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REVIEW

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Mitigation and adaptation strategies to reverse biodiversity decline

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Abstract

The UN Convention on Biological Diversity aims to "take urgent action to halt and reverse biodiversity loss", despite the fact that the underlying drivers of change (i.e., human consumption levels) continue to increase at a global scale. Following the framing of climate change policy, this review aims to identify conservation policies and technologies that can be articulated as '*mitigation*' measures, which seek to reduce the total environmental footprint generated by people. These aim to break or circumvent cause-effect relationships that adversely affect biodiversity and human wellbeing. Illustrating this approach for food production and consumption, it is possible to identify a number of potential social policies and transitions (e.g., in relation to diets, economic norms and equitability) and emerging technological mitigation measures (e.g., microbial and cellular food production and waste-reduction technologies) that could, if supported and scaled up, virtually eliminate food-related drivers (*causes*) of global biodiversity decline within the coming century, and thereby achieve long-term ecosystem recovery. By contrast, most current biodiversity conservation can be regarded as resisting *the consequences* of environmental change, rather than addressing the causes. In relation to food, many conservation successes reduce agricultural intensity or the extraction of other resources from particular locations (e.g., by rewilding, restoring and de-intensifying farmland), so they risk shifting the same demand-driven pressures elsewhere (known as 'leakage') instead of addressing the underlying challenge. Conventional conservation protection and management will still be required, but it would be more effective if conservation strategies were re-articulated as '*adaptation*', a flexible balance between facilitating, accepting and resisting change. The conclusion is that recent biodiversity trends cannot be halted or reversed at a planetary-scale unless the underlying human-associated production and consumptive causes of environmental change are addressed. Mitigation policies that recognise, reduce and replace the drivers of biodiversity change are achievable, but Convention on Biological Diversity and other institutional changes will be required to develop parallel but distinct mitigation and adaptation work streams.

Keywords Adaptation, Anthropocene, Biodiversity, Climate change, Conservation, Convention on biological diversity, Food systems, Leakage, Mitigation, Sustainability

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Background

Global policy and conservation efforts to date have failed to prevent or reverse negative biodiversity trends at a planetary scale [1, 2, 3], even though many individual conservation projects and policies have successfully maintained or restored particular ecosystems, protected certain species and benefited some local communities [4, 5]. Biodiversity declines would likely have been steeper without such interventions, but global declines nonetheless mean that the sum total of biodiversity gains within biodiversity conservation and sustainable use projects has been smaller than the losses over the rest of the world surface, at least for certain biodiversity indicators. Biodiversity conservation is winning many individual battles but, so far, it is losing the war.

In response, an international policy consensus has emerged, indicating that additional efforts and resources are required to maintain biodiversity, as embodied in the Kunming-Montreal Agreement of the Convention on Biological Diversity (CBD 2030 Targets). The CBD advocates the need to replicate these local and regional biodiversity conservation successes more widely, such as by restoring 30% of degraded ecosystems (CBD Target 2), conserving 30% of both the land and the seas by 2030 (CBD Target 3), halting species extinctions (CBD Target 4), and additional sustainability measures; at an estimated cost around US$200 billion per year (CBD Target 19) [6, 7]. These targets reflect a widely-held desire to replicate ongoing conservation successes at increasingly-large scales, as well as to tackle wider societal challenges: for example, Target 16 includes the aspiration to halve human food waste, and Target 18 addresses the need to removes harmful incentives.

To date, many of the successes have been at local and regional scales [4, 5], which are often appropriate because they have the potential to accommodate the multiple voices, aspirations, levels of governance, financial and social pressures, and components of biodiversity relevant to local circumstances [8, 9, 10]. It is not clear, however, that a major up-scaling of local and regional projects will be sufficient to halt or reverse negative biodiversity trends *globally*. This review highlights why such local and regional measures are unlikely to be *sufficient* to turn the tide of loss.

In the terrestrial sphere, the harmful consequences of land use change and intensification are recognised by the Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services (IPBES) as the number one direct driver of biodiversity declines [3]. The main approaches to address this threat have been to protect particular places from change, restore others, attempt to retain low intensity traditional uses, de-intensify farming, and implement other 'sustainable use' measures, all with the aim of saving particular ecosystems, species, ecosystem services and cultural practices [11, 12, 13]. The catch is that restoring land and deintensifying farming typically reduce per hectare food production in those locations, and people still need to eat. The most likely outcome is that production shifts to other locations, harming wildlife elsewhere – framed as environmental 'leakage' or 'offshoring' [14, 15]. Much the same is true of global fisheries. Controlling harvesting levels under particular jurisdictions can shift fishing effort to other species or elsewhere [17, 18], or to fish farming, or to the consumption of terrestrial foods. Leakage places many of the CBD aspirations at risk.

