# The Urgency of Biodiversity Action



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Final report

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# Executive Summary

**Conclusions**

- It is *twice as expensive* to delay action to stabilise biodiversity intactness globally as it is to act immediately.
- It is feasible to *significantly reduce extinction rates* of endemic species if action is immediate. Without greater action than currently implemented policies, more endemic species will go extinct in the coming 30 years than appear to have died out in the entire period 850-1850 CE.
- If action is immediate, there is an option to make a *bigger reduction in extinction rates*. This option would require immediate high-ambition action and is lost when action is delayed.
- If action is delayed, it becomes *infeasible to stabilise biodiversity intactness* globally even at today's depleted level.
- The global cost of food and materials production from 2021 to 2050 is lower under immediate action and higher if action is delayed, as a share of global-average household income.

**Recommendations**

- Improve immediately the effectiveness of protected area enforcement, which is the cheapest form of action.
- Taking the example of forests, develop immediately reforestation programmes using *planting*, which will support biodiversity more quickly than natural regrowth, *prioritising* reforestation in areas of high species endemism in fragmented forest and adjacent to existing forest. Planting achieves outcomes fastest and targeting locations brings the greatest biodiversity benefit.
- Design *biodiversity incentive mechanisms* which complement greenhouse gas payments, to target biodiversity-rich areas and places with high restoration potential. Incentives will drive market action.
- Introduce rules requiring that reforestation and afforestation projects in receipt of funds from greenhouse gas payments (for example, carbon credits) also *maximise biodiversity*. Costs will be higher if carbon projects do not jointly deliver biodiversity.
- Announce immediately the *future ambition* and *likely level* of biodiversity incentives, and translate these into investor-relevant scenarios, so that people can take investment decisions consistent with them. Advance announcement keeps the costs of adjustment down.
- Redeploy immediately *food and materials production subsidies* into (i) yield improving technology adoption including ecological intensification and irrigation (where water is available), in *locations where yields lag behind* their potential; (ii) biodiversity incentives; and, (iii) funding of protected areas. Economic incentives must work for, not against, biodiversity, climate and nutrition outcomes.

**Introduction**

Biodiversity is declining rapidly due to human activities; on this, there is a strong scientific consensus. However, the costs of delaying action to arrest and reverse biodiversity loss have not been examined until now.

Urgent action is needed to stem terrestrial biodiversity loss before it becomes much more costly and much less feasible to address. A delay of ten years from today will likely double the cost and make it infeasible to stabilize biodiversity intactness at even today's degraded levels.

The analysis estimates relative cost, biodiversity intactness and species extinctions between 'immediate' and 'delayed-action' scenarios, each of which reaches a similar biodiversity outcome by 2050. In the immediate-action scenario, the global community acts now to stabilise biodiversity intactness at current levels by 2050. Decisive action begins in 2020 and prevents over 20% of the extinctions of endemic species that might have happened in a baseline scenario of currently implemented policies on climate change, biodiversity and area protection. In the delayed-action scenario, stronger actions to conserve biodiversity commence in 2030, with more abrupt and disruptive action thereafter to restore biodiversity intactness to current levels by 2050 (see Figure 1 a).[1] In addition, a third scenario, 'immediate high-ambition', delivers *an increase* in biodiversity intactness from today's levels by 2050.

The scope of this work is constrained to restoration through reforestation of naturally forested areas to generate positive outcomes for biodiversity as a result of global action. Actions targeting aquatic, coastal, marine and other terrestrial biodiversity lie beyond the scope of this work. However, biodiversity outcomes are estimated for all terrestrial biodiversity, and so the results serve as an indication of the scale of potential costs of inaction in other ecosystems.

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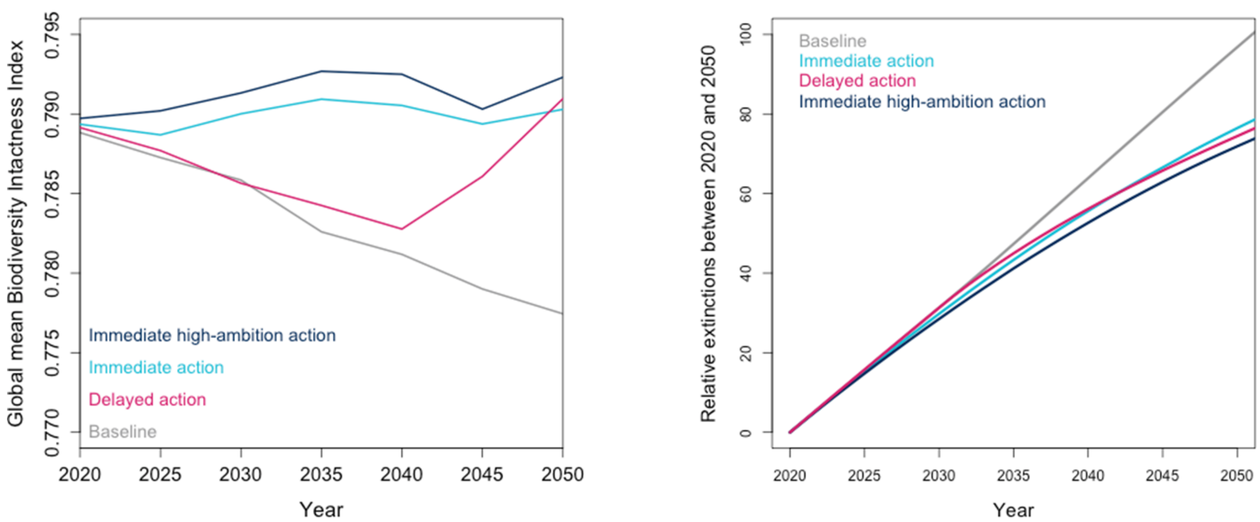
[1] To enable cost comparison the overall global biodiversity outcome is kept similar between scenarios.

Figure 1 Biodiversity intactness index (a) and species extinction (b) across immediate, immediate high-ambition and delayed action scenarios, compared with a baseline of no action

a.) b.)




Note: It should be noted that to reach the similar BII outcome as the immediate action scenario, delayed action requires a historically unprecedented rate of forest expansion. The immediate high-ambition scenario is designed to reduce extinctions by 25% in 2050, relative to the immediate-action scenario.

Source: Vivid Economics and NHM

**Findings on feasibility**

**The delayed-action scenario is probably *not feasible*. It requires forest expansion of 490 Mha distributed across the world, an area equivalent to the size of the Amazon rainforest, over a 20 year period. This would be a historically unprecedented rate of forest expansion**. To achieve similar biodiversity outcomes across both scenarios, delayed action requires 70% more land to be placed under forest expansion (an extra 200 Mha) than the immediate-action scenario, part of which comes through reduction in cropland and pastureland (see Table 1). The additional expansion effort in the delayed scenario compensates for additional forest loss between 2020 and 2030, in the absence of effective protection measures, and for the lower maturity of forest ecosystems expanded in the two decades leading up to 2050. The feasibility of such extensive expansion effort has *never* been tested in practice. For comparison, China, which has achieved more tree planting than all other countries combined, reported up to 43 Mha of plantations between 2000 and 2010, with much of this this comprising exotic trees with low biodiversity value (Antje *et al.*, 2017). It will be harder to achieve biodiversity-rich expansion than plantations of fast-growing, mostly exotic tree species. For these reasons, the delayed-action scenario appears infeasible.

Table 1 2050 land cover projections under immediate and delayed action scenarios

| Land cover | 2020 (Mha) | Net change, 2021-2050, Immediate action scenario, in Mha (%) | Net change, 2021-2050, Delayed action scenario, in Mha (%) | Difference between net change in delayed and immediate action scenarios, in Mha |
|---|---|---|---|---|
| Primary and secondary forest | 3,710 | -40 (-1%) | -110 (-3%) | -70 |
| Land under forest restoration | 270 | +290 (+106%) | +490 (+182%) | +200 |
| Cropland | 1,610 | -40 (-2%) | -50 (-3%) | -10 |
| Pastureland | 3,210 | -50 (-2%) | -130 (-4%) | -80 |
| Other land | 3,960 | -160 (-4%) | -210 (-5%) | -50 |

Delayed scenario requires forest expansion of **490 Mha, 200 Mha** more than the immediate action

Additional **10 Mha** reduction in cropland, and **80 Mha (total 2%)** reduction in pastureland in delayed scenario

Note: For definitions of land cover types, see the Glossary of Terms, on page 12.
Source: Vivid Economics based on MAgPIE analysis

Findings on economics

**The decade-long delay in taking action to arrest and reverse biodiversity loss *doubles the cost* of action over 30 years, discounted at 3.5%.** Delay is estimated to double the cost of biodiversity action by USD 8 trillion, from USD 7 trillion under immediate action to USD 15 trillion. In order to stimulate action by landowners and managers globally, a global-average payment for combined carbon sequestration and biodiversity services might be required, indicatively USD 820 per ha restored per year for immediate action and USD 1,000 per ha restored per year for delayed action between 2021 and 2050. The biodiversity payments may include payments or taxes to encourage changes in land use.

**Biodiversity action globally appears affordable, on average, leading to a relatively small increase in global-average food prices. However, the distributional impact, in particular on lower income households, deserves investigation, as it could be adverse**. Relative food prices will decline in the immediate action scenario but will increase from 4.1% to 4.4% of global-average household income in the delayed action scenario. Higher food prices will disproportionately affect the poor.

**Technology-adoption investment,** such as ecological intensification, use of high yielding varieties and irrigation, allows food and material productivity per hectare improve to the level required to meet demand. In response to the growing global population, changing diets and biodiversity protection, global average yields might need to increase by 50% by 2050 compared to today. This could be achieved through the adoption of technology, changes in land tenure and the amalgamation of smaller farms into larger holdings, among other means. These are potentially disruptive changes which will be more feasible if they occur gradually. The costs of technical change are broadly cost neutral, with the investments paying for themselves. In other words, although the investments consume capital, they also reduce the future costs of production and these effects balance out.

**In most cases, it is wise to signal the form and level of new incentives *in advance* of implementing them.** Substantial incentives will be needed to bring about and maintain forest expansion and associated biodiversity and greenhouse gas mitigation outcomes, through regulatory measures, economic incentives or both. As discussed above, the size of these incentives may double in the delayed-action scenario, compared to the immediate-action scenario. There is no doubt that incentives at the level required could be disruptive to agricultural producers and processors, so it is better to give them advance notice in most cases.

**Common sense tells us that the coordination of biodiversity and climate change policy would achieve GHG green-house gas (GHG) emissions reductions and biodiversity improvements in a cost-efficient way.** Since there is scope for errors to be made given the scale, novelty and disruptiveness of the action, attention will have to be paid to design, driving out rent-seeking behaviour and carbon sequestration that comes at the cost of biodiversity.

**Land prices will rise more steeply in the delayed scenario**. Due to increased food demand and reduced supply, agricultural land prices rise in both scenarios, but more steeply in the delayed action scenario. The political implications of rising land prices deserve consideration: if prices rise rapidly, there may be political resistance to the changes driving price rises.

Findings on biodiversity

**Species extinctions are predicted to be similar across the two scenarios by 2050**. In the baseline scenario, which assumes that only existing biodiversity action continues, 3% of endemic terrestrial animal and plant species are projected to go extinct by 2050; more than were driven extinct by habitat loss in the entire period 850-1850 CE. Immediate and delayed action would reduce the baseline extinction rate by approximately one fifth (Figure 1b), if the necessary actions are implemented. While the number of extinctions is similar in both scenarios, the species mix will be different.

**It appears feasible to increase biodiversity from today's levels** (shown by the immediate high-ambition scenario) **if immediate action is taken but less feasible if action is delayed.** Immediate high-ambition action would reduce the level of extinctions in 2050 by 25% compared to the immediate-action scenario that stabilizes biodiversity outcomes (see Figure 1b) with a similar biodiversity (BII) outcome. Unsurprisingly, this avoidance of extinctions comes at a cost, of approximately USD 2 trillion, 27% higher relative to the immediate-action scenario. The higher ambition scenario gives better outcomes at lower cost than delaying action.

## Methods

**The results were obtained from a land use model and two biodiversity models**. MAgPIE is a partial equilibrium land use model that determines the least-cost way to meet food demand while accounting for biophysical constraints including those on land, water and crop yields (Dietrich, J. et al., 2020). It is coupled with two global models of how land use affects biodiversity. First, MAgPIE is coupled with PREDICTS, which estimates the average biodiversity intactness of local ecosystems (Purvis, A. et al., 2018). It models the Biodiversity Intactness Index (BII), which is defined as the average site-level abundance of functionally diverse species relative to reference populations in unimpacted areas. Second, MAgPIE is coupled with a dynamic species-area model, which estimates the extinction trajectories of habitat-specialist endemic species after habitat is lost (Wearn, Reuman and Ewers, 2012; Purvis *et al.*, 2017; Dietrich *et al.*, 2019). The biodiversity models use land use data and observed species responses from a global database.

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# Abbreviations

| Abbreviation | Definition |
|---|---|
| BII | Biodiversity Intactness Index |
| FAO | Food and Agriculture Organization of the United Nations |
| GDP | Gross domestic product |
| GHG | Greenhouse gases |
| IIASA | International Institute for Applied Systems Analysis |
| IPBES | Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services |
| IPCC | Intergovernmental Panel on Climate Change |
| IUCN | International Union for Conservation of Nature |
| MAgPIE | Model of Agricultural Production and its Impact on the Environment |
| NHM | Natural History Museum |
| NPi | National Policies implemented |
| NPP | Net Primary Productivity |
| PIK | Potsdam Institute for Climate Impact Research |
| PREDICTS | Projecting Responses of Ecological Diversity in Changing Terrestrial Systems |
| RCP | Representative Concentration Pathways |
| SSP | Shared Socioeconomic Pathways |
| UNCBD | United Nations Convention on Biological Diversity |
| USD | United States Dollar |
| WDPA | World Database on Protected Areas |

# Glossary of terms

| Term | Definition |
|---|---|
| **Afforestation** | In this work, afforestation is the conversion from other land uses into natural or managed forest, on not naturally forested land. Forest on not naturally forested land has low potential to improve biodiversity intactness. |
| **Area protection** | Various definitions for protected areas exist. In this work, we assume current area protection is equivalent to the WDPA protected areas, which are equivalent to IUCN WDPA categories I and II. In all scenarios, we assume policy action expands protected areas to a coverage of 22% globally. For this expanded area protection layer we additionally include all areas with WDPA status III-VI plus proposed protected areas (areas which are not protected, but deemed by WDPA to be prioritised for protection in near or distant future) plus key biodiversity hotspots (see Appendix B1 for detail). Area protection is assumed to remove the land from the pool of available land for food and material production. |
| **Biodiversity Intactness Index** | The BII is defined as the average abundance, relative to reference populations in unimpacted areas, of a set of functionally diverse species. 'Novel' species, that is species that would not be present if the site were unimpacted, are excluded. It provides a measure of average local site-level biodiversity, which is more important than the level of global biodiversity for the delivery of many ecosystem services. As BII is a measure of biodiversity integrity or functioning, and losses and gains in BII in ecologically very different regions across the world are considered substitutable in this work, maintaining or increasing average global BII does not imply No Net Loss or a Net Gain of biodiversity[2]. |
| **Biodiversity incentive** | In this work, the biodiversity incentives are policies put in place towards biodiversity stabilization, and may include payments to land managers to alter land management for improved biodiversity outcomes (such as results based payments for biodiversity), or incentives to discourage biodiversity loss (such as biodiversity offsets or tax). |
| **Cropland** | In this work, cropland refers to land used for agricultural crop production, including bioenergy crops and forage |
| **Deforestation** | In this work, deforestation is the conversion of forest to another land use below the carbon stock threshold for forest cover. |
| **Endemism** | Endemism is the condition of a species of being restricted to a particular area with a prescribed extent. |

[2] No Net Loss or Net Gain of biodiversity assumes that losses and gains in biodiversity are ecologically equivalent, including in their composition. This restricts the kinds of gains that can counterbalance a loss (see Business and Biodiversity Offsets Programme (BBOP), 2012).

