Title

Bending the curve of terrestrial biodiversity needs an integrated strategy

Summary paragraph

Increased efforts are required to prevent further losses of terrestrial biodiversity and the ecosystem services it provides[1,2]. Ambitious targets have been proposed, such as reversing the declining trends in biodiversity[3] – yet, just feeding the growing human population will make this a challenge[4]. We use an ensemble of land-use and biodiversity models to assess whether (and if so, how) humanity can reverse terrestrial biodiversity declines due to habitat conversion, a major threat to biodiversity[5]. We show that immediate efforts, consistent with the broader sustainability agenda but of unprecedented ambition and coordination, may allow to feed the growing human population while reversing global terrestrial biodiversity trends from habitat conversion. If we decide to increase the extent of land under conservation management, restore degraded land, and generalize landscape-level conservation planning, biodiversity trends from habitat conversion could become positive by mid-century on average across models (confidence interval: 2042-2061), but not for all models. Food prices could increase and, on average across models, almost half (confidence interval: 34-50%) of future biodiversity losses could not be avoided. However, additionally tackling the drivers of land-use change may avoid conflict with affordable food provision and reduces the food system's environmental impacts. Through further sustainable intensification and trade, reduced food waste, and healthier human diets*,* more than two thirds of future biodiversity losses are avoided and the biodiversity trends from habitat conversion are reversed by 2050 for almost all models. Although limiting further loss will remain challenging in several biodiversity-rich regions, and other threats, such as climate change, must be addressed to truly reverse biodiversity declines, our results show that bold conservation efforts and food system transformation are central to an effective post-2020 biodiversity strategy.

Main text

Terrestrial biodiversity is decreasing rapidly[1,2] as a result of human pressures, largely through habitat loss and degradation due to the conversion of natural habitats to agriculture and forestry[5]. Conservation efforts have not halted the trends[6] and land demand for food, feed and energy provision is increasing[7,8], putting at risk the myriad of ecosystem services people depend upon[9–11].

Ambitious targets for biodiversity have been proposed, such as halting and even reversing the currently declining trends[3,12] and conserving half of the Earth[13]. However, evidence is lacking on whether such biodiversity targets can be achieved, given that they may conflict with food provision[4] and other land uses. As a step towards developing a strategy for biodiversity that is consistent with the sustainable development agenda, we have used a multi-model ensemble approach[14,15] to assess whether and how future biodiversity trends from habitat loss and degradation can be reversed, while still feeding the growing human population.

We designed seven scenarios to explore pathways towards reversing the declining biodiversity trends (**Table 1**; **Methods**), based on the Shared Socioeconomic Pathway (SSP) scenario framework[16]. The *Middle of the Road* SSP2 defined our baseline scenario (denoted as BASE) for future drivers of habitat loss. In six additional scenarios we considered different combinations of supply-side, demand-side and conservation efforts towards reversing biodiversity trends: these were based on the *Green Growth* SSP1 scenario, augmented by ambitious conservation assumptions (**Extended Data Fig. 1**), and culminated in the Integrated Action Portfolio (IAP) scenario which includes all efforts.

Because of the uncertainties inherent in estimating how drivers will change and how these changes will affect biodiversity, we used an ensemble approach to model biodiversity trends for each scenario. First, we used the land-use components of four Integrated Assessment Models (IAMs) to generate four spatially and temporally resolved projections of habitat loss and degradation for each scenario (**Methods**). These IAM outputs were then evaluated by eight biodiversity models (BDMs) to project nine biodiversity indicators (BDIs, each defined as one biodiversity metric estimated by one BDM; **Table 2**) describing trends in five aspects of biodiversity: extent of suitable habitat, wildlife population density, local compositional intactness, regional species extinctions, and global species extinctions. The BASE and IAP scenarios were projected for an ensemble of 34 combinations of IAMs and BDIs; the other five scenarios were evaluated for a subset of seven BDIs for each IAM (ensemble of 28 combinations, see **Methods**). To obtain more robust insights, we performed bootstrap resampling[17] of the ensembles (10,000 samples with replacement, see **Methods**). We used state-of-the-art models of terrestrial biodiversity for global scale and broad taxonomic coverage, however, we note that more sophisticated modeling approaches – currently hard to apply at such scales – might provide more accurate estimates at smaller scales[18]. While we estimate future biodiversity as affected by future trends in the largest threat to biodiversity to date (habitat destruction and degradation), we note that more accurate projections of future biodiversity trends should account for additional threats to biodiversity, such as climate change or invasive alien species.

