REVIEW SUMMARY

CLIMATE CHANGE

Measuring the success of climate change adaptation and mitigation in terrestrial ecosystems

Michael D. Morecroft*, Simon Duffield, Mike Harley, James W. Pearce-Higgins, Nicola Stevens, Olly Watts, Jeanette Whitaker

BACKGROUND: Responding effectively to climate change requires urgent action to halt net greenhouse gas (GHG) emissions and to adapt to changes that cannot be prevented. The Paris Agreement of the United Nations Framework Convention on Climate Change has committed governments to the following: keeping global temperature rise below 2°C, pursuing efforts to limit it to 1.5°C, and adapting to reduce the vulnerability of people and ecosystems to the damaging consequences of a changing climate.

When protected, restored, or managed appropriately, natural and seminatural ecosystems make critical contributions to climate change mitigation and to helping people adapt to climate change. Ecosystems themselves are vulnerable to climate change, but by restoring natural ecosystem processes, resilience can be built, and a wide range of adaptation strategies can ameliorate the impacts.

Both synergies and conflicts between different objectives can arise, and it is essential to have clarity about what constitutes success across the range of adaptation and mitigation outcomes and to track progress. The success of ecosystem-based mitigation can be measured in terms of falling net emissions and stabilization of atmospheric CO_2 concentration. Although this is conceptually straightforward, it can be difficult to measure ecosystem fluxes accurately. Adaptation is more complicated because it encompasses a wide range of objectives, with respect to people and biodiversity, including both reducing vulnerability and managing unavoidable change.

ADVANCES: Many studies have investigated how nature-based solutions can contribute to climate change mitigation and adaptation. The evidence is now clear that protecting and restoring ecosystems is essential to holding global temperature rise to between 1.5° and 2°C. The value of different interventions for reducing GHG emissions and promoting carbon sequestration can be quantified with varying degrees of confidence. The evidence for the effectiveness, opportunities, and limitations of ecosystem-based adaptation in enabling people to cope with climate change is also growing, and these approaches are starting to be implemented. Adaptation to reduce the vulnerability of biodiversity and ecosystems themselves to climate change has been discussed over many years but proposed measures remain largely untested. This is starting to change, with recent studies gathering empirical evidence of the factors that influence the vulnerability of ecosystems and biodiversity. Nevertheless, evaluation and reporting of adaptation is currently focused on planning and implementation of actions rather than on assessment of whether these programs have successfully reduced vulnerability.

OUTLOOK: A picture is emerging of what successful adaptation and mitigation in terrestrial ecosystems looks like when it is built around protecting and restoring natural ecosystem processes. To realize the potential of ecosystems to ameliorate climate change requires integrated actions that are consistent with wider biodiversity and sustainable development goals. High-carbon ecosystems, particularly forests and peatlands, are essential, but other ecosystems, such as savannas, are also important elements of wider nature-based solutions and should be protected and restored. Pursuing mitigation objectives alone risks perverse outcomes that increase rather than reduce vulnerability. Further work is required to test the effectiveness of specific ecosystem-based mitigation and adaptation measures and what works best to support biodiversity in a changing climate. More-robust monitoring and evaluation are needed to drive progress. Measuring adaptation for biodiversity is particularly challenging, and monitoring and management will need to develop together as we learn from experience. ■

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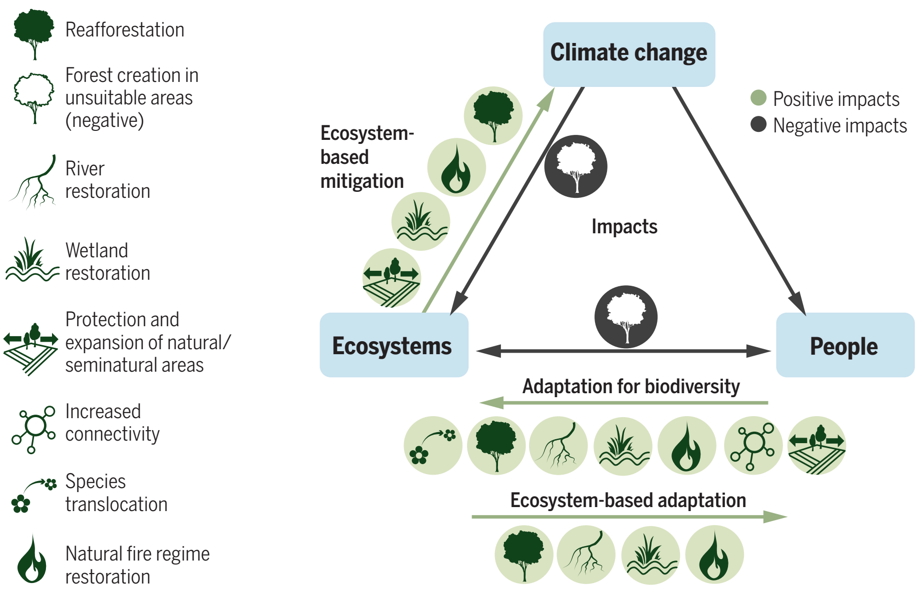