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|---|---|
| Extinction debt | Extinction debt is the diversity number of species without enough habitat for long-term persistence. Not all regions have an extinction debt: it is zero in areas that never had many endemic species and in areas where natural habitat was lost so long ago that all resulting extinctions have already occurred. |
| Forest expansion | In this work, forest expansion refers to the transformation of non-forest to forest through reforestation (assisted growth of natural vegetation or natural forest succession), or afforestation. |
| Habitat | Area providing suitable conditions for the survival of a particular species or organism. |
| Land under forest restoration | In this work, land under forest restoration refers to land that has become forest by afforestation (low increase in biodiversity levels) or reforestation (assisted growth of natural vegetation or natural forest succession on naturally forested biomes) and does not yet qualify for secondary forest. |
| MAgPIE | The Model of Agricultural Production and its Impact on the Environment is a global land use allocation model designed to explore land competition dynamics in the context of carbon policy developed by the Potsdam Institute for Climate Impact Research. |
| Materials of agricultural origin | In this work, materials of agricultural origin include all non-food and non-fodder products grown on agricultural lands, for example timber and agricultural products for cosmetics, chemical usage or textiles. |
| Net Primary Productivity | Net Primary Productivity is the rate at which an ecosystem accumulates energy or biomass in excess of respiration, commonly used as an indicator of ecosystem function. Remotely sensed images can be used to estimate NPP. |
| Other land | In this work, other land refers to non-forest natural vegetation (defined as carbon stock below 20tC/ha), abandoned agricultural land and deserts. Depending on its biome, other land can become forest by afforestation (low increase in biodiversity levels) or reforestation (assisted growth of natural vegetation or natural forest succession on naturally forested biomes). |
| Pastureland | In this work, pastureland refers to land used as pasture for livestock rearing. |
| PREDICTS | Projecting Responses of Ecological Diversity in Changing Terrestrial Systems is a global database of biodiversity surveys combined with high resolution global land use data that estimates the human impact on biodiversity. PREDICTS was built by students and staff at the Natural History Museum, UNEP-WCMC and elsewherefrom data contributions of various researchers. |
| Primary Forest | In this work, primary forest refers to forest that has never been cleared by human intervention, though humans may have affected it. It is assumed that transitions to primary forest are impossible; land can never return to primary forest within the modelling timeframe. |

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|---|---|
| **Range-size rarity** | Range-size rarity is the condition of a species of occupancy occurring infrequently among areas. |
| **Reforestation** | In this work, reforestation is the conversion from other land uses into forest, on land that is naturally forested (assisted growth of natural vegetation or natural forest succession on naturally forested biomes). |
| **Secondary Forest** | In this work, secondary forest refers to forest that is recovering from human or natural disturbance of the original forest vegetation which often displays a major difference in forest structure and/or canopy species composition with respect to primary forests on similar sites. |
| **Urban land** | In this work, urban land refers to urban settlement areas. Urban land is assumed unchanged between 2020 and 2050. |

# 1 Introduction

**Various authors have demonstrated beyond doubt that biodiversity is declining at a rapid rate due to impacts of human economic activities; however, the effect of *delay* on the *cost of action* to stabilize biodiversity and the feasibility of that action has not been reported until now**.

**The average abundance of native species has fallen in most terrestrial biomes by at least 20% relative to reference populations in unimpacted areas.** This decline has largely taken place since the Industrial Revolution, and it may be accelerating (IPBES, 2019). Biodiversity loss ranked in the top five risks of the World Economic Forum 2020 Global Risks Report (WEF, 2020). While it has been reported that pollinators alone contribute between USD 235 billion and USD 577 billion to annual global food production (IPBES, 2019), there are no global estimates of the costs of delaying mitigation action to address biodiversity loss. These themes will be taken up in the 15th Conference of the Parties of the UN Convention on Biological Diversity and the 26th Conference of the Parties of the UN Framework Convention on Climate Change, both of which are scheduled to take place in 2021.

**This report evidences the case for immediate action to address global terrestrial biodiversity loss, by showing the costs of delay and presenting quantitative evidence on the feasibility of delayed delivery.** The evidence is generated by three linked models: MAgPIE, a partial equilibrium land use model that determines the least cost way to meet food demand while accounting for biophysical constraints including those on land, water and crop yields (Dietrich J. et al, 2020); PREDICTS, a framework for modelling and projecting the global average state of local biodiversity (Purvis, A. et al., 2018); and a dynamic species-area model, which projects the extinction trajectories of narrowly-distributed species of habitat specialists after changes in the extent and quality of natural habitat. The scope of this work is constrained to restoration through reforestation of naturally forested areas to generate positive outcomes for biodiversity as a result of global action. Actions targeting aquatic, coastal, marine and other terrestrial biodiversity lie beyond the scope of this work. However, biodiversity outcomes are estimated for all terrestrial biodiversity, and so the results serve as an indication of the scale of potential costs of inaction in other ecosystems.

**The analysis compares estimates of costs, biodiversity intactness and species extinctions between immediate and delayed action scenarios to address biodiversity loss and reduce species extinction, each of which achieves a similar biodiversity intactness outcome by 2050 and one of which reduces the rate of extinction.** In the immediate action scenario, the global community acts *now* to stabilise biodiversity intactness at current levels by 2050. Decisive action begins by 2020 and is projected to prevent over 20% of the extinctions of endemic species that would occur if there were no increase in ambition or coverage of currently implemented policies on climate change, conservation of biodiversity and area protection. In the delayed-action scenario, were it to be feasible, substantive action on biodiversity is delayed until 2030, but more abrupt and disruptive action follows thereafter and restores biodiversity intactness to current levels by 2050. By restoring a much larger area of forest habitat, the delayed action scenario also leads to similar total numbers of extinctions of endemic species by 2050 as in the immediate-action scenario.

This report is structured as follows:

- Section 2 describes the methodology including assumptions and limitations;
- Section 3 presents the key results on biodiversity, physical land use changes and costs of action;
- Section 4 discusses the results;
- Section 5 concludes; and

- Two Technical Appendices contain a sensitivity analysis of results (Technical Appendix A), detailed method statement, data sources and assumptions (Technical Appendix B).

# 2 Methodology

**This work creates insights by linking two global biodiversity projection frameworks (PREDICTS and a dynamic species-area model) with a global integrated land use economic model (MAgPIE).** These frameworks have a track record of being used in high-profile, international scientific studies including in flagship publications by the IPCC and IPBES. Sections 2.1, 2.2 and 2.3 summarise the modelling frameworks applied in this work including key assumptions and limitations. Technical Appendix B contains further detail on the modelling frameworks, assumptions and model integration.

## 2.1 Models

### 2.1.1 MAgPIE

**The Model of Agricultural Production and its Impact on the Environment (MAgPIE) is a global land use allocation model designed to explore land use dynamics in the context of carbon policy.** Developed by the Potsdam Institute for Climate Impact Research (PIK), MAgPIE is a spatially explicit, partial equilibrium model that solves for the least-cost allocations of land uses and investment in technical change to meet future demand for food and materials of agricultural origin, based on assumed population, gross domestic product (GDP) and dietary trajectories (Dietrich et al., 2020). It also allows for land to be protected and set aside. It produces a land use change raster for modelled 5-year timesteps based on policy assumptions, such as carbon pricing and land related policies. MAgPIE accounts for both biophysical constraints on yield, land and water as well as for regional economic conditions. Land use change rasters are passed from MAgPIE to PREDICTS in this work.

**In addition to producing a land use change raster, MAgPIE generates indicative cost estimates of policy instruments associated with a given action scenario**. These cost estimates include land conversion costs, inputs to global food and material production and investment in productivity enhancement and irrigation. The model outputs aggregate food and agricultural commodity prices.[3] Thus, the model indicates producers' costs, cost to consumers and the strength of incentives needed to effect change.

**MAgPIE also estimates the greenhouse gas emissions intensity of land use.** It models three GHG gases, carbon dioxide, nitrogen compounds and methane. It accounts for carbon dioxide emissions from loss of terrestrial carbon stocks, including the depletion of organic matter in soils. Nitrogenous emissions are estimated based on nitrogen budgets for croplands, pastures and the livestock sector. Methane emissions are based on livestock feed and rice cultivation areas. When regrowth of natural vegetation occurs, it is recorded as negative emissions in the GHG accounts.

### 2.1.2 PREDICTS

**Projecting Responses of Ecological Diversity in Changing Terrestrial Systems (PREDICTS) is a global database of biodiversity surveys combined with high resolution global land use data that estimates human impact on biodiversity (Purvis, A. et al., 2018).** The historic relationship between land use change and biodiversity intactness combines with projected future land use changes from MAgPIE to yield estimates of the biodiversity impact associated with each action scenario.

**Based on the land use change rasters passed from MAgPIE, PREDICTS estimates the Biodiversity Intactness Index (BII), which measures how much of a terrestrial site's original biodiversity remains, or is projected to remain, in the face of anthropogenic land use pressures.** The BII is defined as the average abundance,

[3] Following good practice and recognising limitations of the model, this work primarily analyses relative cost, that is cost differences between scenarios, rather than absolute costs.

relative to reference populations in unimpacted areas, of functionally diverse species. 'Novel' species, that is species that would not be present if the site were unimpacted, are excluded. It provides a measure of average local site-level biodiversity, which is more important than the level of global biodiversity for the delivery of many ecosystem services. As BII is intended to be used as a measure of biodiversity integrity or functioning, and losses and gains in BII in ecologically very different regions are substitutable, this measure cannot on its own be used to reflect No Net Loss or a Net Gain of biodiversity[4].

**The PREDICTS database empirically estimates BII from two statistical models**, fitted to data from a large, taxonomically and ecologically representative set of plant, invertebrate and vertebrate species worldwide.

1. **The total abundance of species** at sites in the database is modelled in response to land use, human population density and their interaction.
2. **The compositional similarity of species to sites in minimally-used primary vegetation** is modelled to discount novel species, accounting for human population density at the baseline site of minimally-used primary vegetation and the comparator site.

### 2.1.3 Dynamic Species-Area Modelling

**Building on BII results, Dynamic Species-Area Modelling complements the PREDICTS framework (Wearn, Reuman and Ewers, 2012; Purvis et al., 2017; Dietrich et al., 2019).** The species-area relationship can be used to project how land use change will affect the number of species a region supports over the long term, but does not by itself say how quickly reductions in natural habitat result in extinction. A recent meta-analysis synthesised information on the rate at which the new equilibrium is approached. By focusing on narrowly-distributed (endemic) species dependent on natural habitat, a category that includes many if not most terrestrial plant and invertebrate animal species, these approaches are combined into a dynamic species-area model that allows estimation of the trajectory of extinction of an area's endemic species diversity, given its history of natural habitat loss. The restoration of habitat can avert some of the extinctions that would otherwise occur, provided restoration takes place sufficiently soon after the initial loss of natural habitat. The restoration of larger areas can save more species but, for a given area of restoration, earlier restoration saves more species later restoration.

**Both BII and species extinctions are reported in parallel.** BII, a measure that can rise and fall in response to habitat change, is a broadly-applicable indicator of an ecosystems' ability to function effectively and provide a range of biodiversity-dependent ecosystem services. By definition, BII gains in one region or ecosystem can substitute for losses in others when aggregated globally, even though the underlying species, communities and ecosystems in these regions may differ vastly in their composition, structure and in the way they function. While BII can rise and fall, species extinctions, on the other hand, are irreversible. A species' persistence depends on the persistence of suitable habitat in its natural geographic range which, for endemic species, is by definition a small area and cannot be exchanged for habitat elsewhere. The work does not address other dimensions of biodiversity such as genetic diversity or functional diversity.

## 2.2 Scenario assumptions

**Two scenarios with similar outcomes for biodiversity intactness in 2050 and one which targets lower rates of extinction are compared**. The first two scenarios assume policy actions that realise a biodiversity outcome in 2050, that is equal to the level of BII today. In other words, they both stabilise this measure of biodiversity

[4] NNL or NG of biodiversity assumes that losses and gains in biodiversity are ecologically equivalent, including in their composition. This restricts the kinds of gains that can counterbalance a loss (see (Business and Biodiversity Offsets Programme (BBOP), 2012).

intactness. The question of urgency is assessed by comparing costs and quantitative indicators of feasibility between the immediate and delayed action scenarios.

- In the **immediate action scenario**, the global community acts now to reverse loss and stabilise biodiversity intactness by 2050 at today's levels. Decisive action begins in 2020 in this scenario.
- In the **delayed action scenario**, substantive action on biodiversity is delayed until 2030, but more abrupt and disruptive action thereafter restores biodiversity intactness, stabilising it by 2050 at today's levels. Decisive action begins in 2030 in this scenario.
- In addition, the **immediate high-ambition action scenario** is a variant of the immediate action scenario. It tests the incremental cost of moving from stabilisation to improvement in biodiversity intactness. The global community acts now to reverse loss and rebuild biodiversity intactness and reduces extinctions by 25% between 2020 and 2050 compared to baseline, which is a greater reduction than seen under immediate (21%) and delayed (23%) action scenarios. Decisive action begins in 2020 in this scenario.

**A reference scenario serves as a comparator.**

- The **baseline scenario** indicates BII levels and extinctions of endemic species that would have happened if no increase in ambition or coverage of currently implemented policies on climate change, biodiversity and area protection were to take place, and no current policy announcements were implemented. It serves as baseline against which the biodiversity outcomes of the action scenarios can be compared but is not a possible or likely path of action.