Table 1 | The seven scenarios picturing efforts to reverse declining biodiversity trends. *In addition to the baseline scenario, we considered three scenarios each with a single bundle of action aimed at reversing biodiversity trends due to future habitat loss (indicated with x) and three scenarios with combined bundles of action.*

	Additional efforts towards reversing trends in biodiversity					
Scenarios	Sustainable crop yield increases	Trade increases in agricultural goods	Reduced waste of agricultural goods from field to fork	Diet shift to lower share of animal calories	Increase in Protected Areas extent &	Increased restoration & landscape-level conservation
Baseline scenario						
Baseline (BASE)	-	-	-	-	-	-
Single bundle of action scenarios						
Supply-side efforts (SS)	x	x	-	-	-	-
Demand-side efforts (DS)	-	-	x	x	-	-
Increased conservation efforts (C)	-	-	-	-	x	x
Combined bundles of action scenarios						
Inc. conservation efforts & supply-side efforts (C+SS)	x	x	-	-	x	x
Inc. conservation efforts & demand-side efforts (C+DS)	-	-	x	x	x	x
Integrated action portfolio (IAP)	x	x	x	x	x	x

Table 2 | Key features of the nine estimated biodiversity indicators (BDIs)*. Using eight global biodiversity models (BDMs, see* ***Methods****), we estimated the relative change from 2010 (=1) in the value of six different biodiversity metrics grouped in five biodiversity aspects.*

Biodiversity indicator (BDI)	**Biodiversity model (BDM)**	**Biodiversity metric**	**Biodiversity metric definition**	**Biodiversity aspect**
ESH metric (AIM-B BDM)	AIM-B	Extent of Suitable Habitat (ESH)	Measures the extent of suitable habitat relative to its value in 2010, geometrically averaged across species; ranges from 0 (no suitable habitat left for any species) to 1 (mean extent equal to that of 2010) or larger (mean extent larger than that of 2010)	Extent of suitable habitat
ESH metric (INSIGHTS BDM)	INSIGHTS			
LPI metric (LPI-M BDM)	LPI-M	Living Planet Index (LPI)	Measures the population size relative to its value in 2010, geometrically averaged across species; ranges from 0 (zero population for all species) to 1 (mean population size equal to that of 2010) or larger (mean population size larger than that of 2010)	Wildlife population density
MSA metric (GLOBIO BDM)	GLOBIO	Mean Species Abundance Index (MSA)	Measures the compositional intactness of local communities (arithmetic mean across all species originally present of the species relative abundance - truncated to 1 - in comparison to an undisturbed state) relative to its value in 2010; ranges from 0 (population of zero for all original species) through 1 (intactness equivalent to that of 2010) or larger (intactness closer to an undisturbed state than in 2010)	Local compositional intactness
BII metric (PREDICTS BDM)	PREDICTS	Biodiversity Intactness Index (BII)	Measures the compositional intactness of local communities (arithmetic mean across all species originally present of the species relative abundance in comparison to an undisturbed state, truncated to 1) relative to its value in 2010; ranges from 0 (population of zero for all original species) to 1 (intactness equivalent to that of 2010) to larger values (composition closer to an undisturbed state than in 2010)	
FRRS metric (cSAR_CB17 BDM)	cSAR_CB17	Fraction of Regionally Remaining Species (FRRS)	Measures the proportion of species not already extinct or committed to extinction in a region (but not necessarily in other regions) relative to its value in 2010; ranges from 0 (all species of a region extinct or committed to extinction) to 1 (as many species of a region are extinct or committed to extinction as in 2010) or larger (fewer species of a region are extinct or committed to extinction than in 2010)	Regional extinctions
FGRS metric (BILBI BDM)	BILBI	Fraction of Globally Remaining Species (FGRS)	Measures the proportion of species not already extinct or committed to extinction across all terrestrial areas, relative to its value in 2010; ranges from 0 (all species extinct or committed to extinction at global scale) to 1 (as many species are extinct or committed to extinction at global scale as in 2010) or larger (fewer species are extinct or committed to extinction at global scale than in 2010)	Global extinctions
FGRS metric (cSAR_CB17 BDM)	cSAR_CB17			
FGRS metric (cSAR_US16 BDM)	cSAR_US16			