The role of natural and seminatural ecosystems in adaptation to and mitigation of climate change. The flow diagram shows the relationships between adaptation for biodiversity, ecosystem-based adaptation for people, and ecosystem-based mitigation. Negative impacts of climate change are shown in dark gray, and positive responses are shown in green. Successful ecosystem response to climate change depends on an integrated approach to ensure that synergistic effects are maximized and harms are avoided.

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REVIEW

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Measuring the success of climate change adaptation and mitigation in terrestrial ecosystems

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Natural and seminatural ecosystems must be at the forefront of efforts to mitigate and adapt to climate change. In the urgency of current circumstances, ecosystem restoration represents a range of available, efficient, and effective solutions to cut net greenhouse gas emissions and adapt to climate change. Although mitigation success can be measured by monitoring changing fluxes of greenhouse gases, adaptation is more complicated to measure, and reductions in a wide range of risks for biodiversity and people must be evaluated. Progress has been made in the monitoring and evaluation of adaptation and mitigation measures, but more emphasis on testing the effectiveness of proposed strategies is necessary. It is essential to take an integrated view of mitigation, adaptation, biodiversity, and the needs of people, to realize potential synergies and avoid conflict between different objectives.

Ecosystems are an essential element of climate change mitigation and adaptation, with the potential to reduce both net greenhouse gas (GHG) emissions and vulnerability to climate change. Approximately a quarter of postindustrial GHG emissions have come from the degradation of ecosystems (*1*), and the need for climate change mitigation based on restoring ecosystems or more sustainable land management is increasingly recognized (*2*). Over the past 10 years, carbon uptake by terrestrial ecosystems has been ~3.2 metric gigatons of carbon per year (GtC y^{-1})—equivalent to one-third of emissions from fossil fuel burning (9.4 GtC y^{-1}) (*3*). However, land-use change simultaneously caused emissions of 1.5 GtC y^{-1}. Reversing this flux is an essential element of climate change mitigation. There is also increasing evidence that adaption responses that use ecosystems can reduce the risks of climate change–associated events to people (*4*), such as flooding or heat waves. Ecosystems are themselves vulnerable to climate change, but an increasing number of studies are showing that this vulnerability can be reduced when they are protected, restored, or managed for adaptation.

Ecosystem-based, or nature-based, solutions are distinctive in that they provide mitigation and adaptation benefits at the same time as benefitting biodiversity and human health and well-being (*5*). Furthermore, they have the potential to deliver adaptation and mitigation in a synergistic way. However, there is also the potential for conflicts between different objectives. A clear understanding of what success looks like (*6*) for both adaptation and mitigation alongside broader biodiversity and human factors is needed.

Monitoring and evaluation of actions aimed at adapting to and mitigating climate change is essential to driving progress and developing techniques (*6*). Progress with mitigation can be measured in terms of changes in GHG fluxes. However, adaptation is more conceptually challenging (*7*, *8*). First, because it may not be possible to fully assess the effectiveness of an adaptation strategy in preventing adverse impacts until decades later. Second, because no single metric or even a small range of metrics will adequately sum up progress across the many and varied aspects of adaptation. Third, because there are risks that reducing vulnerability in one sector may increase vulnerability in another. Finally, objectives may need to change over time, because what constitutes good adaptation at a global temperature rise of 1.5° to 2°C does not necessarily constitute good adaptation at 3° to 4°C. It is also possible that there may not be agreement among different actors about the goals of adaptation.

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What constitutes success in climate change adaptation and mitigation in ecosystems?