**In all action scenarios, convergence on the intended biodiversity outcome is driven by three policy instruments within the MAgPIE model: climate policy, biodiversity policy and area of land protected.** *Climate policy* is introduced in the form of incentives to mitigate greenhouse gas (GHG) emissions, comprised of disincentives for emitting GHGs and rewards for carbon sequestration. *Biodiversity policy* takes the form of disincentives (penalties) for biodiversity losses and rewards (payments) for forest expansion, adjusted to range-size rarity of the location.[5] All policy instruments are active in all action scenarios, but they are introduced gradually starting in the stated starting year, which varies between immediate and delayed action scenarios. In addition, the climate and biodiversity incentives are imposed at higher levels in the delayed action scenario compared to the immediate action scenario, as both scenarios were calibrated to the same BII outcomes in 2050, requiring higher incentive levels when action starts late. *Area protection* occurs at an identical scale and location in the immediate and delayed action scenarios, but with different timing. The protected areas comprise the designated WDPA protected areas (all categories) and the proposed protection areas and key biodiversity hotspots (Leclère D, Obersteiner M, Butchart SHM, Chaudhary A, De Palma A, DeClerk FA, Di Marco M, Doelman JC, 2019).

**All scenarios adopt the population and GDP growth projections of SSP2 of the Shared Socioeconomic Pathways** (O'Neill *et al.*, 2014; Riahi *et al.*, 2017). It is assumed that diets and corresponding food demand exhibit a reduction of 25% in ruminant meat share of diet by 2050. In all scenarios, the physical impacts of climate change affect crop yields in a location-specific way via changes in water availability and temperature.[6] Table 2 summarises the scenario assumptions.

[5] Range-size rarity is the condition of a species of occupancy occurring infrequently among areas.
[6] MAgPIE builds on pre-computed results of the Lund-Potsdam-Jena managed Land Dynamic Global Vegetation and Water Balance Model (LPJmL) for this.

Table 2 Scenario Assumptions: Delayed and immediate action scenarios differ in scale and starting year of climate policy and biodiversity policy, and in starting year of increased area protection

| Design element | Immediate action scenario | Delayed action scenario | Immediate high-ambition action scenario | Baseline scenario |
|---|---|---|---|---|
| **Area protection** | 22% of global land area, starting in 2020* | 22% of global land area, starting in 2030* | 22% of global land area, starting in 2020* | No change from current policies implemented |
| Climate policy | SSP2 RCP2.6 consistent trajectory with GHG prices phasing-in globally in 2020 | SSP2 RCP1.9 consistent trajectory with GHG prices phasing-in globally in 2030 | SSP2 RCP2.6 consistent trajectory with additional ambition in $CO_2$ pricing, GHG prices phasing-in globally in 2020 | SSP2 NPi trajectory consistent with existing National Policies implemented |
| **Biodiversity policy** | SSP2 RCP2.6 consistent trajectory | SSP2 RCP1.9 consistent trajectory | SSP2 RCP2.6 consistent trajectory | SSP2 NPi consistent trajectory consistent with existing National Policies implemented |
| Socioeconomic pathways<br>- Population growth<br>- GDP growth | SSP2 – 'Middle of the road' consistent pathways | | | |
| Diets (food demand) | 25% reduction in ruminant meat share of diet by 2050 | | | |

Note: *Protected area expansion is introduced as a single pulse into the model in the specified year, although this is not practically realistic. The Technical Appendix B provides more detail on scenario assumptions including sources of each data layer.
Source: Vivid Economics, IIASA (for SSP2)

## 2.3 Limitations

**This work assesses the relative cost of delaying reforestation action to stabilise terrestrial biodiversity and takes this as a proxy for a wider set of possible conservation efforts.** This work does not assess or draw any conclusions regarding conservation of aquatic, coastal and marine biodiversity. Furthermore, except for area protection, which covers areas of all terrestrial land types, the conservation actions in this work do not target terrestrial biomes other than forests.[7] While terrestrial biodiversity is broader than the biodiversity of forests, forests have been central to global biodiversity conservation efforts as tropical forests represent the most species-rich habitat type worldwide (Gibson *et al.*, 2011) and pressures from human activities today are leading to forest degradation, fragmentation, forest loss and homogenisation (FAO, 2020). By assessing the cost of delaying forest restoration action, this work focuses on the biggest lever of terrestrial biodiversity conservation and the results proxy for a more diverse set of terrestrial biodiversity conservation actions.

**Conclusions should be drawn from the relative costs of scenarios rather than the absolute cost figures.** This is on the one hand because the model can never fully reflect all aspects of the subject it describes, and on the other hand because model sensitivity to key assumptions is unavoidable. For example, in real life, the policy costs might be lower or higher than those assumed in this work. Policy instruments in the model which operate as incentives for forest expansion, climate policy in the form of incentives to mitigate and sequester greenhouse gas (GHG) emissions, and biodiversity policy in the form of disincentives for biodiversity losses and rewards for forest expansion, display high, feasible prices but a different policy mix could be applied leading to different levels of transfers. Other important assumptions driving cost results include speed of technological progress and crop productivity potential, among others. While technical assumptions are based on latest research where possible, they remain imperfect reflections of reality. To account for this characteristic of the models, the findings focus more on the relative results of scenarios than the absolute results.

**This work does not explore the question of who bears the cost of immediate or delayed action.** While model results indicate in which global regions added costs of land conversions, production inputs, investment in technological change and other costs of land use occur, the work does not investigate which regions bear these costs, nor does the work explore how the costs would be distributed between producers, consumers and governments. Similarly, no claim is made regarding relative gains and losses in BII levels of world regions.

**The work does not consider the justice of outcomes.** It contains no distributional analysis and does not show the likely differential effects across nations or between poor and rich households. However, it is not controversial to state that, because of an increase in food prices, the delayed-action scenario is likely to make the poor worse off.

**MAgPIE does not take into account regional differences in land-tenure arrangements and imperfections in land markets.** Land prices are a relevant determinant for cost of protection measures and food-production decisions, but real-life market characteristics would lead to land use changes that are different to those the model predicts. The model assumes land prices always perfectly reflect the opportunity cost of the land, resulting in globally optimal land use at every timestep.

**The work is calibrated to empirical estimates of how BII increases as recently expanded forest ages, in particular for reforestation.** The results are sensitive to the calibration between BII in reforested land and the date after planting, see further discussed in Technical Appendix A2 on the sensitivity of results.

**In all action scenarios, protected area expansion is introduced and fully implemented immediately at the action start date, rather than gradually**. This unlikely to be realistic and slower implementation would lead to lower BII levels over time and in 2050 in all scenarios.

**The benefits of restoring and conserving biodiversity, such as enhanced ecosystem services, which would feature in a full cost benefit analysis, are not assessed in this work.** This work instead contributes to that

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[7] While two of the three conservation actions in the model target forest expansion only, all reported biodiversity outcomes of scenarios in this work (BI levels and extinction of endemic species) were calculated for all terrestrial biodiversity.

broader cost benefit question by studying one important aspect of it, namely the relative additional cost of delaying action.

**Lastly, biodiversity is a richer concept than a static, averaged benchmark such as BII.** Similar BII levels in 2050 describe a point in time on dynamic scenarios of immediate and delayed action scenario. The biodiversity levels would not follow the same path beyond 2050. In addition, BII is a measure of ecological functioning or integrity. When used in a global model, with losses and gains in BII considered substitutable across regions, maintaining (or increasing) BII does not imply No Net Loss or a Net Gain of biodiversity.

# 3 Results

## 3.1 Key results

There are five key findings.

- **It is *twice as expensive* to delay action as to act immediately.** Delay results in nearly three times as much primary and secondary forest and associated biodiversity being lost, see Sections 3.3 and 3.5.
- **It is feasible to significantly reduce *extinction rates* of endemic species if action is immediate**, see Section 3.2.2. In a baseline scenario without greater action than currently implemented policies, more endemic species will go extinct in the coming 30 years than appear to have died out in the entire period 850-1850 CE.
- **If action is immediate, there is an option to *make a bigger reduction in extinction rates***, see Section 3.2. This option would require immediate high-ambition action and is lost when action is delayed.
- **If action is delayed, it becomes *infeasible to stabilise biodiversity* intactness globally even at today's depleted level.** This is because the scale of reforestation becomes so great with delay, that the incentives needed to change land use rise three-fold. The incentives thus become so disruptive, the yield improvements required by some farmers so immense, and the land and the food price changes so rapid, that the necessary reforestation could only be achieved with levels of political will, effort and coordination well beyond the capabilities of the institutions we currently have or are likely to have.
- **The global cost of food and materials production from 2021 to 2050 is lower under immediate action and higher if action is delayed, as a share of global-average household income,** see Section 3.5.

## 3.2 Biodiversity outcomes

**Box 1 Biodiversity outcome results**

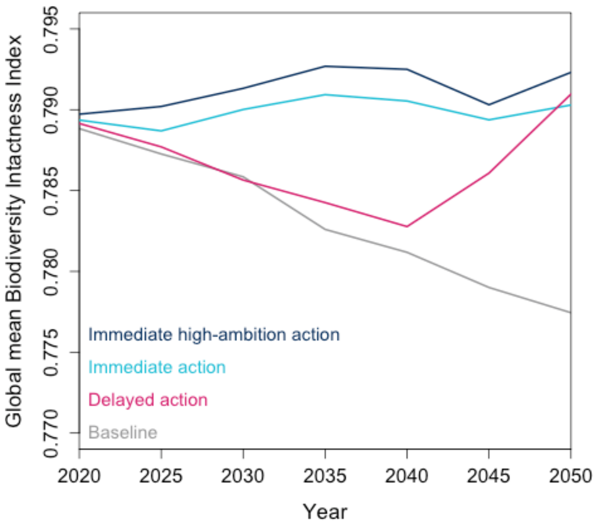
- The forest extension in the delayed action, immediate action and immediate high ambition scenarios would reduce the global number of extinctions of endemic species between 2021 and 2050 by 23%, 21% and 25% respectively.
- The immediate and delayed action scenarios are calibrated to reach equivalent BII shortly before 2050, but average BII levels under delayed action are lower in the years leading up to 2050.
- The feasibility of maintaining global BII, especially under the delayed scenario, is very questionable.
- Note that the BII substitutes biodiversity gains and losses globally in producing a single global index value.

**This section presents BII and species extinction outcomes of the three action scenarios relative to a baseline scenario of current policies**. The baseline shows BII levels and extinctions of endemic species that would have happened if *no increase* in ambition or coverage or enforcement of *currently implemented policies* on climate change, biodiversity and effective area protection were to take place. All scenarios are characterised in Section 2.2, with additional detail provided in Technical Appendix B.

### 3.2.1 Biodiversity Intactness Index

**While both immediate and delayed action scenarios are calibrated to deliver BII stabilisation by 2050, BII levels between 2020 and 2050 are on average higher under immediate action.** Figure 2 presents pathways of global average BII between 2020 and 2050. In the chart, BII rises as a result of projected forest expansion and the maturation of forest and falls as a result of projected forest loss. The difference in average biodiversity levels over time is an important characteristic of the results; for example, the level of biodiversity-dependent ecosystem services across this time interval (not assessed in this work) would depend on the whole time series, not just the value in 2050.

Figure 2 Biodiversity intactness index across immediate and delayed action scenarios, compared with a baseline of no action




Note: Immediate and delayed action scenarios were calibrated to reach similar mean BII levels by 2050 by selecting higher levels of climate and biodiversity action in the latter scenario. The poor feasibility of the rapid and strong policy action of the delayed action scenario is discussed further in Section 3.6.

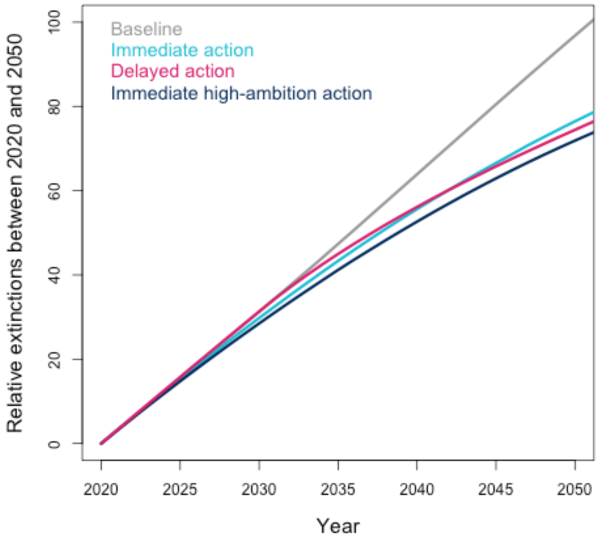
Source: NHM

### 3.2.2 Extinctions

**Forest expansion in the delayed, immediate and higher ambition scenarios reduces the number of extinctions of endemic species between 2020 and 2050 by 23%, 21% and 25%, respectively, relative to the baseline scenario** (**Figure 3**). Global extinction is permanent and irreversible, but its pace can be lessened by habitat restoration and protection. In the baseline scenario of no additional biodiversity action, 3% of endemic terrestrial species included in the BII measure and modelling will become extinct by 2050, more than are estimated to have died out in the period 850-1850 CE. Across the action scenarios, this figure is cut by between a fourth and a fifth due to forest expansion.

**Immediate action visibly prevents extinctions from 2025 onwards, while delayed action begins to have visible effects after 2030.** The delayed action scenario prevents relatively more extinctions than the immediate action scenario by 2050, as it includes much more forest regrowth than the immediate action scenario, and a higher proportion of that growth is in naturally forested biomes. Ambitious immediate action reduces extinctions by nearly a fifth more than the lower-ambition early action. The species saved will not necessarily be the same in each scenario.

Figure 3 Cumulative extinctions in the immediate action and delayed action scenarios by 2050 are 21-23% lower than extinctions under the baseline




Source: NHM

## 3.3 Land use change

Box 2 Land use change results

- Nearly three times as much primary and secondary forest is lost, an additional 70 Mha, when action is delayed.
- To compensate for the losses in primary and secondary forest, a total of 490 Mha land must be restored to forest under delayed action, 200 Mha more than under immediate action.
- Net reductions in cropland and pastureland between 2020 and 2050 are twice as large when action is delayed.
- 290 Mha greater forest expansion is required when action is delayed.

**Nearly three times as much primary and secondary forest is lost, an additional 70 Mha, when action is delayed compared with immediate action.** Under delayed action, a total of 40 Mha or 3% primary forest is lost to deforestation between 2020 and 2050, compared to only 20 Mha under immediate action. Similarly, 70 Mha, 3% of secondary forest is lost to deforestation in the same period under delayed action, compared to only 20 Mha under immediate action. Jointly, this adds up to an additional 70 Mha of primary and secondary forest lost under delayed action. This difference is largely explained by a difference in timing of the increase in the effectively-protected area from 4% to 22% of land area.

**The scale of forest expansion required under delayed action is unprecedented and, based on current evidence, its feasibility is unclear.** To compensate for the extent of losses in primary and secondary forest, a total of 490 Mha land must be restored to forest under the delayed action scenario within 20 years, 200 Mha more than under immediate action and within a significantly shorter timeframe. More than one unit of young forest is needed to replace one unit of primary or secondary forest lost, in order to reach similar BII levels by the census date of 2050, since the age class of a forest affects its BII, with young forest achieving lower BII (see Technical Appendix B for detail) . Expressed in area, the scale of afforestation and reforestation effort that would be required between 2030 and 2050 under the delayed action scenario is comparable to 90% of the area of the Amazon rainforest, the largest rainforest in the world. The immediate action and immediate high-ambition action scenarios translate into 290 Mha and 300 Mha of forest land coming under restoration over 30 years (see Section 3.3). Forest restoration of such unprecedented scale may not be feasible due to limits of political will and the extent of global coordination required may not be possible with the institutions we have (see Section 3.6).