Levels of leakage for biodiversity – actions to protect biodiversity in one location that directly or indirectly result in increased pressures and biodiversity loss in other places – are difficult to gauge because trade networks are diffuse, and biodiversity in different parts of the world is not equivalent. The leakage associated with conservation projects can potentially exceed 100% (i.e., net loss) if wildlife-friendly farming (deintensification) or abandonment (rewilding, strict protected areas) in one location results in increases in the area or intensity of farming in more biodiverse or socially vulnerable parts of the world [15]. It is important to note that there are exceptions, for example where reversing desertification and establishing sustainable fisheries may increase both biodiversity and food production. However, only a modest proportion of biodiversity conservation projects aim to maintain or increase food production (or extraction of other resources), especially in the terrestrial sphere.

Local conservation actions would still be globally beneficial if the areas that were protected contained, for example, disproportionate numbers of rare, localised and threatened species [16]. Any leakage would then, in principle, shift food production and resource extraction to locations that contained fewer such species. This is the principle of the biodiversity hotspot approach, as championed by NGO Conservation International [19], and enumerated by 'conservation prioritisation' softwares that use algorithms to estimate where the maximum amount of biodiversity could be conserved in the minimum areas of land or sea (e.g., [20]). While this approach can enable international NGOs and other bodies to target priority areas globally, and works well in countries that contain large numbers of endemic species [21], it has not been as successful as one might have wished at a global scale. That is because of politics. The implementation of agreements made under the Convention on Biological Diversity are devolved to nation states, rather than applied internationally. For instance, conserving 30% of the land by 2030 (CBD Target 3) is agreed by each signatory state, whereas the globally efficient solution would be to conserve considerably more than 30% of the land in species-rich or endemic-rich nations such as

Indonesia and Madagascar, and far less than 30% of most north-temperate countries [19, 20]. In addition, when nations are left to prioritise separately, they often aim to protect nationally-rare species and locations that may not be threatened globally, such that the total amount of biodiversity protected is far lower than if prioritisation is global [22, 23].

Even if global priorities were adopted (which it can be argued is appropriate when biodiversity is the primary focus), this simply minimises the negative biodiversity consequences. Many authors have identified that there is also an urgent need to recognise and tackle the human economic drivers and social processes that underpin the growth of consumption (per capita consumption and continued population growth), the harms associated with that consumption, and the global connectedness of environmental pressures (e.g., [1, 24, 25, 26]). Otherwise, the sum total impact of humanity on the planet's biodiversity will almost certainly continue to increase, and those who are most impoverished and disenfranchised are likely to experience the negative consequences disproportionately [27]. Biodiversity conservation needs to address the *causes* of environmental change [28, 16] in a systematic way.

Aims

The aim of this work is to follow this cause-effect logic, whereby:

i. *mitigation* measures are required to address the *causes* of change, and
ii. *adaptation* measures to adjust to the *consequences* of environmental change.

The focus of this review is on measures that aim to achieve biodiversity recovery on decadal to centennial time scales (longer term importance) rather than on remedial conservation actions focussed on immediate challenges (short term urgency). Since this review touches on many allied subject areas, the approach here is to provide indicative references that enable readers to explore different areas in greater detail, rather than to provide exhaustive coverage of each sub-discipline.

Main text

Cause & effect, mitigation & adaptation

In climate change science [29] and policy development [30], there is a clear distinction between '*mitigation*' of the causes and '*adaptation*' to the effects of climate change. *Mitigation* includes all measures that aim to minimise the amount of human-caused climate change that takes place, primarily by reducing greenhouse gas emissions via alternative 'clean' energy technologies. *Adaptation* is everything people might do to live with the consequences of nonetheless inevitable climate change, including the design of buildings, migrating out of tidal zones, and adjusting working hours to avoid the heat of the day. In a climate-biodiversity context, adaptation options include the establishment of ecological corridors and physically moving species and genes to regions where the developing climate is suitable for them [31, 32]. Some measures can achieve both. For example, restoring mangroves or tree planting in a river catchment may simultaneously sequester carbon (mitigation) and reduce risks of flooding (adaptation) [33, 34], but the functional distinction remains.