In simple terms, success in mitigation means preventing emissions and increasing carbon sequestration. Historically, the main source of GHG emissions from terrestrial ecosystems has been deforestation (*9*), but emissions from degraded peatlands, melting permafrost, more frequent or more intense wildfires, and other sources are compounding the problem (*10*). Natural and seminatural ecosystems are important elements of mitigation strategies because of their capacity to remove CO_2 from the atmosphere, which could partially offset emissions in sectors that are hard to decarbonize, such as aviation (*11*, *12*). Measures that have the greatest potential to deliver climate change mitigation in terrestrial ecosystems include protection of intact carbon stores, avoided deforestation, reforestation of formerly forested land, and restoration of degraded peatlands. (Other habitats, including coastal and marine systems, also store carbon but fall outside the scope of this Review.)

There is good evidence that reforestation of formerly forested land can create a large carbon sink in its early decades and, in the longer term, store considerable amounts of carbon. From 2001 to 2010, for the moist tropics and boreal Siberia, Pugh *et al.* (*13*) estimated a carbon sink of 1.30 GtC y^{-1} in forest stands regrowing after past disturbance and 0.85 GtC y^{-1} in intact old-growth forest. Likewise, allowing natural regeneration of forest on 350 Mha of formerly forested land in the tropics and subtropics has been estimated to store 42 GtC y^{-1} by 2100 (*14*). Restoring degraded peatlands can substantially reduce (*15*) the large GHG emissions resulting from draining, burning, and cultivation (*16*). Climate change will have an increasingly negative impact on the capacity of many natural ecosystems to sequester or store carbon. There is also an increasing risk of exceeding tipping points that cannot easily be reversed, such as catastrophic permafrost melt (*17*). Rapid GHG emission reduction in all sectors is a priority to reduce such risks.

What constitutes success in adaptation has been widely discussed over the past two decades (*6*, *18*). For biodiversity conservation, adaptation includes a wide range of actions at different scales, from individual species to habitats and ecosystems (*19*, *20*). The evidence for these actions' effectiveness in supporting biodiversity conservation in a changing climate has grown rapidly in recent years. Nevertheless, many approaches have been based on theory, modeling, and observations comparing different locations or changes in time; relatively few studies have assessed the effectiveness of these measures experimentally (*21*). Three broad approaches to adaptation for biodiversity conservation can be identified: ecological restoration, direct intervention to reduce vulnerability of species and habitats, and adjusting conservation management and objectives.

Ecological restoration is important because the impacts of climate change are often exacerbated in degraded ecosystems. Restoration in this sense is focused on restoring natural

Box 1. Assessing the potential for synergistic outcomes from ecosystem-based adaptation and mitigation actions.

Will the action:

1. Reduce GHG emissions or promote sequestration of carbon?
2. Continue to be viable for a range of plausible future climate scenarios?
3. Increase the resilience of biodiversity to climate change?
4. Help people adapt to climate change?
5. Maintain or enhance the biodiversity of a region, now and under future climates?
6. Maintain or increase the provision of ecosystem services on which local people depend, including water, food, and materials, now and under future climates?
7. Lead to the displacement of emissions to another location?

processes, including catchment hydrology (22, 23) and fire regimes (24, 25). "Renovation" has been proposed as an alternate term (20), to distinguish this process from seeking to restore a former state, which may no longer be possible with climate change. Increasing habitat patch size can support more-resilient populations (26), and increasing habitat connectivity (27) enables some species to track changing climatic conditions in fragmented landscapes. Direct interventions range from targeted management of vulnerable species (28) and species translocation (29, 30) to manipulating habitats, e.g., by shading watercourses with trees to reduce water temperatures (31, 32). Adjusting conservation objectives and ways of working is becoming increasingly necessary as climate change impacts increase; for example, changing species distributions may mean that species will need protection in places they did not formerly inhabit (33, 34). The longer that warming continues, the more that adaptation for biodiversity will need to shift toward managing change (20, 35, 36) rather than building resilience. However, recent research has demonstrated the existence of refugia (37, 38) in which species survival is more likely because of microclimatic conditions, for example, on north-facing slopes and other locally cool spots in a landscape. Identifying and protecting these areas is therefore a good strategy for promoting species survival and is consistent with protecting and restoring large heterogeneous areas.

Ecosystem-based adaptation (EbA) is the use of biodiversity and ecosystem services to help people adapt to climate change. EbA includes natural flood management, in which peak flows are reduced and flood storage capacity is increased by restoring wetlands and natural features of rivers, such as meanders and woody debris; creation of green space and planting of trees to provide local cooling for people or livestock; and establishment of vegetation on slopes prone to landslip during extreme rainfall events. The evidence base for EbA has developed rapidly, with many studies demonstrating that the approach can be more cost-effective in the delivery of adaptation outcomes, and that it provides multiple cobenefits and represents a more sustainable approach than engineered adaptation measures (39). However, the adoption of EbA approaches is patchy (40) and the involvement and empowerment of local communities and stakeholders is essential for successful EbA (41, 42).