**Related to the scale of forest expansion effort, net reductions in area of cropland and pastureland between 2020 and 2050 are twice as large when action is delayed.** Under immediate action, both cropland and pastureland decrease by 2% (40 Mha and 50 Mha respectively). Under delayed action, decreases of 4% and 5% respectively occur (50 Mha and 130 Mha respectively). Under immediate action, the reductions in cropland and pastureland are driven by increased effective area protection, accompanied by improving yields arising from technology adoption. Under delayed action, very strong policy incentives in addition to increased effective area protection appear to be necessary to drive rapid large-scale forest expansion efforts, causing significant land use conversion from cropland and pastureland to forest. A greater proportion of pastureland than cropland is converted to forest. Table 3 shows land cover and conversion by category under each scenario.

Table 3 Land use changes under different scenarios: When action is delayed, an additional 200 Mha of forest has to be restored, causing additional scarcity of cropland and pastureland

| Land cover | 2020, Mha | Net change, 2021-2050, Immediate action, Mha (%) | Net change, 2021-2050, Delayed action, Mha (%) | Net change, 2021-2050, Immediate high-ambition action, Mha (%) | Difference in net change in between delayed and immediate action, Mha |
|---|---|---|---|---|---|
| Primary forest | 1,340 | -20 (-2%) | -40 (-3%) | -30 (-2%) | -20 |
| Secondary forest | 2,370 | -20 (-1%) | -70 (-3%) | -3 (0%) | -50 |
| Land under forest restoration | 270 | +290 (+106%) | +490 (+182%) | +300 (+112%) | 200 |
| Cropland | 1,610 | -40 (-2%) | -50 (-3%) | -60 (-4%) | -10 |
| Pastureland | 3,210 | -50 (-2%) | -130 (-4%) | -50 (-2%) | -80 |
| Other land | 3,960 | -160 (-4%) | -210 (-5%) | -170 (-4%) | -50 |
| Total land cover | 12,800 | | | | |

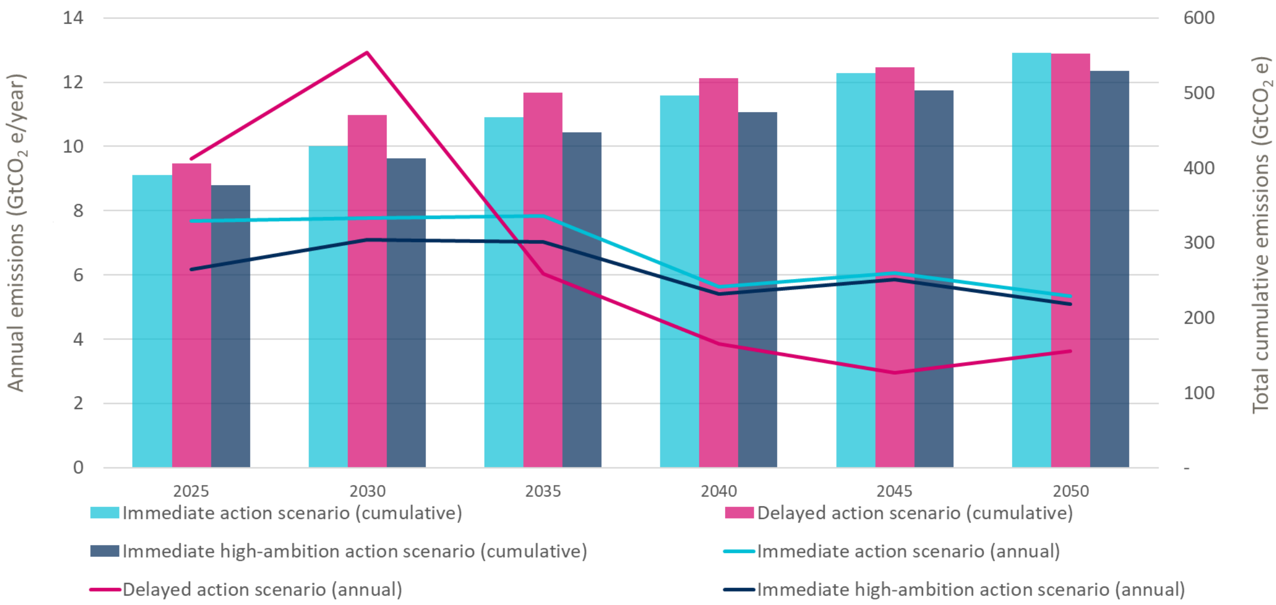
Note: Total land cover also includes urban land, which is not listed here. Other land is defined as other natural land which includes non-forest natural vegetation, abandoned agricultural land and deserts.
All values stated are MAgPIE outputs. MAgPIE is based on the LUHv2 land use layer from the University of Maryland Land Use Harmonisation project.

Source: Vivid Economics using MAgPIE

## 3.4 Greenhouse gas emissions

**GHG emissions from land use are projected to rise and peak under delayed action, but are projected to decline gradually under immediate action.** Aggregated annual estimates for $CO_2$, $CH_4$ and $N_2O$ net-emissions from land use expressed in $CO_2e$ gradually decline under immediate action, while they rise, peak and strongly decline under delayed action (see Figure 4). Cumulative undiscounted net emissions between 2020 and 2050 are comparable across the two action scenarios. Declines in GHG emissions across both scenarios are strongly driven by negative $CO_2$ emissions from the creation of carbon sinks and the implementation of abatement technologies.

Figure 4 Cumulative GHG emissions from land use are comparable across action scenarios




Note: GHG emissions from land use, including $CO_2$, $CH_4$ and $N_2O$. Annually (left axis) and cumulative (right axis)

Source: Vivid Economics using MAgPIE

## 3.5 Costs of action

**Box 3 Cost results**

- Twice the magnitude of land use change incentives is needed under delayed action compared with immediate action.
- Delay raises the total cost of food and material production between 2021 and 2050.

### 3.5.1 Definitions

**The total costs of land use and land use change encompass food production, production of materials of agricultural origin and forest expansion**. These comprise:

1. **Private cost (90%-95% of discounted cumulative costs over the period 2021-2050).** These are the costs of producing food and materials and restoring land. There are four components of private costs:[8]
   a. **input factors**: costs of labour, energy, physical inputs and non-land capital costs;
   b. **technical change:** costs of adoption of new technology, including irrigation expansion and national investment in research and development (R&D);
   c. **processing, transport and trade:** all downstream costs;
   d. **land conversion:** costs of conversion from one land use to another, including land clearing and land preparation for agriculture or forest expansion.

2. **Social cost (5%-10% of discounted cumulative costs of the period 2021-2050)**: The social costs comprise the sum of biodiversity and greenhouse gas incentives. The biodiversity incentives may include payments to land managers to alter land management for improved biodiversity outcomes (such as results based payments for biodiversity), payments for sequestering carbon in the form of standing timber, or incentives to discourage biodiversity loss (such as penalties or taxes). Payment could be in the form of transfers between governments, producers and consumers; the direction of the transfer depends on the allocation of property rights. The total incentive paid reflects society's decision to secure the outcome and hence the strength of its preference for that outcome, a proxy for its willingness to pay. This argument justifies calling this element the social cost. The quality of policy design and delivery will affect the magnitude of the social cost, see Section 4.

**All cost estimates are cumulative for the period 2021-2050 in 2019 USD and discounted at 3.5% per annum, in line with the Green Book guidelines of HM Treasury.** As this exercise compares cumulative costs over time, the choice of discount rate affects the difference in cost between immediate and delayed action. The cost difference between the immediate action and delayed action scenarios would appear larger if the costs were not discounted. An assessment of sensitivity of results to the discount rate is conducted in Appendix A. Note that the discount rate has been applied globally to costs in all world regions. Although there is a case to differentiate discount rates by region, that would have been outside the scope of work.

**The key costs to compare between the scenarios are the biodiversity incentives, that is, the social costs**. While other components of land use costs are important to consider, they do not show significant cost differences, and offset each other. The incentives for encouraging behavioural shift (such as technical change, reforestation, adaptation etc.) show the largest absolute cost increase between the immediate and

[8] See technical appendix B1 for further explanation on all of the below.

the delayed action scenarios. In addition, while the change in land use costs to achieve the same biodiversity outcomes across scenarios by 2050 are interesting to note, the incentives indicate the direct costs associated with biodiversity action, and are therefore represented in the headline message on cost differences between scenarios.

### 3.5.2 Differences in total cost

**The total costs of food and materials production are 8% higher under delayed action relative to the immediate action scenario** (**see Table 4**). The excess cost of delayed action is caused by more land conversion (16% larger cost) and stronger incentives (114% larger cost), while the remaining cost categories are at similar levels for both scenarios (Figure 5).

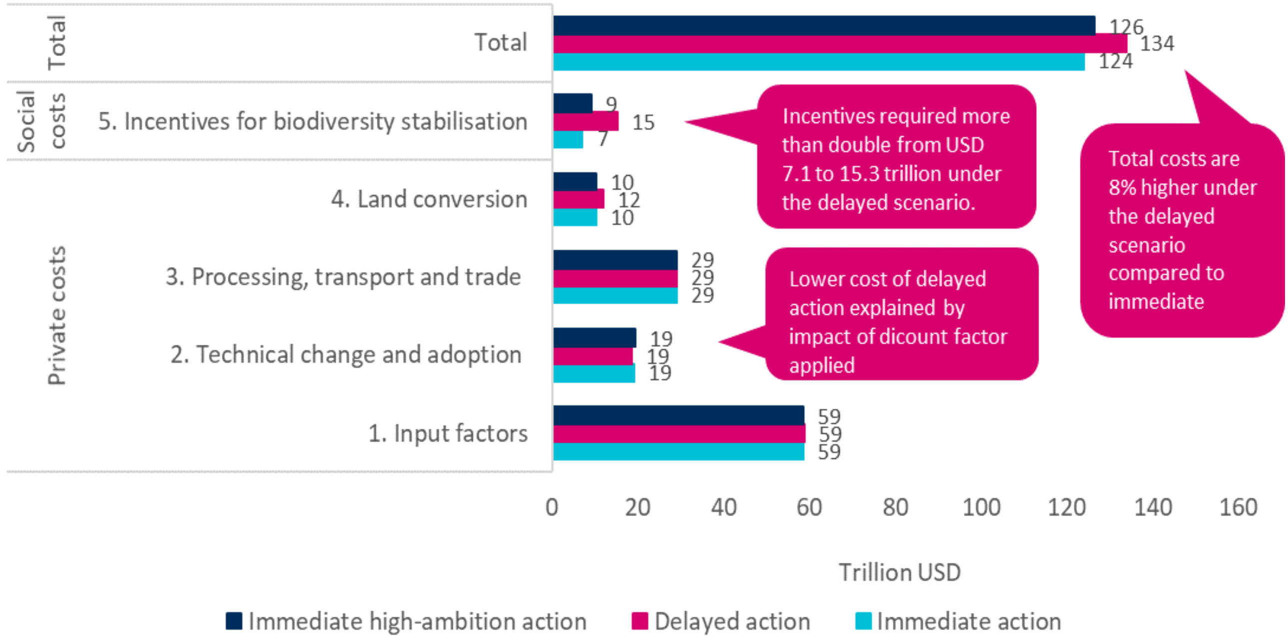
Table 4 The discounted costs of land use and land use change are USD 9.8 trillion, 8%, higher under delayed action than under immediate action

| | Cost type | Immediate action | Delayed action | Immediate high-ambition action | Delayed versus immediate action | Immediate high-ambition versus immediate action |
|---|---|---|---|---|---|---|
| | | (Cumulative cost, 2021-2050, Trillion USD) | | | (Difference in %) | |
| Private cost | **1. Costs of input factors for producing food and materials** includes labour, energy, physical inputs including fertilizer, non-land capital cost | 58.6 | 58.9 | 58.6 | **1%** | **0%** |
| | **2. Costs of technical change and adoption** includes R&D, adoption, including irrigation expansion | 19.1 | 18.6 | 19.4 | **-2%** | **2%** |
| | **3. Costs of processing, transport and trade** includes all downstream cost to consumer | 29.0 | 29.1 | 29.1 | **0%** | **0%** |
| | **4. Cost of land conversion** from one land use to another, including land clearing, land preparation, for agriculture or forest expansion | 10.3 | 11.9 | 10.3 | **16%** | **0%** |
| Social | **5. Incentives for biodiversity stabilisation** | 7.1 | 15.3 | 9.1 | **114%** | **27%** |
| | **Total 2021-2050** | **124** | **133.8** | **126.4** | **8%** | **2%** |

Note: Cumulative costs for 2021-2050 by category, discounted at 3.5 %
Absolute costs are reported here for completeness only. Following good practice and recognizing limitations of the model, this work primarily analyses relative cost – that is cost differences between scenarios – rather than absolute costs. The costs in the table are not incremental to a baseline scenario, but are the absolute costs incurred within the scenario.

Source: Vivid Economics using MAgPIE

Figure 5 The cost difference between delayed and immediate action scenario is driven by the social cost (biodiversity stabilisation incentives), as well as by the costs of land conversions




Note: Cumulative 2021-2050, discounted at 3.5 %
Absolute costs are reported here for completeness only. Following good practice and recognizing limitations of the model, this work primarily analyses relative cost – that is cost differences between scenarios – rather than absolute costs.

Source: Vivid Economics using MAgPIE

**When action is delayed, the total cost of land conversion is higher.** Since policy action, including area protection, only gets under way in 2030 in the delayed action scenario, more forest is lost in the years before 2030, and some land may be converted twice, first being deforested and later reforested, adding cost. In addition, a greater area of forest expansion has to take place between 2030 and 2050 under delayed action, since the loss of primary and secondary forest has to be compensated by forest expansion of *more than* the amount of land originally lost, because habitat function is not fully restored by 2050. While the unit cost of land conversion is identical, more hectares of land are converted under delayed action.[9] This cost difference would be larger in the absence of the shrinking effect of the discount factor on later costs.

