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Astonishingly Hyperconnected

Climate change and biodiversity loss are inextricably linked problems that cannot be solved without science and policy that acknowledges this integration.

The dual problems of climate change and biodiversity loss are interconnected, and are among the most urgent scientific and social issues of our time. Yet until recently they have largely been treated separately, as illustrated by their distinct governing bodies. The United Nations Framework Convention on Climate Change and the Intergovernmental Panel on Climate Change (IPCC) focus on climate change, while the UN Convention on Biological Diversity (CBD) and the Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services (IPBES) focus on biodiversity.

Of the two issues, climate change dominates the current environmental narrative and policy agenda. It is covered by the media in the United States, the United Kingdom, and Canada at least eight times as often as the biodiversity crisis, has been the focus of twice as many peer-reviewed scientific articles over the last decade, and garners more than twice as much research funding. Yet biodiversity is critical for ameliorating climate change, and its stabilizing effects on climate are well documented in past and current ecosystems.

Current climate science policy discussions tend to focus on the changing climate's effects on temperatures, droughts, extreme weather, ice sheet melting, and sea level rise, but climate change is driving biodiversity loss in equally drastic ways. Similarly, discussion of contributors to warming focus largely on abiotic factors, such as anthropogenic fossil fuel emissions and rising greenhouse gas concentrations, often overlooking the fact that destruction of biodiversity—particularly in complex ecosystems that store carbon—also drives climate change. Furthermore, the primary climate solutions under development today are economic or technological (carbon pricing, renewable energy, and biotechnological climate mitigation), but nature-based solutions (based on existent biodiversity) have significant potential for climate change mitigation.

The phenomena of climate change and biodiversity loss are inextricably linked and mutually reinforcing. There is no solving the climate challenge without solving the biodiversity crisis, and biodiversity itself should be viewed as a primary solution to climate change. This integrative perspective is particularly necessary today, as policymakers weigh conservation strategies alongside biotechnological innovations such as synthetic biology for climate change mitigation and biodiversity restoration.

Only by recognizing the complexity of biodiversity and the ancient and ongoing evolutionary and ecological processes that drive it will it be possible to develop coherent policies for sustaining the planet's biodiversity and the services that it provides.

Biodiversity's services to the planet

It is well known that biodiversity contributes to human well-being by supporting food security, healthy soils, pest control, nutrient recycling, pollution mitigation, clean air and water, medical/medicinal discoveries, economic resources, biological innovations, and other social benefits. But less recognized is the substantial climate-stabilizing carbon offset that biodiversity provides:

over half of anthropogenic carbon dioxide emissions are removed from the atmosphere through natural carbon storage and sequestration.

Such linkages between the biosphere and the atmosphere are legacies of ancient evolutionary and ecological processes. Earth's biodiversity has played a critical role in planetary health for billions of years, including helping to maintain a fairly stable climate. Terrestrial forests, for example, keep large amounts of carbon in the biosphere rather than in the atmosphere. Coastal mangrove forests provide a powerful "blue carbon" sink, sequestering carbon at an even faster rate than terrestrial forests. Oceanic phytoplankton trap carbon through a mechanism known as a "biological carbon pump" whereby large-scale photosynthesis followed by plankton die-offs carry carbon from the surface to the deep ocean, to be consumed by marine species or stored for thousands of years. Significant amounts of carbon are also stored in peat soils, which have recently been discussed as potentially Earth's largest carbon store. And scientific studies of current and paleontological ecosystems continue to reveal more about the wide diversity of natural climate stabilizers.

Biodiversity will continue to play an important role in determining how warm the world will become and how a warmer world will operate. The targets established by the 2015 Paris Agreement for curtailing global warming below two degrees Celsius will be impossible to reach without a healthy, functioning biosphere. But even two degrees may be too high to maintain functional biodiversity that provides critical climate-stabilizing services. This creates an urgent need to scale up efforts to prevent continued reductions in biodiversity and to restore what has already been destroyed to help curtail further warming.

Current status and future prospects of biodiversity

Planetary biodiversity is declining at an unprecedented rate, even as its scope, structure, and function are not fully understood. This presents a challenge for policymakers, who must simultaneously try to understand the complex dynamics of natural systems while acting quickly to strategically protect them.

Although climate change is a significant driver of biodiversity loss, it is only one of many contributing factors, which include habitat destruction, invasive species, pollution, population increases, and overconsumption of natural resources. Precise global extinction rates are difficult to measure, largely because scientists do not have a solid estimate of how many species actually exist. In the most recent Convention on Biological Diversity, scientists concluded that up to 150 species are going extinct every day. Up to one million species extinctions could occur over the next few decades because of human activities. The mitigation of such biodiversity loss is not only necessary to stabilize the biosphere and its critical role in curtailing climate change; it is also central to achieving most of the goals of the UN's 2030 Agenda for Sustainable Development. Accordingly, the biodiversity crisis requires massively scaled-up science and policy attention on par with climate change.