The particular value of nature-based solutions in addressing climate change is their capacity to simultaneously provide mitigation and adaptation along with a wide range of other benefits for biodiversity and people. Box 1 summarizes the key issues that determine success or failure across all these areas.

Synergies

Protecting existing natural areas is a cornerstone of conservation, which is even more important in a changing climate, especially areas where there are important carbon stores or potential refugia for species. Intact forests are important for a range of climate-related, ecological, and societal reasons, including carbon storage, carbon sequestration, local climate regulation, water supply, and biodiversity (43). Similarly, peatlands are important carbon stores and, like other natural wetlands, support biodiversity and contribute to water resources and flood management.

Given the degraded state of most of Earth's ecosystems, restoration is essential to realize their full potential for adaptation and mitigation. Restoring natural ecosystem functions, particularly hydrology and carbon dynamics, is central to this goal (Fig. 1). Catchment restoration (44), including regeneration of wetlands and reversing the canalization of rivers, can reduce flood risk by retaining water higher in the catchment. The additional advantages of such measures include maintaining water supplies during periods of drought, enhancing biodiversity, and contributing to carbon storage and sequestration. Reforestation can both sequester carbon and have benefits for adaptation, including increased rainfall infiltration into soil (45, 46), floodwater impedance (44), and provision of shade (31). Restoring savannas, by removing trees, reseeding grasslands, and reinstating natural fire regimes (47), increases resilience, supports carbon storage in soils (48), protects water resources (49), and reduces the risk of catastrophic fires (50).

Restoration of natural processes is likely to have multiple benefits in tackling climate change. However, it will increasingly need to be complemented with active intervention or adjustment of conservation objectives, as described above, to reduce vulnerability to climate change and continue delivering adaptation and mitigation services.

Conflicts

Although nature-based solutions offer the potential for win-win-win outcomes for mitigation, adaptation, and biodiversity, these are not guaranteed, and there is potential for conflict, especially when inappropriate interventions are employed. There are real risks in pursuing one objective without taking proper account of others. An important current concern is tree planting in inappropriate places. Although reforestation of formerly forested land can bring great benefits for adaptation, mitigation, and biodiversity, tree planting in other places can cause serious problems and can even exacerbate climate change impacts (48). Naturally open ecosystems are uniquely adapted to local conditions. Grass-dominated savannas have diverse communities and many endemic species (51) that have evolved in a high-light environment with vegetation-environment feedbacks, including high levels of herbivory and fire (52). Tree planting in historically open ecosystems would be harmful. Unfortunately, global scale analyses aimed at identifying degraded forest areas suitable for afforestation (53) cannot reliably separate naturally open ecosystems, such as savanna, from degraded forests. Here, other sources of knowledge and data, including the involvement of local communities, are essential. Similarly, the afforestation of formerly treeless peatlands that have been drained may not supply any mitigation benefits from growing timber because of release of GHGs from the drained peat (54) and may, in addition, lead to biodiversity losses (55).

Ecosystem restoration will not be possible in all places. Many formerly forested and peatland areas have been cleared and drained for agriculture. Ecosystem restoration in these regions may reduce crop production or displace it to other locations where it may have an equally or even more negative impact. A wider and coordinated strategy to tackle climate change and promote sustainable development therefore needs to include actions such as reducing food waste and dietary change and sustainable increases in agricultural productivity in some places to allow