It is widely accepted among climate-change policy makers that both are required; to minimise the speed and levels of climate change that occur *and* adjust to the consequences. Ultimately, however, mitigation matters most. Otherwise, society faces a never-ending future of having to undertake increasingly difficult, extensive and expensive adaptation measures to cope with increasing levels of climate change.

Causal hierarchies can also be recognised in relation to biodiversity change, but conservation policy is not currently structured in the same way. The 2019 IPBES Global Assessment identified a number of key direct and indirect drivers of biodiversity change [3], which can be caricatured as a three-level cause-effect hierarchy of indirect drivers, direct drivers, and consequences (effects) for biodiversity (Fig. 1) and for people.

While causal chains are typically much longer and more complicated than the three levels depicted, and contain both positive and negative feedbacks on different temporal and spatial scales, this caricature is nonetheless useful in that it helps to articulate different levels and types of causation. The indirect drivers include human population size and average per capita consumption (amounts and types of which vary greatly among individuals and nations) that together set the total global consumption of any particular resource. And it includes social, economic and technological drivers of change, such as the values, power structures and incentives that result in economic growth and profits being rewarded over human and environmental wellbeing in most countries [24, 25, 26, 27].

Despite the complexity, this framework can be used to identify potential mitigation measures that target causal chains which have negative outcomes. One can then consider the practicality and effectiveness of undertaking each of a number of candidate mitigation options, some of which are changes to our social and economic systems that affect total consumption and the equity of its distribution, while others represent social and technological interventions that reduce harmful environmental outcomes despite similar or increased total levels of consumption (e.g., Table 1). Note that most of the measures recognised within the existing 'mitigation hierarchy

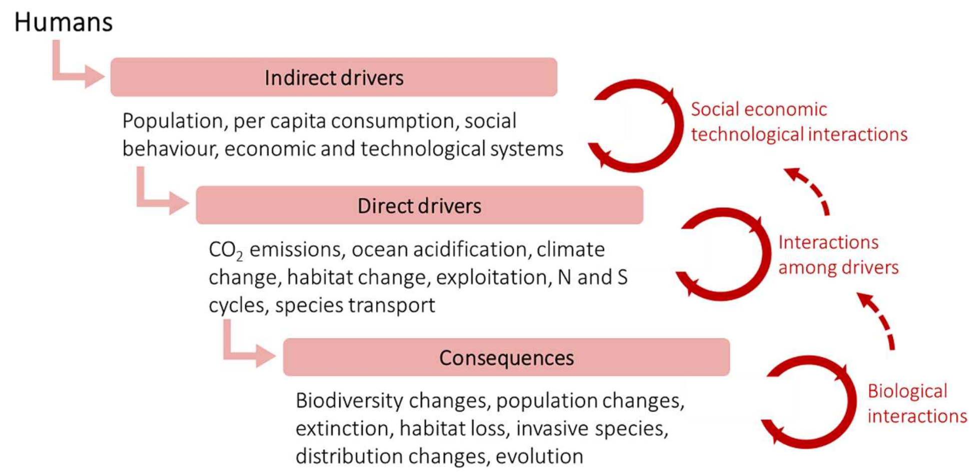

Fig. 1 Hierarchy of cause-effect relationships influencing biodiversity change. The specific items listed at each level are 'high level' categories for illustration purposes, and not exhaustive (for example, social behaviour includes social drivers of consumption choices and governance, etc.). Specific causal chains are typically longer and contain interactive effects and feedbacks, with the consequences for people arising from those feedbacks

Table 1 Examples of suggested and actual conservation and environmental mitigation and adaptation strategies

Mitigation (alleviating causes of biodiversity change)	Adaptation (dealing with the consequences)
• minimise human population and / or per capita consumption (stabilisation / degrowth) • equitable consumption, avoiding over-consumption & reduced waste • vegan, microbial, cultured meat & other diets to reduce agricultural / marine footprint • reduce greenhouse gas emissions • prevent biological invasions (transport) • remove social demand and economic drivers of wildlife trade	• ex-situ conservation, including zoos, botanic gardens & gene banks • restore ecosystems, establish protected areas (land / sea sparing) • subsidies supporting conservation in areas used for food production (land / sea sharing) • reintroduce & translocate species • control established invaders • make poaching, trade and ownership of organisms / parts illegal, and enforcement

for nature conservation' [16] fall within what is termed 'adaptation' here since they aim to avoid, minimise, remediate and offset the *consequences* of human consumptive behaviour, rather than address the consumption itself or means of production. These options are not mutually exclusive. As with climate change policy, a combination of both mitigation and adaptation measures is appropriate.