Current efforts are not enough. As part of the 2010 CBD, over 190 countries agreed to meet specific biodiversity targets by 2020. The 2020 Global Biodiversity Outlook contains a bleak progress report: none of the targets have been reached and only some have been even partially met.

Biodiversity requires protected and connected spaces, and it is crucial that the scientific research supporting these specific enabling capacities should inform policy actions. Experts are beginning to converge on targeted goals for protection and restoration of spaces to slow the rate of biodiversity loss. Currently, about 4% of oceans and 15% of land have protected status. According to some prominent environmental biologists and organizations, nations should target at least one-third of their natural systems for protection by 2030, and half by 2050. The CBD emphasizes that conservation targets must comprise not just numbers but well-connected and properly protected natural systems.

Biotechnological approaches to environmental change

Policies to stop biodiversity loss have not been as effective as they need to be, raising the stakes for another emerging field: biotechnological approaches to mitigating and managing environmental change.

Biotechnological innovations for protecting, conserving, restoring, and sustainably managing ecosystems are part of the solution for both climate and biodiversity stability but, as with all technologies, they come with benefits, risks, tradeoffs, and social and ethical considerations. For instance, the benefits of biotechnology, when applied to biodiversity, may include bioengineered solutions to environmental degradation or innovative tools that could enhance natural species' resilience and carbon storage capacity. However, it carries significant risks of introducing elements or new approaches that may harm natural systems. For example, replacing degraded natural forests by planting fast-growing trees or monocultures as a carbon sink can have harmful effects on other aspects of the environment, such as altering soil balance, disrupting associated native species, and introducing new pests or diseases. Research shows that diverse natural systems tend to regenerate naturally and have higher resilience than engineered systems to disease, fire, and invasive species.

Thus, effective strategies for reforestation and afforestation (establishing new planted areas) must take this biological knowledge into account.

Furthermore, because the mechanisms by which complex natural systems interact and maintain stability are not always well understood or considered, the wider effects of human-engineered synthetic approaches—such as enhancing natural systems or organisms, bio-inspired design of synthetic systems, and the creation or alteration of organisms and ecosystems thought to better withstand or mitigate climate change—can be unpredictable in the long term. For example, the replacement of natural forests with plant monocultures that are intended to store carbon or increase yield has been demonstrated to negatively impact Earth's natural water cycle, ultimately leading to more disturbance and extreme climatic events—an unanticipated feedback loop. Because of the ancient complexity of biological, geological, and atmospheric interactions and feedbacks, the short- and long-term consequences of bioengineered solutions call for careful, interdisciplinary scientific impact assessments.

A call for more research on biological complexity

Whether natural or biotechnological, effective mitigation strategies rely on developing a much better understanding of the structure and function of natural biological systems. Thus, the research community and its enabling institutions must work quickly to increase collaborations between scientists and bioengineers to develop that understanding. These collaborations must be grounded in an approach that recognizes the immense complexity of natural systems that have coevolved over deep time, as well as a multidimensional approach that looks beyond species to consider the full spectrum of the diversity of life on the planet—from genes to ecosystems.

Many conservation efforts focus on specific threatened species or ecosystems—static and limited concepts of biodiversity that are insufficient to the task ahead. Genomes, species, and ecosystems are dynamic entities that constantly evolve. Loss, gain, and reorganization of biodiversity is common. Life rearranges itself as the environment changes, with some species shifting ranges or declining and new species moving in and replacing endemic ones—a process that can have many detrimental effects. How and why this happens depends on many factors. Changes may occur faster in some ecosystems than in others, and the rate of reorganization in biodiversity "hotspots" is much higher than in other areas.

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From a social perspective, biotechnological approaches may also risk reinforcing or worsening existing economic, social, and political dynamics. Environmental decisionmaking is already fraught with multiple interests and agendas. If limited sectors of society set broad biotechnological agendas without stakeholder input, they may fail to anticipate the negative consequences of reconfiguring the natural world, including unequal social or cultural impacts. More inclusive alternate approaches, such as those used in responsible research and innovation, should be applied to biological sustainability efforts.

There is another profound, but perhaps more oblique, risk that bioengineering may be viewed as a substitute for the difficult systemic work of transforming society to achieve a more sustainable relationship with nature.