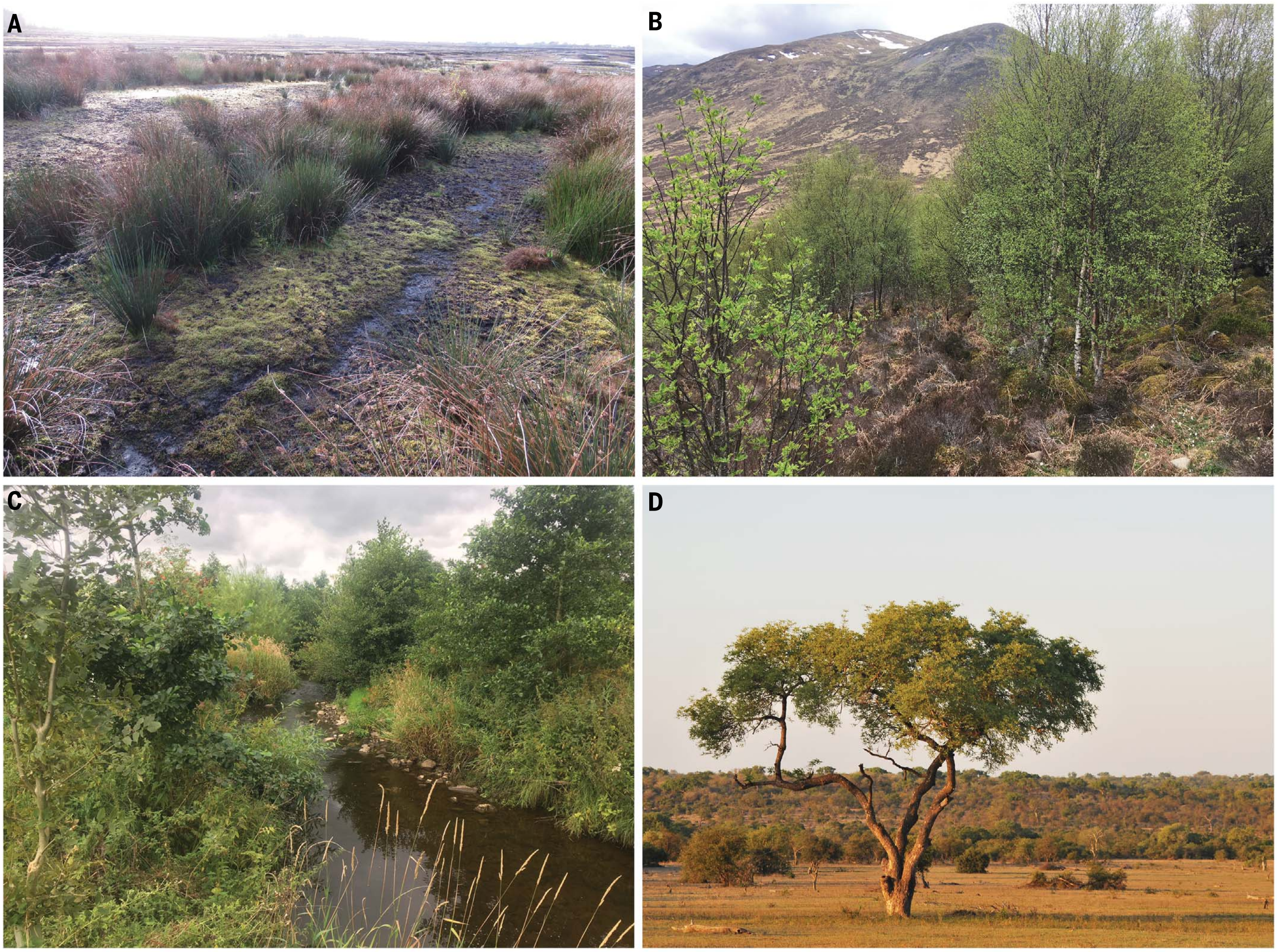

Fig. 1. Examples of nature-based solutions to climate change. (**A**) Restoration of a lowland raised bog at Bolton Fell Moss, Cumbria, England—a former commercial peat extraction site. (**B**) Natural regeneration of trees following reduction in grazing at Creag Meagaidh National Nature Reserve, Scotland. This is a landscape that would once have been forested below the natural treeline, but the forest was subsequently cleared, and grazing prevented reestablishment. (**C**) Establishment of woodland next to a stream provides shading to maintain lower water temperatures and contributes to carbon sequestration. (**D**) Savanna in a natural state, with large areas of open grassland and scattered trees. Protection and restoration of this state using native herbivores and natural fire regimes is the best approach to climate change adaptation as well as biodiversity. This ecosystem is not suitable for tree planting.

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restoration in others. Sustainable approaches, including organic and regenerative farming (56), which can support some aspects of biodiversity and contribute to climate change mitigation, can also play a role in wider land-use strategies. Negative emissions technologies, especially biofuels with carbon capture and storage (BECCS), are often included in scenarios for meeting the Paris Agreement commitments, but these technologies create a demand for land (11, 57). The benefits of BECCS for mitigation need to be considered alongside the implications for adaptation, biodiversity, and food security and will require careful management and monitoring (58). When a broader frame of reference is considered, the protection and restoration of natural ecosystems may, in many circumstances, be a better option than resorting to BECCS.