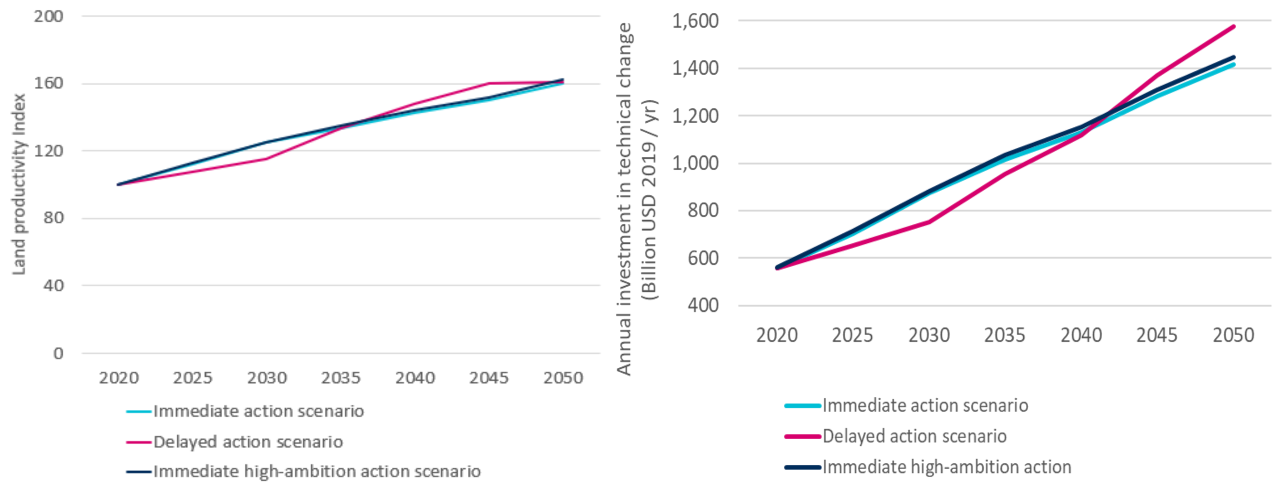
**When action is delayed, the cost of input factors for producing food and materials is higher.** The input factors for food and material production closely reflect quantity produced, but the mix of input factors is affected by land availability, and when less land is available, more fertilizer use is required. Thus, small cost differences occur from the higher use of fertilizer. This cost difference would be larger in the absence of a discount factor on costs. Other input factors such as labour, energy and seeds are similar across scenarios.

**The costs of transport, processing and trade are similar across the two action scenarios.** The increased agricultural land scarcity from forest expansion and protection slightly increases the cost of transport, processing and trade because food is produced on average further away from its place of consumption. While this effect is larger under delayed action, it occurs later in time, so once it has been discounted, the total cost is comparable across action scenarios.

[9] Costs of land conversions are defined by land cover pair, that is the land cover type before conversion and the land cover type after conversion, and also depend on the volume of biomass that has to be removed in the process, if any.

**When action is delayed, more sudden investment in technical change is needed, because the same output has to be achieved from less land (see Figure 6).** In all scenarios, higher food prices reward investment in yield-improving technical change, including the adoption of techniques and R&D. Use of irrigation expands. Land productivity accelerates under immediate action, until 2035, when productivity growth is larger in the delayed action scenario. Investment in technical change takes place later under delayed action, it occurs later in time, and, after discounting, has a lower present value. Only small differences in investment levels and land productivity exist between the immediate and the immediate high ambition scenario, with slightly higher investment levels and slightly larger land productivity under the immediate high-ambition action scenario compared to the immediate action scenario.

Figure 6 Annual investment in technical change and adoption increases rapidly after 2030 under delayed action, driving increases in yields




Note: Annual global investment in technical change and adoption, 2021-2050 (right)
Land productivity index (increase in production per ha cropland relative to 2020) (left)

Source: Vivid Economics using MAgPIE

### 3.5.3 Differences in social cost

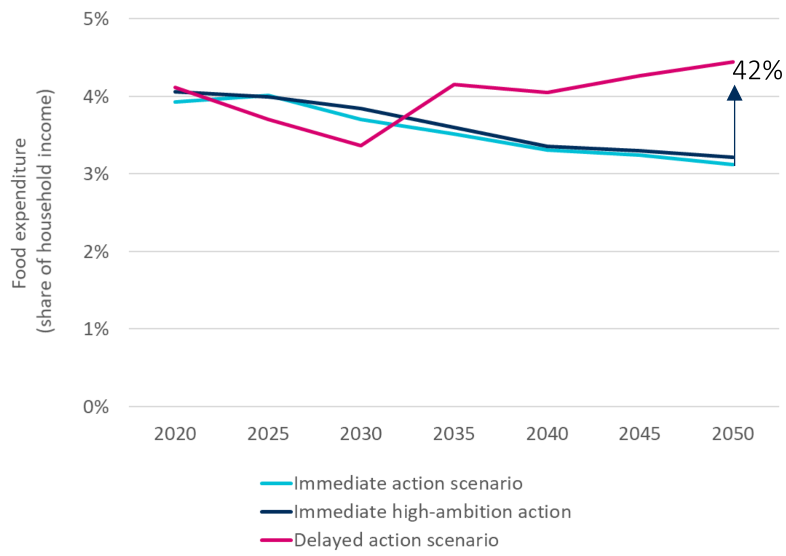
**When action is delayed, the social cost is twice as large.** The estimated total social cost to 2050 reaches USD 15 trillion under delayed action, compared to USD 7 trillion under immediate action. Social cost drives the greatest difference in the costs of delayed and immediate action.

**When action is delayed, incentive levels nearly three times higher are needed to stimulate the necessary action.** This is because land use change happens at a faster rate and to a greater extent when action is delayed (see the Technical Appendix for the incentive level applied under each scenario).

### 3.5.4 Results for household spending on food

**When action is delayed, the share of food expenditure relative to household income could be 40% higher, on average, globally (see Figure 7).** Delay causes the metric to rise, from a current level of around 4% of household income, to 4.4%, instead of falling from 4% to around 3%. Some households will experience higher expenditure shares and steeper rises. This effect will be regressive: higher food prices will disproportionately affect poorer households.

Figure 7 Average food expenditure as share of household income in 2050 is 40% higher under delayed action




Source: Vivid Economics using MAgPIE

## 3.6 Feasibility of action

**The feasibility of policy action to stabilise biodiversity may be limited by political will, limited by means of international cooperation, by public resistance to policy changes and by technical barriers such as means of effective area protection.**

**There is not yet a global agreement on terrestrial biodiversity restoration targets, and previous efforts to coordinate the actions of nations have not succeeded in creating momentum**. The Bonn Challenge, a global effort to bring 150 Mha of the world's degraded and deforested lands into restoration by 2020 and 350 Mha by 2030 was announced in 2011. The year 2020 stands halfway through the Bonn commitment period. Assessing progress, there has been limited reporting on progress against the commitments. The joint pledges of signatory parties collectively account for less than 50% (i.e. less than 175 Mha) of the target commitments and there has been limited reporting on progress against these commitments (IUCN, 2017). Independent voluntary national restoration targets and commitments that were announced over the last decade total 400 Mha globally today, with target years ranging from 2020 to 2030 (FAO, 2020).[10] At present, there are no global datasets measuring progress in forest restoration systematically (NYDF Assessment Partners, 2019). In comparison to the scale of global pledges, in the delayed action scenario, the global community jointly expands forests by 490 Mha in less than 20 years (290 Mha and 300 Mha respectively over 30 years under immediate and immediate high-ambition action scenarios). Given the gap between commitments and parties' pledges, and the lack of institutional capacity on reporting, the Bonn Challenge commitments are unlikely to be honoured. If the Bonn Challenge was not feasible, the feasibility of future action also falls under question.

[10] Selection of regional land restoration targets: the African Forest Landscape Restoration Initiative (Afr100) (100 million hectares of degraded land under restoration by 2030); the Agadir Commitment for the Mediterranean (restore at least 8 million hectares of degraded forest ecosystems by 2030); ECCA30, an initiative of countries in Europe, Caucasus and Central Asia (restore 30 million hectares of degraded land by 2030); the Great Green Wall for the Sahara and the Sahel initiative (restore 100 million hectares by 2030). Initiatives apply varying criteria to land restoration, and not all of the listed targets may refer to actions with positive impact on biodiversity.

**Individual large-scale reforestation programmes do not necessarily achieve the desired outcomes for biodiversity unless they are designed for biodiversity impact.** The world's largest single reforestation program, conducted in China and restoring 28 Mha of forest within 14 years, was the Grain-for-Green Program (Hua *et al.*, 2016). It was initiated primarily to control soil erosion and alleviate poverty, but forests established in the program are overwhelmingly monocultures that fall short of restoring biodiversity to levels approximating native forests.

**The restoration of forest at the scale and pace required under delayed action would involve joint and coordinated efforts from most countries, together with plans for the cultivation of native tree species in unprecedented numbers.** The restoration of 290 Mha of forest over 30 years, as occurs in the immediate action scenario, appears much more feasible, but still means a significant increase in the pace of annual forest expansion compared to today. It will be considerably less feasible to mobilise large scale effort if nations do not behave cooperatively.

**Protected area enforcement remains incomplete and funding arrangements have not been solved.** An expansion of effectively protected areas from 4% (WDPA Categories I and II) currently to 22% of global terrestrial area appears unlikely in the near term, but could occur gradually over the next decade and beyond. WDPA reports an upwards trend in terrestrial protected areas, reaching 14.7% in 2018, however WDPA counts all fully and *partially* protected areas in this figure (WDPA Categories I to VI), some of which are under intense human pressure despite their status of partial protection (Jones *et al.*, 2018). The UNCBD proposed a target to protect at least 30% of the land and sea area with at least 10% under strict protection by 2030, and countries will discuss this target at COP15 in 2021 (CBD, 2020). The share of 22% of terrestrial area protected in 2050 assumed in this work is likely to be more ambitious than the proposed UNCBD target, given the very strict definition of area protection in this work. Ownership and enforcement of protection represent barriers to effective area protection and have not been assessed in this work. In summary, there are many obstacles to be overcome to achieve the effective expansion of protected areas.

**Pricing of GHG emissions around the world has seen increased uptake in recent years around the world, but carbon price levels today are lower, more geographically limited and sectorally limited than assumed in the model**. Today, 22.3% of global GHG emissions are covered by an operational pricing scheme or are scheduled to be covered in a scheme starting in 2020 (World Bank, 2020). Price levels vary a great deal, between 1 USD and 120 USD, with a large majority of jurisdictions applying prices below 30 USD. GHG prices and pricing coverage could rise rapidly over the next few decades as the world embarks on more stringent climate targets. GHG pricing levels in the immediate and delayed action scenarios are purposefully set ambitiously in line with SSP2 RCP2.6 and SSP2 RCP1.9 respectively, to reflect the observed trends towards greater ambition in climate policy globally. Biodiversity pricing, on the other hand, is assumed to play a smaller role in the future policy mix, given that it is largely undeveloped today. Comparable policy instruments to the pricing of biodiversity loss and rewarding of reforestation apply today in the form of REDD+, forest bonds and biodiversity subsidies.

**Food price increases might cause diets to shift and could trigger political opposition to area protection and incentives unless complementary measures are introduced**. While food prices stabilise under immediate action, delayed action drives food prices upwards. Countries might decide to introduce policies to protect vulnerable households in response to substantial food price increases. Although changes in diet are a reasonable response to high food prices, this work assumes a fixed 25% reduction in the share of ruminant meat in diets across all scenarios by 2050.

**The scale of yield-improving technical change and adoption represented in the model is technically feasible, but practically challenging**. Globally, there is a cropland intensity gap, a measure of the gap between actual and potential cropping intensity, caused by inefficient choices of crops and lack of technology adoption (Wu *et al.*, 2018). While a global increase in cropland productivity of 60% in 2050 compared to 2020 is technically possible, it would require large effort in promoting technology adoption of practices such as fertilizer use and irrigation in least developed countries, with precision agriculture and site specific crop management rolled out globally in the long run. Multiple studies have highlighted barriers to adoption of yield improving technologies in least developed countries (Abbott, 2005; Mwangi and Kariuki, 2015) and assessed potential policy approaches to overcoming barriers (Aker, 2011; Lybbert and Sumner, 2012; Deichmann, Goyal and Mishra, 2016). Stronger institutions would be needed to improve yields globally at scale than are in place today.

**In summary, the projected outcomes from biodiversity action might be difficult to achieve, even if immediate action is taken.** However, delayed action is significantly more risky and significantly more costly in implementation than immediate action, in particular due to the potential lack of feasibility of globally coordinated and effective forest expansion efforts at such an unprecedented scale and within a very tight timeframe, as well as the risk of political opposition to the scale of incentives required to stimulate action.

# 4 Discussion

## 4.1 Interpretation of results given the limitations of the modelling

**The results illustrate the cost of delaying biodiversity action through the examples of area protection and forest expansion**. Modelling of this type requires a highly disciplined approach to structuring the problem and assembling evidence and that discipline helps to develop understanding. Even though this work focuses only on terrestrial biodiversity and is restricted to analyses of direct and indirect costs of reforestation and afforestation, the issues it reveals are likely to be encountered in other biomes and with other actions, so the approach offers a proxy for a wider set of possible conservation efforts. Forests and woodlands are worthy of attention because they include the most species-rich terrestrial habitat type worldwide, and forests have been central to global biodiversity conservation efforts. The analysis of the cost of delaying action offers clues as to the costs of delay for a more diverse set of terrestrial biodiversity conservation actions. The true cost of delayed action, across the full biosphere and covering all costs of action and forfeit benefits of biodiversity, would be significantly larger than stated in this report.

**Stabilisation of BII may require more forest expansion effort than shown, should the model underestimate the global pace of forest loss.** In the three decades between 1990 and 2020, there was a global net loss in forest area of 180 Mha, but with a declining rate of forest loss. During 2015–2020, the rate of deforestation was estimated at 10 million hectares per year, down from 16 million hectares per year in the 1990s (FAO, 2020). Across all action scenarios, cumulative primary and secondary forest loss between 2020 and 2050 is optimistically limited to between 33 Mha and 110 Mha in total, which requires a reduction in average annual primary and secondary forest loss by two thirds or more. In reality, performance in avoiding deforestation could be much worse than assumed, meaning that more effort has to be put into stabilising biodiversity and raising the area to be reforested (assuming this can achieve adequate outcomes for biodiversity and BII). High forest loss over the next decades would further reduce feasibility of delayed action.

**Stabilisation of BII may require more forest expansion effort than shown, should the model overestimate the pace or accuracy of policy implementation.** The action scenarios modelled have very fast starts to reforestation and expansion of the area under effective protection is assumed to occur immediately. If these two actions have a longer, slower onset, biodiversity outcomes will be less good, especially for the delayed action scenario. Furthermore, the scale of reforestation envisaged, especially in the delayed action scenario, is likely to mean that some reforestation will be far from remnant patches of high-quality native forest from which endemic species could recolonise, with the result that BII may increase more slowly over time in restored habitat than assumed here.

**An analysis of the sensitivity of results across MAgPIE and PREDICTS outputs shows that the cost estimates and consequently the relative costs of immediate versus delayed action are relatively insensitive to some assumptions, but the choice of discount rate is a key factor for results (see Technical Appendix A).** Changes in assumptions on diets, carbon prices, population growth and GDP growth affect the total cost estimates by less than 1%, while the results are more sensitive to assumptions on the costs of technical change and adoption. Furthermore, the discount rate is important for the relative results, as the additional costs of delayed action occur mainly between 2030 and 2050, while costs of immediate action accrue earlier in time. Some might argue in favour of a lower discount rate and this would make delayed action look even more expensive, so the 3.5% discount rate used leads to a lower bound for the cost of delayed action with respect to the choice of discount rate. The application of regionally-specific discount rates was outside the scope of work.