Mitigating the causes of change - world food systems

The IPBES Global Assessment identified the top two direct drivers of biodiversity change as "*changes in land and sea use* [and the] *direct exploitation of organisms.*" (3, Page 12). Taking a causal hierarchy approach, these direct drivers are all primarily driven by the same indirect drivers - *what and how much people eat*. What human population eats in total depends on how many people there are, which is set to increase by a further ~25% globally this century [35], multiplied by our still-growing per capita food intake. Globally-averaged per capita caloric, protein and fat intakes are increasing, including growing levels of meat and dairy consumption, despite considerable geographic and social variation [36, 37, 38, 39]. Around 30% of the Earth's land surface (excluding ice / rock) is already devoted to meat and dairy production (especially of / by ruminants; and including the land area where plants are grown to feed to livestock), while 9% is allocated to plant production for direct human consumption [40]. It has been forecast that human appropriation of the Earth's annual photosynthesis is likely to increase to between 27% and 44% by 2050, depending on how agricultural development progresses [41, 42]. This food is going to have to come from somewhere.

The literature highlights, however, that approaches to transform the world's food supply already exist (Table 2), without the need for ever-increasing amounts and intensity of farming, or the over-exploitation of marine resources. The approaches in Table 2 can be seen as complementary contributions to a broader aspiration rather than competing alternatives. For example, food waste can be reprocessed by microbes to generate proteins that are recycled into the food chain [64, 65]. It is unclear which specific combinations of social and technological measures will be most successful but, in combination, there is considerable potential for there to be a progressive reduction in pressure on the land and seas in the second half of the 21st century.

Table 2 Approaches to transform the world's food supply and thereby release land for other uses, including biodiversity conservation

Mitigation measure	Rationale / example actions	Example references
(i) Reduce food waste	With ~ one-third wasted at present, focus on reducing: on-farm, transport and processing losses in lower income countries and uneaten household waste in higher income countries	[7, 28, 43, 44]
(ii) Reduce meat and dairy consumption	Develop social attitudes (reduced-meat, dairy-free, vegetarian, vegan diets), embed carbon and biodiversity footprints of products in their price, remove subsidies on meat and by governmental and other financing support for meat alternative products; with equitable consumption	[7, 39, 45, 46, 47, 48, 49]
(iii) Adopt industrialised food production systems	Photosynthetic and non-photosynthetic microbial systems (e.g., yeast genetically modified to produce milk); cell cultures for meat and dairy products; and atmospheric extraction of CO_2 to generate carbohydrates industrially. These could lead to at least 80% of current farmland becoming available for other uses, but requires acceptance, large efficiency gains, taxation relief or subsidies to encourage the uptake of new technologies, and removal of counter-subsidies for space-inefficient meat and dairy production	[7, 38, 39, 47, 50, 51, 52, 53, 54, 55, 56]
(iv) Genetically modify crops to provide 'animal' products	Examples include omega-3 fatty acid fish oils expressed in transgenic plants	[57]
(v) Vertical farming	Multiple stacked layers produced close to consumers throughout the year reduce space requirements	[58, 59]
(vi) Intensification of existing farmland	Continued intensification to minimise the area of land required to produce food	[12]
(vii) Concentrated animal feeding operations	Livestock are kept in sheds, barns and feedlots, and fish tanks and cages, bringing the food to the animals; this requires less land/water than extensive grazing or fishing operations. Concentration is the current trend, but it is only achieved at the cost of animal liberty, often welfare, disease risk, and generates point pollution challenges. It is considered the least ethical option by many	[60, 61, 62, 63]

Only once this is achieved will it be possible to adopt less intensive ('sustainable') farming systems and other 'wildlife friendly' regenerative approaches on the *remaining* land at a global scale. This is not currently feasible because, e.g., organic systems produce about 20–25% less food per hectare than intensive farming [66, 67] – the global biodiversity consequences of increasing the area of land devoted to crops and pastures by this amount would be extremely damaging to biodiversity [12]. If this transformation can be achieved primarily using the first five approaches (i to v in Table 2), then the reduced pressure on the land would allow de-intensification of all the remaining farmland, enabling the removal of most chemicals from agricultural land, virtually eliminating concentrated faecal matter and other pollutants, and greatly reduce or eliminate the ethical concerns associated with intensive farming.