Policymakers require more information to gain a better sense of the optimal balance between preservation and stewardship of natural systems versus beneficial mitigation technologies. More pragmatically, can the functional biodiversity produced by over 4 billion years of evolution—that is, biodiversity's full range of benefits—be approximated by human technological efforts? The answer to this question lies in a comprehensive understanding of biocomplexity.

To strategically preserve, manage, or restore biodiversity, policymakers depend on science that investigates the resilience and adaptive capacity of biodiversity at all its levels in the face of changing environments. The ability of species to adapt and persist through environmental change can be thought of on a spectrum ranging from failure (extinction) to gradual adaptation (adaptive capacity) to rapid evolutionary response (resilience). Where the outcome falls in any particular case depends on many underlying factors, such as genetic diversity, ecological processes, environmental pressures, and ancient evolutionary drivers and constraints.

Clearly, different organisms and species have different "evolutionary clocks" in this respect. Take, for

instance, the rapid shift in the structure and function of oil-eating microbial communities in the wake of recent marine oil spills. The relative abundance of different lineages within the communities shifted quickly, and genes involved in breaking down heavy oil components were replicated and increased proportionally in some organismal genomes. This exemplifies a high rate of evolution, which resulted in a degree of system stabilization. At the other end of the spectrum, hundreds of species that are more vulnerable to environmental disturbances and perturbations have gone extinct just in the past year. Thus, resilience to environmental changes varies across the evolutionary tree of life.

Scientists lack a comprehensive understanding of this variability, and the evolutionary processes that contribute to it are key, but understudied, aspects of adaptive capacity and resilience. In addition to providing ecosystem benefits, natural systems provide what could be characterized as "evosystem services"—the benefits derived from evolutionary processes. As the engine that generates and maintains genetic diversity, evolution drives the diversification of species, facilitates organismal adaptation to environmental change, produces unique innovations for such adaptation, and selects for species survival. But evolution requires genetic diversity and, when natural systems are damaged, fragmented, or isolated, the chances for a species to interact with a large gene pool may decrease. Over a longer timeframe, the unique evolutionary histories of organisms can also constrain "evolvability" due to coevolved features with related species and other factors.

There is also a need for more research into the elaborate connections among organisms—symbiotic biology. Recent studies show that these intricate connections are facilitated by boundaries between organisms and species that are much blurrier than previously thought. For example, some organisms may transfer portions of their genomes to each other, even across species boundaries. This movement of genetic information between organisms may facilitate evolutionary innovations and increase adaptive capacity, but we need more research to understand this process. At other levels, organisms often acquire and integrate other organisms that contribute to their functionality and survival. Such cooperation and interdependencies are now known to be the biological norm.

Because life is astonishingly hyperconnected on scales much larger than we thought just a few decades ago, the fate of any species in the face of environmental change is intertwined with the fate of many others. Thus research and policy concerning global environmental change require an integrated, systems-level approach. The complex ecological and evolutionary dynamics operating over large spatial and temporal scales must be carefully investigated, and biodiversity policy should be formulated accordingly.

Planetary futures

Recently, the IPCC and IPBES issued their first joint report. It provides welcome high-level recognition that the climate and biodiversity crises are fundamentally connected. The growing acknowledgement that climate change and biodiversity loss are interdependent aspects of global environmental change is encouraging, but that recognition must also translate to integrative approaches in both the science and policy domains.

In science, this entails convergent research in ecology, evolutionary biology, geology, and paleontology to enable a deeper understanding of biodiversity dynamics. The collaborative integration of this understanding with the bioengineering community is also a priority for development of effective biotechnological solutions.

In policy, this means developing a cohesive climate-biodiversity agenda for bold, synergistic, and integrative action. Those goals must then be operationalized and implemented in a similarly integrative manner, by designing policies that are systems-based and mutually reinforcing in beneficial ways. The current operational disconnect risks the possibility that actions taken to mitigate climate change may reduce biodiversity, and vice versa. Conversely, approaching the issues jointly could lead to synergistic approaches and outcomes.

Researchers and policymakers must work quickly to specify clearer and bolder targets for preserving and safeguarding biodiversity along with its spatial habitat requirements, to articulate a conservation agenda that recognizes all levels of biodiversity, and to emphasize that natural systems are climate solutions on par with greenhouse gas reductions and other objectives.

Amid calls for large investments in new biotechnological approaches that aim to synthesize the benefits of existing ecosystems and mitigate the degradation of natural systems, policymakers will need to evaluate benefits, risks, and tradeoffs based on a thorough scientific understanding of the diverse capabilities of natural biological systems. Biotechnology will certainly play an important role in sustainability efforts, but the most effective mitigation strategies will be grounded in biological realism and in the context of broad societal input.

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