**This work does not claim to implement an optimal or a feasible global policy mix or pathway to stabilisation of biodiversity intactness**. The three policy instruments active in the model, area protection, climate policy and biodiversity policy, are each suitable instruments for achieving the respective targets, but in the way they have been set up in the model, may not deliver lowest cost outcomes. Among the three policy instruments in the model, climate policy enjoys the largest international current and planned uptake, suggesting that it will remain a key driver for land use decisions in the years to 2050. Therefore, while policy mixes at lower cost than the one reported are possible, the model was set up with strong climate policy. A particular risk is if poorly-implemented carbon policies encourage forest restoration or afforestation in areas of low biodiversity potential. A range of government and market failures might occur, meaning that delivery occurs much less efficiently and at a much higher cost than shown in the results of this study.

**The conventional intensification of agriculture decreases biodiversity on cropland and pastureland, but ecological intensification approaches exist**. The intensification of agriculture is unavoidable across all scenarios. Conventional land-use intensification, for example industrial management of large-scale monocultures with chemical fertilizer and pest control inputs homogenises landscape structure and reduces biodiversity intactness. Ecological intensification approaches in agriculture represent a strategic alternative to reduce adverse effects of intensification while supporting sustainable food production, by promoting biodiversity beneficial to agricultural production through management practices such as intercropping, crop rotations, farm-level diversification and reduced agrochemical use. While ecological intensification is only rarely adopted today, a growing evidence base and know how as well as increasing worldwide concern about the environmental costs of conventional intensification of agriculture may increase global uptake in the next decade (Kovács-Hostyánszki *et al.*, 2017; Kleijn *et al.*, 2018).

# 5 Conclusions

**Immediate action would halve costs and improve feasibility.** Delay of a decade will double the cost, over 30 years, even after discounting, to achieve the modest goal of stabilising intactness. In comparison, more ambitious immediate action aimed at improving, rather than just stabilising, biodiversity intactness would reduce extinctions of endemic species further and would cost only 27% more. Without doubt, improvement and even stabilisation of global BII is only feasible if action is taken immediately. This is because delayed action entails a level of forest expansion that may not be economically or biophysically feasible. Delayed action demands substantially more organisational, financial and political resources to execute, when the world has not mobilised capacity to execute on existing commitments. Immediate action involves a massive step change in pace and scale of current action, but still much less than will be required in the future if action is delayed.

**Species extinctions will be similar across the immediate and delayed action scenarios by 2050, if one is willing to assume that large scale forest expansion is feasible.** In the baseline scenario, with only current biodiversity action, 3% of the endemic terrestrial species included in the modelling will become extinct by 2050, more than appear to have died out in the period 850-1850 CE. Immediate and delayed action both reduce the number of extinctions by approximately one fifth.

**In most cases, the introduction of incentives should be announced to landowners, managers and investors early**. Substantial incentives will be needed to bring about and maintain reforestation and associated biodiversity and carbon outcomes, through regulation and economic incentives. These incentives will be disruptive, raise questions of a just distributional impact, and will be politically demanding. They will be less feasible to deliver politically if the sector is not given advance notice.

**There is a strong case for commencing a revolution in land productivity in regions with yields that languish at low levels relative to their potential.** A combination of factors such as population growth, nutrition improvement and land sharing and sparing for biodiversity demands that global average yields increase by 50% by 2050 compared to today, which will only be achievable through investment in technology adoption and may trigger other changes, such as in land tenure and the consolidation of smaller farms into larger holdings. The costs of technical change are broadly cost neutral at a global aggregate level, as they are largely repaid by the efficiency improvements which they deliver.

**Greenhouse gas and biodiversity incentive mechanisms should be complementary and designed to target biodiversity-rich areas and places with high reforestation potential.** There is scope for errors to be made given the scale, novelty and disruptiveness of the action required. Coordination between biodiversity and carbon policy, employing integrated land use planning at a bioregional level, will help to achieve efficiency, including avoiding misdirected investment. In addition, attention needs to be paid to three aspects in particular: tackling rent seeking behaviour, adaptation to the effects of rising land prices and ensuring that carbon sequestration does not come at the cost of biodiversity.

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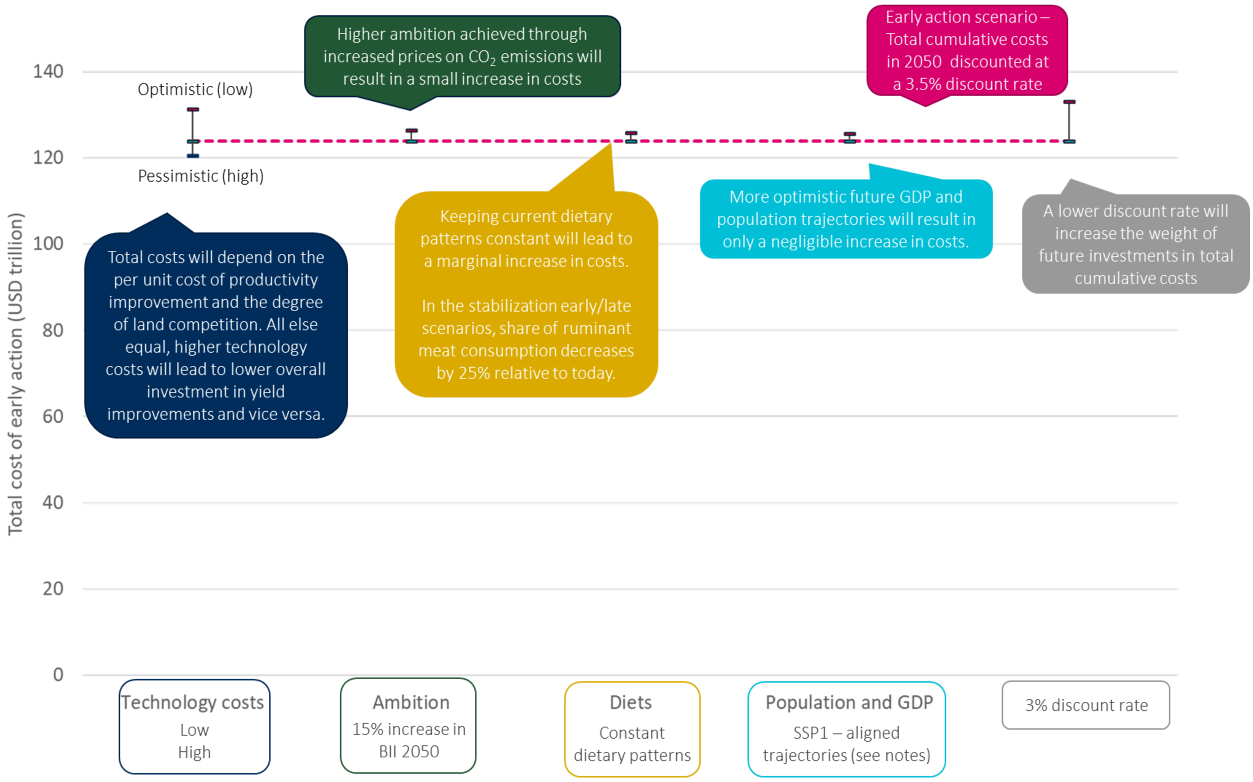
# Technical appendix A: Sensitivity analysis

## A1 Sensitivity analysis on costs

**The food and material production and transportation costs in the immediate action scenario are particularly sensitive to assumptions on technology costs and discount rates.** The immediate action scenario was subjected to sensitivity testing on technology costs, level of ambition, diet, population and GDP projections, and the discount rate (see Figure 8). The costs are most sensitive to technology costs and the choice of discount rate:

1. **technology costs**: total costs depend on the per unit cost of productivity improvement and the degree of land competition. All else being equal, higher technology costs lead to lower overall investment in yield improvements and vice versa;
2. **discount rates**: a lower discount rate of 3% increases the weight of future costs in the total costs.

Figure 8 Total cumulative costs of the immediate action scenario are most sensitive to assumptions on technology and adoption costs, as well as the discount rate



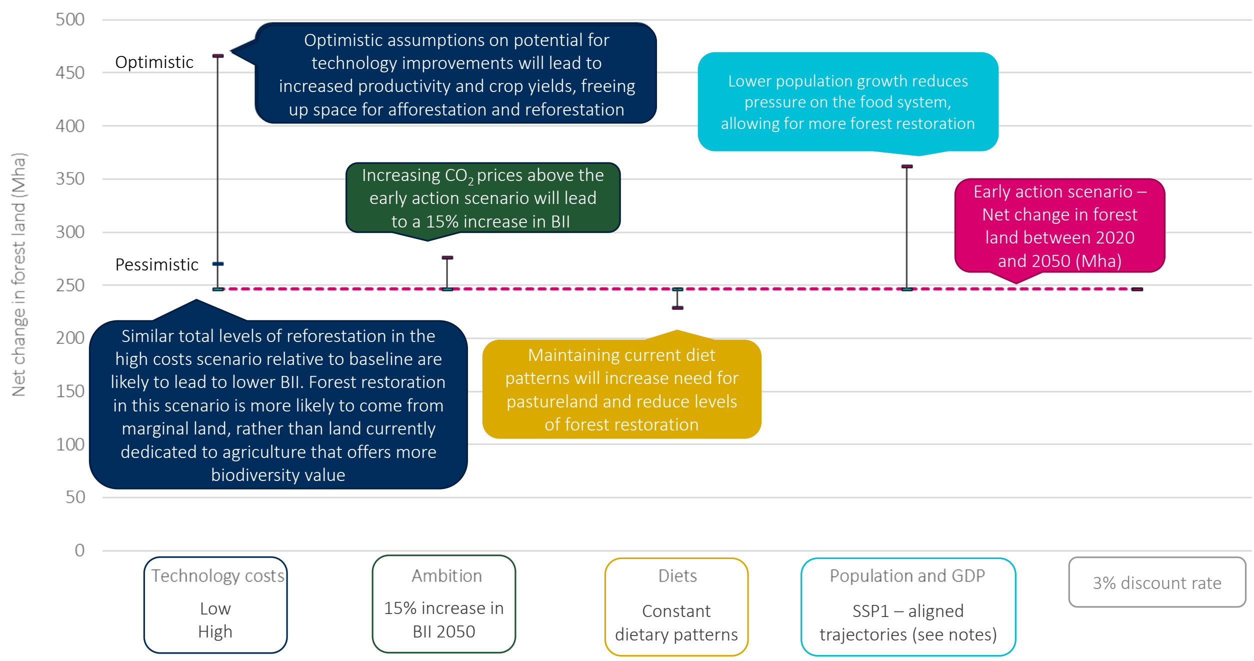

Source: Vivid Economics

**The population projections and future costs of technological change have the greatest impact on biodiversity outcomes.** While total costs are most sensitive to technology costs and discount rates, the biodiversity outcomes are driven by effects on forest area (see Figure 9). Net increase in forest area is highest with lower technology costs and lower population growth:

1. **technology costs**: optimistic assumptions on potential for technology improvements (lower costs) will lead to increased productivity and crop yields, freeing up space for afforestation and reforestation;

2. **population growth**: lower population growth reduces pressure on the food system, allowing for more forest expansion.

Figure 9 The 2050 forest cover in the immediate action scenario is most sensitive to assumptions on technology and adoption costs, as well as population growth and GDP trajectories




Source: Vivid Economics

## A2 Sensitivity analysis on the biodiversity intactness

**The relationship between BII and age of land under forest restoration affects biodiversity stabilisation.** The main results apply a relationship between BII and the age of restored habitat that is derived from modelling secondary vegetation sites of known age. Since this data set is small and may not be representative, sensitivity analysis was used to test an alternative, much larger but coarser dataset of secondary vegetation whose age is not known quantitatively but which are classed as young, intermediate or mature. The alternative approach results in a strong initial loss in biodiversity in delayed action scenarios, particularly in tropical forests (which is possible if stable, sometimes diverse agricultural systems are converted), meaning that it takes until 2060 until any delayed action scenario reached the same level of BII as immediate action.

## A3 Sensitivity analysis on extinction of endemic species

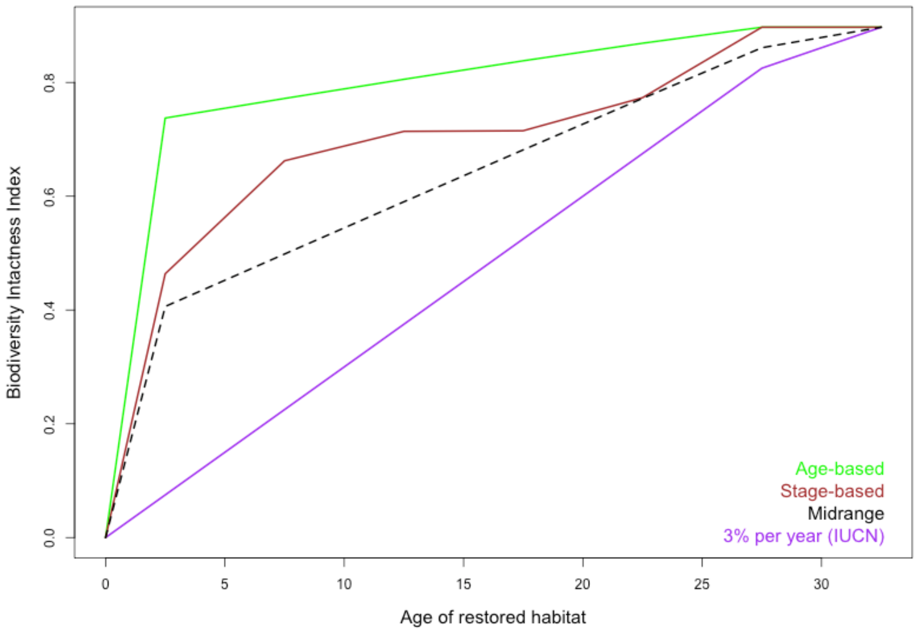
**Three possible recovery curves are considered in addition to the mid-range assumption used for the main results, resulting in similar changes to extinctions across immediate and delayed action scenarios** (Figure 10). As expected, the percentage reduction that each scenario achieves in the numbers of endemic species going extinct (compared with the no action baseline scenario) is greatest with the steepest recovery curve (Table 5).

a. **Using sites of known age to estimate the BII recovery curve**. This relationship, with the most rapid initial increase of BII with age, yields the largest reduction of extinctions between 2020 and 2050. Immediate action reduces extinction by 23.3% relative to baseline; delayed action (with nearly twice as large an area being restored as under immediate action) overtakes the immediate action scenario by 2040 and reduces extinction by 26.5%; and the immediate high-ambition action reduces it by the largest amount, 28.5%.

b. **Using sites at different stages of succession to estimate the BII recovery curve**. This recovery curve is slower but still shows deceleration as restored habitat ages. The slower recovery means that the reductions in extinction are less than those seen above; while the deceleration means that the delayed action (with nearly twice as much land being restored as in the early action) still overtakes the lower-ambition immediate action scenario by 2050. Immediate action reduces extinction by 21.9%; delayed (but more extensive) action reduces it by 24.4%; and the high-ambition immediate action reduces it by 26.7%.

c. **Using a linear recovery of 3% per year**. This, the slowest rate of recovery, yields the smallest reductions in extinction relative to the baseline scenario. Furthermore, the linear recovery means that the delayed-action scenario does not catch up with the immediate-action scenario, despite a larger area being restored. The immediate-action scenario reduces extinction by 17.8%, the delayed-action scenario by 16.4% and the high-ambition immediate-action scenario by 20.9%.