The focus on food for human consumption (and via livestock) here is because this initially appears to be *the most intractable* of all of the indirect drivers facing biodiversity – since people must eat, and that food must be produced somewhere. Of course, conservation benefits will not be realised if any land that is released is simply converted into monocultures for biomass and other forms of energy production, or exploited for other intensive human uses [e.g., 68, 69, 70]. Hence, overarching mitigation policies are required to ensure that gains in one direction are not cancelled by developments in others. Nonetheless, technological and social approaches do exist that could ensure that positive biodiversity trends outnumber negative ones by the middle of the 21st century, and beyond. Mitigation does have the potential to work.

Adapting to change

Change is nonetheless inevitable. All types of species and ecosystems respond dynamically to changes in the physical and biological environment, including to human-induced changes [33, 71, 72]. As such, organisms that are best suited to the new conditions tend to increase, while those better suited to the past conditions of a particular location dwindle [73, 74]. This represents adaptive evolutionary change in most instances, whereby the genes and individuals that have the highest fitness (evolution) and populations and species that are most successful (macroevolution, ecology) in the new environment increase, relative to (now) less successful genes, individuals, populations and species [75, 76].

In contrast, Anthropocene biodiversity change is typically framed [2, 3, 7, 29] as a deviation from what would otherwise be regarded as 'normal', as epitomised by concepts such as 'ecological baselines' and 'intactness indices' [77, 78]. Each of these represents a vision of a preferred or historic state of the world, with conservation aiming to stop change, and then restore biodiversity as far as possible towards its previous condition [7].

This framing sets conservation up to fail. To take one example, atmospheric CO_2 concentrations today are already likely to be higher than for three million years [79, 80], altering the growth of individual plants and ecosystem development [81], increasing the carbon: nitrogen ratio of plant materials that herbivorous animals consume [82] and changing the climate, potentially for the next 100,000 years or more [83, 84]. As a result, which species are present and their relative abundances have already changed in most ecological communities [85, 86, 87] and will continue to do so for all realistic conservation planning time horizons. Whole ecosystems will also change [81, 88], even within protected areas. Given that environmental change and biological responses have already taken place everywhere, and that future change is inevitable, adaptation is not a synonym for resisting the biodiversity consequences of environmental change, or restoring past communities. It is about enabling ecological systems to adjust.

Appreciation of this challenge has led a number of researchers and conservationists to suggest that conservation strategies should formally recognise the tension between resisting change and accepting the inevitability of continuing change [31, 89, 90, 91, 92]. These include the Resist-Accept-Direct (RAD) framework [93] that was specifically developed in the context of managing National Parks (initially in the US), and which has since been rearticulated as a general approach that could be applied more broadly across all aspects of conservation adaptation [94]. This is a Facilitate–Accept–Resist (FAR) framework, whereby decision-makers, practitioners and communities would assess whether one wishes to:

1. *Facilitate* change, by encouraging adaptive changes to the composition of biological communities and enabling species to exploit suitable new conditions (e.g., altered management interventions that encourage novel combinations of species and provide ecosystem services under the new conditions, and translocation projects),
2. *Accept* change, not intervening as community compositions change and species shift their ranges; with people also accepting changes to which ecosystem services are provided in particular places, or,
3. *Resist* change, which might be prioritised when entire species (rather than local populations) are endangered, or where an ecosystem service that people regard as essential cannot be provided by any other means.

When dealing with the biodiversity consequences of direct and indirect drivers (Fig. 1; Table 1), acceptance and facilitation should normally be considered first, enabling ecological and human communities to adjust to the new environmental conditions. Many existing practical conservation strategies that attempt to protect, reintroduce or restore towards some historical 'baseline' can be valuable in specific contexts [4, 5, 7, 95], but managing change is often more realistic. Resisting biodiversity change remains part of the armoury, but facilitating and accepting change are increasingly important components of adaptive conservation strategies.

