosystems are managed for multiple services and transcend institutional, geographic, or habitat-based boundaries.

By promoting the evidence base that exists more widely to inform decisions, identifying and investigating tractable knowledge gaps in ecosystem science, and researching how key elements of complexity that enhance resilience and climate adaptation can be supported and enhanced, natural and social scientists may be able to advance conversations that put science into action. Although this is a difficult task, the rewards of these efforts have the potential to be vast, providing a more secure future for both ecosystems and society where both are able to thrive.

"Ultimately, we need to change the zeitgeist of our relationship with nature and bring its value central to decision making. To help achieve this, we, as natural scientists, must go outside our comfort zones and forge more "radical collaborations" with social scientists, economists, engineers, and policy makers—with all the end users of our research. Only by doing that will we be able to ensure our deep knowledge about the workings of the natural world and inform the process by which high-level pledges for nature get translated into action."

—**Nathalie Seddon,** University of Oxford

NATIONAL ACADEMY
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