Figure 10 The sensitivity analysis tests three alternative recovery curves




Source: NHM and Vivid Economics

Table 5 Relative numbers of endemic species going extinct by 2050 under each scenario are dependent on the underlying recovery curve

| | Recovery curve assumed for each scenario | | | |
|---|---|---|---|---|
| Scenario | Mid-range (Main analysis) | a. Age-based BII model | b. Stage-based BII model | c. 3% per year |
| Baseline | 100% | 100% | 100% | 100% |
| Immediate | 79.0% | 76.6% | 76.9% | 82.1% |
| Delayed | 76.9% | 73.3% | 75.6% | 83.6% |
| Immediate high-ambition | 74.3% | 71.4% | 73.2% | 78.0% |

Note: Numbers in bold indicate, for each recovery curve, whether Immediate or Delayed action reduces extinction by more; Immediate high-ambition action always outperforms both.

Source: NHM and Vivid Economics

**The immediate and delayed scenarios consistently project broadly similar numbers of extinctions, but which of them shows the greater reduction depends on the initial steepness of the recovery curve**. The area of forest restored in the delayed action scenario is almost twice that of the immediate action scenario. Although the land under forest restoration in the delayed scenario is a decade younger than that in the immediate scenario, its BII is not much lower in the top three curves (Figure 10), so this large area is able to prevent a large fraction of extinctions. However, with the linear recovery curve, the age of land under forest restoration is more important. Therefore, an even greater area would need to be restored in the delayed action scenario to reach equivalence with the immediate action scenario.

**The more slowly restored sites accrue the ability to sustain endemic species, the harder it is to avoid extinctions by restoring habitat, and the more important it is to act immediately**. The immediate high-ambition action scenario reduces extinction by 22%-23% more than the immediate action scenario. Whether the delayed action scenario ever catches up with the immediate high-ambition action scenario depends on the linearity of the relationship between restored habitat's age and its ability to sustain endemic species.

# Technical appendix B: Method, data inputs and assumptions

## 5.1 B1 MAgPIE

**The Model of Agricultural Production and its Impact on the Environment (MAgPIE) is a global land use allocation model designed to explore land competition dynamics in the context of carbon policy.** Developed by the Potsdam Institute for Climate Impact Research, MAgPIE is a spatially explicit, partial equilibrium model that solves for the least-cost way to meet future demand for food and materials of agricultural origin based on assumed population, GDP and dietary trajectories. It produces land use change raster for modelled 5-year timesteps based on policy assumptions, such as carbon pricing and different land related policies. MAgPIE accounts for both biophysical constraints on yield, land and water as well as for regional economic conditions. MAgPIE estimates total costs of land use and land use change as policy constraints and land use patterns change. These costs span costs of food production, production of materials of agricultural origin and restoration of habitat.

**This work applied MAgPIE 4.2, the latest version of the model.** A full model documentation is available at https://rse.pik-potsdam.de/doc/magpie/4.2 .

**MAgPIE consists of 38 modules, most of which require several choices on assumptions**. Table 6 lists selected assumptions for the immediate and delayed scenarios in this work respectively.

Table 6 Immediate and delayed action scenarios differ in assumptions regarding scale of policy action

| Variable | Description | Source | Immediate Action (includes immediate high ambition) | Delayed Action | Baseline scenario |
|---|---|---|---|---|---|
| **1.GHG price trajectory** | Defines global price trajectories for $CO_2$, $N_2O$, $CH_4$. | IIASA Database and PIK integrated assessment modelling exercise | SSP2 RCP2.6 consistent trajectory with carbon prices phasing-in globally in 2020 (higher for immediate action) | SSP2 RCP1.9 consistent trajectory with carbon prices phasing-in globally in 2030 | SSP2 NPi trajectory consistent with existing National Policies implemented |
| **2.Reduction factor for $CO_2$ price** | Lowers economic incentive for $CO_2$ emissions reduction from avoided deforestation and afforestation compared to carbon price level | - | 0.5 (higher for immediate action) | 1 | 1 |

| | | | | | |
|---|---|---|---|---|---|
| **3.Bioenergy trajectory** | Defines demand for second generation bioenergy crops (only used for fuel production, not for food) | IIASA Database and PIK integrated assessment modelling exercise | SSP2 RCP2.6 consistent trajectory | SSP2 RCP1.9 consistent trajectory | SSP2 NPi consistent trajectory |
| **4.Population** | Sets trajectories based on SSPs (Shared Socioeconomic Pathways) | SSP database | SSP2 – 'Middle of the road' consistent pathways | SSP2 - 'Middle of the road' consistent pathways | SSP2 - 'Middle of the road' consistent pathways |
| **5.GDP** | Sets trajectories based on SSPs (Shared Socioeconomic Pathways) | SSP database | SSP2 – 'Middle of the road' consistent pathways | SSP2 - 'Middle of the road' consistent pathways | SSP2 - 'Middle of the road' consistent pathways |
| **6.Protected areas** | WDPA categories plus all proposed areas and key biodiversity hotspots | (Leclère *et al.*, 2018)* | 2708 Mha in 2020 | 2708 Mha in 2030 | 351 Mha (no change from current levels) |
| **7.Ruminant meat fadeout** | Defines decline in proportion of calories from ruminant meat in total meat demand relative to baseline scenario where it is treated as constant | (Bodirsky *et al.*, no date) | 25% reduction in ruminant meat share of diet by 2050 | 25% reduction in ruminant meat share of diet by 2050 | 25% reduction in ruminant meat share of diet by 2050 |
| **8.Trade liberalisation** | Defines change in current trade patterns | (Schmitz *et al.*, 2012) | 10 % trade liberalisation for secondary and livestock products in 2030, 2050, 2100 and 20 % for crops | 10 % trade liberalisation for secondary and livestock products in 2030, 2050, 2100 and 20 % for crops | 10 % trade liberalisation for secondary and livestock products in 2030, 2050, 2100 and 20 % for crops |
| **9.Future costs of investment** | Selected options for the expected costs of future productivity improvement. | (Dietrich *et al.*, 2014) | Trajectories for future investment costs in line with historical trends | Trajectories for future investment costs in line with historical trends | Trajectories for future investment costs in line with historical trends |

Note: * The default protection in MAgPIE is defined by the WDPA protected areas. It includes IUCN WDPA categories I and II. The WDPA protection covers approximately 400 Mha of the terrestrial land surface. For a world with increased protection, this work follows a procedure similar to the Bending the Curve project, where a 'potential protected area layer' is created - i.e. areas of the world that should be a priority to protect. Two criteria served for selection - (i) expanding the WDPA protection from Cat I and II to cover all categories, and in addition to designated WDPA protected areas, proposed PAs are also included (areas which are not protected, but deemed by WDPA to be prioritised for protection in near or distant future, using a variety of local factors). (ii) Key biodiversity hotspots, similar layer as used in Bending the Curve. The created potential protected layer is named the 'WDPA+', which comes to around 2700 Mha, which is ~21-24% of the terrestrial land surface and 600% more than present WDPA protection.

Source: Vivid Economics

## 5.2 B2 PREDICTS and dynamic species area modelling

**Projecting Responses of Ecological Diversity in Changing Terrestrial Systems (PREDICTS) is a global database of biodiversity surveys combined with high resolution global land use data using statistical models to estimate the global impact of land use and related pressures on local terrestrial biodiversity worldwide.** PREDICTS estimates the Biodiversity Intactness Index, defined as the average abundance, relative to reference populations in unimpacted areas, of functionally diverse species, as an estimate of how much of a terrestrial site's original biodiversity remains, or is projected to remain, in the face of anthropogenic land use pressures, for different land use scenarios. A full description of PREDICTS is provided by Purvis et al. (2018) and an overview can be accessed here: https://www.predicts.org.uk/

**Two contrasting measures of biodiversity were considered in this work, to account for the complexity of terrestrial biodiversity**. The complexity of terrestrial biodiversity, the total variability among all living organisms on land, means that analyses such as this need to consider more than a single metric. BII and extinction rate are the two metrics used to demarcate the 'Planetary Boundary', a proposed 'safe limit' for biodiversity loss (Steffen, W. J. et al., 2015), and can be viewed as indicators of 'nature for people' and 'nature for its own sake', respectively (Purvis, 2020). Thus, although including additional measures might enrich the analysis, this contrasting pair captures important dimensions of biodiversity.

- **The Biodiversity Intactness Index.** The BII estimates the average fraction of naturally-present biodiversity that still remains (Scholes, R. J. & Biggs, 2005), and is useful as a broadly-applicable indicator of ecosystems' ability to function effectively and so provide a range of biodiversity-dependent ecosystem services (Mace, G et al., 2014). BII can rise, for example, as a result of habitat restoration, as well as fall; and averaging BII across ecosystems, as done in this work, assumes that gains in one region or ecosystem can substitute for losses in others.

- **The relative number of global extinctions of endemic (narrowly distributed) species.** Global extinction is permanent, so the number of them can only ever increase; and a species' persistence depends on the persistence of suitable habitat in its natural geographic range which, for endemic species, is by definition a small area and cannot be exchanged for habitat elsewhere

### 5.2.1 BII estimation

**The Biodiversity Intactness Index (BII) was originally proposed as a practicable measure of the average biotic integrity of terrestrial ecosystems in a region of interest** (Scholes, R. J. & Biggs, 2005). It estimates the average fraction of naturally-present biodiversity that still remains despite land use change and related pressures, which can be used as an indicator of the biota's ability to contribute towards ecosystem services over the short to medium term. Originally estimated using expert judgement, the first data-based implementation of BII came from PREDICTS (Newbold, T. et al., 2016), and showed that land use and related pressures had already reduced the global average BII below the level proposed as a 'safe limit' for biotic integrity in the Planetary Boundaries framework (Steffen, W. J. et al., 2015).

**BII is estimated by comparing data from ecological communities in different land uses, with communities in primary vegetation and having minimal human use used as a proxy for the natural assemblage.** The analytical framework used here (De Palma et al. 2019) improves on the original PREDICTS implementation of BII, reducing its tendency to overestimate BII in some circumstances (Martin et al. 2019; Newbold et al. 2019).

**The analyses presented here include estimation of how BII of restored habitat increases with time since restoration began, a relationship termed the 'recovery curve'.** Given its importance in the projections of both BII and extinctions, it is important to note two caveats about the BII recovery curve. First, most of the sites within the PREDICTS database from which the recovery curve was estimated are reasonably close to primary vegetation that can act as a source of individuals, facilitating rapid recovery. The recovery curve used in analyses is therefore best suited to small to moderate restoration programs where some primary vegetation remains in the landscape, rather than to efforts to restore large landscapes in the absence of any remnants of primary vegetation. Second, BII (as defined by Scholes & Biggs 2005 and as implemented by PREDICTS) is a more permissive measure of biotic integrity than is often recognised. In particular, it is largely insensitive to changes in the relative abundance of naturally-present species (i.e., previously rare species can now be common and vice versa without BII changing), and the local disappearance of some naturally-present species can be compensated for by the increased abundance of others (Faith et al. 2008).

**Biomes were classified as forested or non-forested and in forested biomes, as subtropical/tropical and temperate/boreal**. In forested biomes, we allowed the effects of human impacts and distance decay to vary with climatic region (temperate/boreal vs tropical/subtropical, classified according to biome names). The land uses in these models were collapsed to match the land use classes in the MAgPIE model (see Table in Section B3). Data availability allowed us to split primary vegetation and pasture into low intensity (minimally-used) and higher intensity (lightly and intensively-used combined) categories. These models provide estimates of biodiversity relative to the baseline (minimally-used primary vegetation with a human population density of zero) that can be projected using spatial data over time. In non-forested biomes, restoration cannot be natural reforestation so we assumed that biodiversity recovery would respond more similarly to perennial cropland (planted, usually non-natural systems). Human population density (HPD) data for each site were extracted from the Gridded Population of the World Version 4 (2018) and environmental data were extracted from WorldClim (elevation, maximum temperature of the warmest month, minimum temperature of the coldest month, precipitation of the wettest and driest month,

**In order to estimate BII for the year 2050, it is necessary to estimate how the biodiversity value of restored land in forested biomes increases with time since restoration began**. To do this, we used the subset of PREDICTS' minimally- and lightly-used secondary vegetation sites for which the age since conversion or abandonment is known. Generalized additive models (with limited curvature based on theory) were used to model recovery in secondary vegetation relative to other land use classes, accounting for other variables as above, and allowing recovery to vary with climate. This model was used to project the BII in secondary vegetation and minimally-used primary vegetation at the midpoints of successive 5-year intervals which could be used in projections, assuming that restored land responds to human population density in the same way as MAgPIE's other land that is not primary (i.e., young secondary vegetation). Using sites of known age may provide precise recovery curves but, particularly in temperate regions, the shortage of minimally-used primary vegetation may lead to overestimates in biodiversity. A second approach was therefore tried for a sensitivity analysis (see Appendix A2).

**After combining estimates from the BII models and restoration models, we then projected abundance and compositional similarity from 2020 to 2060 using land use scenario data from MAgPIE**. Human population density projections for the same period were taken from the Shared Socioeconomic Pathway 2 scenario

(Jones and O'Neill, 2016). MAgPIE does not distinguish between primary vegetation and other land use classes in the Other category; however for our models, minimally-used primary vegetation must be modelled separately as a baseline category to which we compare biodiversity in other land use classes. Therefore, we assumed that the proportion of primary to secondary vegetation for each year and grid cell was equivalent to that shown in the Land use Harmonization project (www.luh.umd.edu) for the SSP2 scenario. Projections of abundance and compositional similarity were expressed relative to the diversity in minimally-used primary vegetation with a human population density of zero. Compositional similarity was not permitted to extend above 1, although abundance may increase above 1 (habitat disturbance can result in more individuals being present than in an undisturbed site, particularly if novel species invade the site). Projections of abundance and compositional similarity were then multiplied together to provide projections of BII, which were weighted by Net Primary Productivity (NPP) to produce global and regional averages.

### 5.2.2 Extinctions estimation

**The PREDICTS framework is complemented by dynamic species-area modelling, providing insights on extinctions and extinction debt.** The species-area relationship can be used to project how land use change will affect the number of species a region can support over the long term, and a recent meta-analysis has synthesised information on the rate at which this equilibrium is approached. By focusing on narrowly-distributed (endemic) species dependent on natural habitat, combining these approaches into a dynamic species-area model allows estimation of how species extinction has eroded an area's endemic species diversity, given its land use history. This approach estimates impacts on global biodiversity, so complements the BII estimates of average local diversity from PREDICTS.