Conclusions – addressing the causes

Despite numerous governmental, NGO and other efforts to protect biodiversity, the IPBES [2, 3] consensus is that many (but not all) aspects of biodiversity continue to decline. The common conservation refrain is that even more effort and resources are required, as articulated in the UN Kunming-Montreal targets. Hence, economic and policy drivers have been introduced which aim to increase the level of resources available and scale up conservation programmes. These newer approaches include biodiversity credits [96, 97, 98], no net loss approaches to development [99] and biodiversity net gain [100]. The problem, however, is that they are potentially mechanisms that enable the core drivers (economic and consumptive growth) of environmental change to continue, generating yet more leakage and externalities. Unless there is a greater focus on mitigation, as defined here, it is unclear how they can succeed in the long term at a global scale.

Returning to climate change, scientific consensus building is coordinated through the Intergovernmental Panel on Climate Change (IPCC), which feeds into the United Nations Framework Convention on Climate Change (UNFCCC) to develop globally agreed policy goals and approaches to climate change, namely to hold "*the increase in the global average temperature to well below 2°C above pre-industrial levels*" and to attempt *"to limit the temperature increase to 1.5°C above pre-industrial levels*" [101]. The UNFCCC (since the run-up to the 2015 Paris agreement) requires signatory countries to set their own Nationally Determined Contributions to greenhouse gas controls and additional mitigation measures, appropriate to the condition of each nation. Progress can then be evaluated against those goals. It is far from perfect (even the 2 °C target is likely to be missed) but, nonetheless, scientific and other knowledge informs the appropriate body, which then has a mechanism to devolve globally-agreed aspirations to nations that develop national policies and actions to achieve climate change mitigation. Thus, there is good structural alignment between the body that builds scientific consensus and the UN framework that seeks to develop appropriate policies to mitigate as well as to adapt to change. As such, the focus of global mitigation efforts is on controlling greenhouse gas emissions, the main cause of climate change.

The organisations generating biodiversity consensus and those with the greatest capacity to establish mitigation policies are not so well aligned. IPBES summarises the scientific and related information, which then (from a conservation perspective) predominantly feeds into the UN Convention on Biological Diversity (CBD). The CBD is more focussed on trying to ameliorate the consequences of biodiversity change than the causes (above). The causes of biodiversity change stem primarily from our need for food (the remit of the Food and Agriculture Organization of the United Nations; FAO), energy (the consequences falling under UNFCCC), trade (United Nations Conference on Trade and Development, UNCTAD, and the World Trade Organisation, WTO), and many issues that relate to the UN Sustainable Development Goals (SDGs) and to the United Nations Environment Programme (UNEP); and a myriad of associated national and international bodies. This is not to criticise any of these bodies or the efforts of anyone involved, and National Biodiversity Strategies and Action Plans (stated approaches of nations to the CBD's Global Biodiversity Framework) are well-meaning, but the institutional complexity of the relevant national and international organisations and interest groups is such that it has, to date, proven impossible to develop concerted action to address the underlying *causes* of biodiversity change.

To address the causes of biodiversity change in a systematic manner requires formal 'mitigation' work streams to be established at scales ranging from local communities to intergovernmental conventions. The central argument is that the CBD should reimagine itself into mitigation and adaptation work streams (informed by IPBES, FAO and others; mirroring the mitigation and adaptation work streams of IPCC and UNFCCC) and drive the mitigation agenda forwards, with stronger representation from institutions, researchers and practitioners who focus on the indirect drivers of change (food, energy, trade and more). Until this happens, the conservation movement risks treating the biodiversity symptoms of planetary change rather than tackling the causes of change. Traditional conservation will still be required, but adaptation must mean adaptation, not simply resistance, so as to avoid the risk of 'throwing good money after bad'. Mitigation is even more important. As outlined above, mitigation strategies could make serious progress towards addressing the causes of biodiversity change in the coming decades, and could achieve a massive reduction in the human footprint within a century. But it will not happen by chance.

Abbreviations

CBD	Convention on Biological Diversity
FAO	Food and Agriculture Organization of the United Nations
FAR	Facilitate–Accept–Resist framework
IPCC	Intergovernmental Panel on Climate Change
IPBES	Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services
NGO	Non-Governmental Organisation
UN	United Nations
UNFCCC	United Nations Framework Convention on Climate Change

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