Measuring and reporting progress

It is important that success in deploying nature-based solutions can be monitored and evaluated, to ensure that all intended benefits are delivered, that progress is being made, and that actions can be prioritized on the basis of evidence. To enable this to happen, metrics are required for biodiversity, mitigation, and adaptation parameters, which reflect the needs of local communities as well as international reporting.

Mitigation is measured by quantifying emissions and removal of GHGs in terms of CO_2 equivalents. The Paris Agreement of the United Nations Framework Convention on Climate Change (UNFCCC) requires countries to report emissions on the basis of observation-constrained models (3). However, there are considerable gaps and challenges in reporting ecosystem emissions and removals. Many confounding factors can influence assessment of mitigation outcomes, including the slow rate of carbon sequestration in many ecosystems and the risk of stored carbon being released by wildfire or land-use change. Hence, long-term measurement is required, as patterns of carbon uptake change over time.

Under the UNFCCC, adaptation reporting is based on the development and delivery of broad-ranging National Adaptation Plans (59, 60). The Paris Agreement also stipulates a "global stocktake," to review adaptation effectiveness and progress made toward the global adaptation goals of enhancing adaptive capacity, strengthening resilience, and reducing vulnerability to climate change. Many variables that affect human vulnerability can be measured in a straightforward way. For example, fluvial flood risk relates closely to water flow in rivers, which can be measured directly (*61*). However, for biodiversity, especially at the species level, vulnerability is harder to measure and is associated with a high degree of uncertainty (*62*–*64*).

Lessons can be learned from the long history of species monitoring. Although well-chosen individual species can act as indicators for a wider range of species (*65*), in the context of climate change, more-robust indicators can be developed from the contrasting responses of different species (*66*, *67*), including sophisticated assemblage structure indicators (*68*).

Several indicators of climate change impact have been developed that track observed species' population and community responses to climate change (*69*–*71*). It may be possible to develop indicators of adaptation on the basis of further development of these impact indicators, but when doing so, it will be important that attribution to climate change is not confounded with other drivers of change, which may vary between species. In addition, the efficacy of species as indicators may change over time, as a result of altering interspecific interactions, density dependence, and even evolutionary adaptation. Finally, we need to consider that the past, upon which the indicators are devised, may not be a good predictor of the future.

Given these concerns, the development of true outcome-based adaptation indicators is challenging, particularly where adaptation actions are targeted at managing change. An alternative approach is to monitor the deployment of adaptation measures for which there is good evidence of effectiveness, such as increasing patch size (*26*) and protecting refugia (*36*), in combination with existing biodiversity surveillance. At present, the main limitation to this approach is our understanding of the effectiveness of adaptation measures (*21*) and the narrow geographical representation of existing studies, but this evidence base should improve over time. The concept of adaptive monitoring linked with adaptive management (*72*, *73*), in which both monitoring and management of the natural environment develop and evolve as situations and knowledge change, is a powerful one that will need to be embraced given the need for prompt action in the face of an uncertain future.

Outlook

Tackling climate change is an urgent priority and a drive to restore degraded ecosystems needs to be at the heart of it. Natural ecosystems take up approximately a third of current fossil fuel emissions and will be vital for future carbon sequestration. The distinctive value of natural ecosystems in climate change mitigation is that they can protect biodiversity and help societies to adapt to climate change. To realize the potential of nature-based solutions to climate change requires more investment, technical expertise, and the active participation of local communities. There is a pressing need for clear measures of success and effective monitoring and evaluation that cover mitigation, adaptation, and biodiversity outcomes to drive progress.

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Measuring the success of climate change adaptation and mitigation in terrestrial ecosystems

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Measuring mitigation and adaptation

As more and more carbon dioxide is emitted into the atmosphere, humans and the natural world are beset by the damaging consequences of a rapidly changing climate. Natural and seminatural ecosystems are likely to be the best starting place for immediate adaptation and mitigation solutions. First, though, many natural environments need restoration to maximize their own resilience to climate change. In reviewing our options, Morecroft *et al.* point out that we can directly observe the success of mitigation strategies by quantifying atmospheric carbon dioxide. Successful adaptation is more challenging because it involves a range of social and biodiversity measures. However, we could make matters worse if we do not constantly monitor the effects of the interventions we devise and react flexibly as changing conditions unfold.

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