**Most of the world's animal and plant species have very narrow geographic distributions, i.e., they are endemic to small areas, within which they depend on natural habitat**. Although such species are, owing to their small ranges, typically very poorly known (most have probably not yet even been described by taxonomists) they are concentrated in 'hotspots', typically in landscapes that combine high productivity and topographic complexity, such as mountain ranges in the moist tropics (Pimm et al. 2014).

**Habitat loss is the main driver of terrestrial biodiversity loss and endemic species are intrinsically vulnerable because even a localised impact can cause their extinction.** However, extinction is typically delayed rather than immediate: the impact causes population sizes to start to decline, with extinction resulting only when population size reaches zero, which (especially for long-lived species) may be many years after. The term 'extinction debt' is used to describe these pending extinctions (Kuussaari et al. 2009). By increasing the amount of suitable habitat, habitat restoration can arrest and even reverse population declines and thereby forestall the pending extinctions. Historical habitat loss means that the extinction debt may currently stand at as many as half a million animal and plant species (Fonseca 2009; Purvis et al. 2019).

**The modelling undertaken here considers four factors that determine how far habitat restoration will reduce the global number of extinctions of endemic species between now and 2050**:

a. **the amount of land restored**;
b. **the location of land restored**: the greatest benefit comes from restoring areas that are rich in endemic species but that have seen recent loss or degradation of habitat (Wearn et al. 2012);
c. **when restoration starts**: earlier restoration is obviously better, other things being equal; but a delay in restoration could in principle be offset by restoring a larger area;
d. **how quickly restored land becomes able to sustain the endemic species**: The speed with which restored land matures sufficiently to reduce extinctions is a key relationship.

**The main analysis uses the mid-range of three different estimates, each of which was also used in turn in a sensitivity analysis**. Two of these are based on BII recovery curves estimated from the PREDICTS data and have initially rapid recovery followed by deceleration, whereas the third (Jones et al. 2018) assumes a slower linear recovery. The main analysis finds that immediate restoration is slightly overtaken by delayed restoration of a very much larger area. However, this overtaking is facilitated by the decelerating recovery curve: with a linear recovery, younger restored habitat is always much less useful to endemic species than habitat restored ten years earlier, so delayed restoration even of a much larger area does not overtake immediate action.

**The modelling assumes that immediate and delayed restoration follow the same recovery curves**. However, there are several reasons why recovery curves may be slower if action is delayed: the extinction of key species before action takes place could impede subsequent ecological recovery, as could climate change over the intervening years (which will be worse in the absence of widespread forest regeneration than if action is taken immediately). Lastly, the delayed-action scenario attempts to restore an unprecedentedly large area, including in areas under intensive agriculture and with few or no remaining fragments of primary (or even high-quality secondary) habitat that could act as sources of individuals; the probability of success of restoration under such circumstances is likely to be lower - perhaps much lower - than under the more favourable conditions of the early-action scenario (Crouzeilles et al. 2016; Jones et al. 2018).

**Dynamic species-area modelling aims to estimate, across a range of scenarios, the numbers of extinctions of narrowly-distributed (endemic) species that depend on natural habitat.** The number of such species that a region can support in the long run (S) scales with the amount of natural habitat (A), according to

$$S = cA^z$$

where c is a constant that reflects the region's natural diversity and z is typically around 0.25. When A falls, S does not fall immediately to its new equilibrium value ($S_{eq}$). Rather, the rate of extinction is proportional to the extinction debt, defined as the number of species that the natural habitat cannot support, expressed as $dS/dt = k(S - S_{eq})$, where k is a rate parameter, enabling the trajectory of S to be modelled given estimates of z, k and how the A changes over time. All analyses modelled the trajectory of S within non-overlapping 2° grid cells, rescaling the resulting time series so that S in 2015 was proportional to the IUCN range-size rarity data (aggregated to the same 2° grid cells) to reflect natural diversity gradients. Values for z and k came from a published meta-analysis.

**In regions where S is above $S_{eq}$, restoring natural habitat can prevent extinction, as increasing A reduces the rate of species loss.** However, habitat restoration takes time, with restored habitat's ability to prevent extinctions increasing with its age; and restored habitat is unlikely ever to be able to support as many endemic species as the original natural habitat.

**Several adjustments were made to prepare inputs data for utilisation in this modelling**. Historical land use estimates (for the years 850-2015) were taken from the Land Use Harmonization project (www.luh.umd.edu) while scenario land use estimates (for 1985-2100) came from MAgPIE. Natural land was estimated from the extents of primary (Pri) and secondary (Sec) vegetation according to A = Pri + 0.897 x Sec, 0.897 being the average BII for secondary vegetation across PREDICTS models of tropical forest, temperate forest and nonforest biomes. Historical and scenario time series showed good agreement on the distribution of natural land across grid cells ($r^2 > 0.95$ for all years of overlap) but were not identical; historical estimates were therefore rescaled to agree with the scenario estimates in the year 1985, the year of closest agreement. In the scenarios, natural land from 2020 onwards was augmented by restored land in different 5-year age-classes ($Res_{age}$) such that $A = Pri + 0.897 \times Sec + \sum(BII_{age} \times Res_{age})$, with the main analysis using $BII_{age}$ values for ages up to 30 years given by the mid-range of three different ways of estimating them.

The $BII_{age}$ values were scaled such that $BII_0 = 0$, as agricultural land provides no suitable habitat for the species considered in this analysis, by design; and were capped at 0.897, the value for secondary vegetation. Sensitivity analyses (Section A2) explored using the three separate sets of $BII_{age}$ estimates. Although S can rise in response to A increasing over time in many applications of species-area modelling, it cannot do so here because only species endemic to each grid cell are considered; S was therefore constrained never to increase in any grid cell.

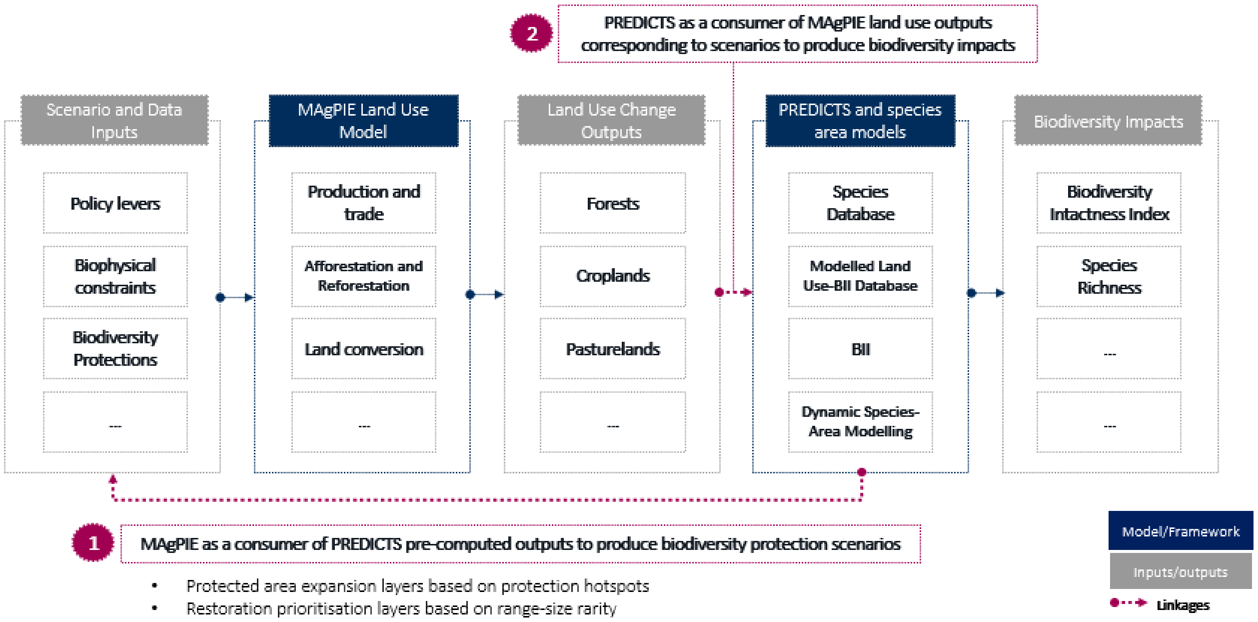
**Model output was, for each year, the relative number of endemic species in each grid cell**. From each scenario's number of extinctions were calculated for each year between 2020 and 2050. The absolute number of extinctions cannot be known, because the absolute global number of endemic habitat-specialist species is not known; we therefore rescale the extinction trajectories such that the number of extinctions seen by 2050 in the intervention scenarios are expressed as percentages of the number seen in the baseline (no-intervention, i.e., business-as-usual) scenario.

## 5.3 B3 Model integration

**The links between MAgPIE and the biodiversity models is based on spatially explicit biodiversity protection and land use projections.** The integrated modelling framework relies on three key steps:

1. **First, existing narratives of the strength of present and future biodiversity protection and restoration are gathered.** This step requires explicit spatial data on the potential protected areas and a restoration priority layer. Data on protection and restoration is processed in the PREDICTS framework to input into MAgPIE.
2. **The second step involves generating and quantifying the immediate and delayed action scenario of land use change using MAgPIE based on the timing of the protection and restoration efforts**. Immediate and delayed action scenarios are calibrated to arrive at similar average BII by adjusting scale of the policy instruments in the delayed action scenario.
3. **In the final step, the PREDICTS model estimates the impacts of land use change projections on the Biodiversity Intactness Index, for all scenarios; and the dynamic species-area model estimates the impacts on endemic forest-specialist species.** The dynamic species-area modelling uses spatially-explicit land use output from MAgPIE for the years 1985-2100 alongside estimates from PREDICTS of how BII increases with the age of restored habitat. These are combined with external data on longer-term land use history and the present-day pattern of range-size rarity to develop spatially-explicit projections of extinction of endemic species through time.

Figure 11 The linkage between MAgPIE and PREDICTS is based on spatially explicit land use rasters and BII projections




Source: Vivid Economics and NHM

Table 7 Mapping of land use classes between the Magpie land use model and PREDICTS

| MAgPIE land use class | PREDICTS land use class |
|---|---|
| Cassava, cotton, fodder, groundnut, maize, others, potato, pulses, rapeseed, rice, soybean, sugar beet, sunflower, temperate cereals, tropical cereals | Annual crops |
| Biofuel grasses, woody biofuels, oil palm, sugar cane | Perennial crops |
| Pasture | Pasture |
| Secondary forest | *For land that was Secondary forest in 2015:* Minimally-used Intermediate Secondary Vegetation, Minimally-used Mature Secondary Vegetation<br><br>*For land that became Secondary forest in or after 2020:* Minimally- and Lightly-used Secondary vegetation of known age |
| Land under forest restoration | *For land that was Land under forest restoration in 2015:* Timber, Lightly-used Intermediate Secondary Vegetation, Intensively-used Intermediate Secondary Vegetation, Lightly-used Mature Secondary |

| | |
|---|---|
| | Vegetation, Intensively-used Mature Secondary Vegetation<br><br>*For land that became Land under forest restoration in or after 2020:* Minimally- and Lightly-used Secondary vegetation of known age |
| Primary forest | Primary Vegetation (forested biomes) |
| Other | Young Secondary Vegetation and Primary Vegetation (from non-forested biomes). Note that Other is split into two categories, *Other non-primary* and *Other primary* (see below for details). |
| Urban | Urban |

Source: Vivid Economics and NHM

## 5.4 B4 Additional detail on cost reporting and land cover changes

Table 8 Additional detail on reported cost

| Cost category | Definition |
|---|---|
| Private cost of land use and land use change | These are the costs of producing food and materials and restoring land. There are four components of private costs: cost of input factors, cost of technical change, cost of processing, transport and trade and cost of land conversion. This category is an aggregate of all cost categories in MAgPIE with exception of costs listed under social cost of land use and land use change, costs and yields relating to bioenergy production (bioenergy production removed for better scenario comparability), and costs that are part of model functionality. |
| Social cost of biodiversity stabilisation | Social cost of biodiversity stabilisation are total transfers in the form of shadow prices for greenhouse gas emissions and biodiversity loss. Social cost of biodiversity stabilisation are total transfers in the form of shadow prices for greenhouse gas emissions and biodiversity loss, multiplied by the bases for each transfer. The shadow prices are the prices set in MAgPIE in order to achieve BII stabilisation in 2050. The base for greenhouse gas emissions transfers is the emissions from land use and the base for biodiversity transfers is the BII loss multiplied by range rarity and terrestrial land area. These transfers are between governments, producers and consumers; the direction of the transfers depends on the allocation of property rights. They can also be regarded as a proxy for willingness to pay. If the biodiversity outcome is chosen by society, the implication is that society would be willing to pay, at the margin, at least these amounts to achieve that outcome. It is this latter interpretation which allows us to call them social costs. These costs are not an estimate of the value of the ecosystem services. This category is an aggregate of the following cost categories in MAgPIE: payments for GHG emissions, rewards for carbon sequestration, payments for biodiversity loss, rewards for afforestation. |
| Cost of input factors (Part of private cost) | Cost of input factors for producing food and materials of agricultural origin include factor cost of labour, energy, physical inputs including fertilizer cost and non-land capital cost. For selected crops, technical options to reduce direct emissions exist, these abatement costs are also reported in this category. Since MAgPIE is a global land use optimization model, there is no direct cost of land. However, unprotected land is always put to its most productive value which results in the same dynamics and cost impact on production of land scarcity that would occur under an undistorted market for land. |
| Cost of technical change (Part of private cost) | Cost of technical change includes the cost of technology adoption including irrigation expansion and investment in yield increasing R&D. Investment in technical change is triggering yield increases on cropland and to a smaller extent in pastureland, largely driven by irrigation expansion. |

| | |
|---|---|
| Cost of processing, transport and trade (Part of private cost) | Cost of processing, transport and trade covers the transport of inputs such as fertilisers to the production site as well as the transport of products to the processing site and the market. It furthermore includes cost of processing (or converting) primary products to final products, specific to product type, process, and cost of trade (transaction cost including insurance, margins, tariffs and freight). |
| Cost of land conversion (Part of private cost) | Cost of land conversion is the cost of converting land from one land use to another, including land clearing (the cost of removing biomass from the land) , land preparation (the cost of preparing the soil for the new use, also called land establishment, applies to conversion to cropland, pasture and land under forest restoration), and re-/afforestation (applies to conversion to land under forest restoration only), which includes initial planting of trees and maintenance and monitoring costs for newly established forest. Cost of land conversion does not include cost of regulation and is assumed to be static over time. |

Source: Vivid Economics

Figure 12 shows land cover and conversion by category under each scenario.

Figure 12 Land use change over time: Under delayed action, land under forest restoration area would have to nearly double by 2050


Source: Vivid Economics using MAgPIE

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