Reversing biodiversity trends by 2050

Without further efforts to counteract habitat loss and degradation, we projected that global biodiversity will continue to decline (BASE scenario; **Fig. 1**). Rates of loss over time for all nine BDIs in 2010-2050 were close to or greater than those estimated for 1970-2010 (**Extended data Extended Data Table 1**). For various biodiversity aspects, on average across IAM and BDI combinations, peak losses over the 2010-2100 period were: 13% (range: 1-26%) for the extent of suitable habitat, 54% (range: 45-63%) for wildlife population density, 5% (range: 2-9%) for local compositional intactness , 4% (range: 1-12%) for global extinctions, and 4% (range: 2-8%) for regional extinctions (**Extended Data Table 1**). Percentage losses were greatest in biodiversity-rich regions (Sub-Saharan Africa, South Asia, South East Asia, the Caribbean and Latin America; **Extended Data Fig. 2**). The projected future trends for habitat loss and degradation and its drivers[8,16], biodiversity loss[7,8], and variation in loss across biodiversity aspects[7,19,20] are consistent with those reported in other studies[1] (**Extended Data Fig. 2-5; Supp. discussion *1***).

In contrast, ambitious integrated efforts could minimize further declines and reverse biodiversity trends driven by habitat loss (IAP scenario; **Fig. 1**). In the IAP scenario, biodiversity loss was halted by 2050 and was followed by recovery for all IAM and BDI combinations except for one (IMAGE IAM x GLOBIO-MSA BDI). This reflects reductions in habitat loss and degradation and its drivers, and restoration of degraded habitats in this scenario (**Extended Data Fig. 3-5**; **Supp. discussion *1***). Although global biodiversity losses are unlikely to be halted by 2020[6], rapidly stopping the global biodiversity decline due to habitat loss is a milestone on the path to more ambitious targets.

Uncertainties in both future land use and its impact on biodiversity are significant, reflecting knowledge gaps[15]. To maximize the robustness of conclusions in the face of these uncertainties, we used a strategy with three main elements. First, as recommended by the IPBES[15], we conduct a multi-model assessment, building on the strengths and mitigating the weaknesses of several individual IAMs and BDMs to characterize uncertainties, understand their sources and identify results that are robust to these uncertainties. Looking at one BDI across multiple IAMs (e.g., ribbons in individual panels of Fig. 1), or comparing two BDIs informing on the same biodiversity aspect (e.g., MSA and BII BDIs in Fig. 1 c.) illuminates uncertainties stemming from individual model features such as initial condition, internal dynamics and scenario implementation. This shows, for example, that differences between IAMs in the initial area of grassland suitable for restoration and in the intensity of restoration efforts induce large uncertainties in biodiversity trends in all scenarios involving increased conservation efforts (C, C+SS, C+DS and IAP scenarios, **Supp. discussion *2***). Similarly, differences between BDMs in the timing of biodiversity recovery under restoration introduces further uncertainties, as do differences in taxonomic coverage and input data source between BDMs modeling the same BDI (**Supp. discussion *2***).

Second, rather than the absolute values of BDIs, we focus on the direction and inflexion in their relative change over time and their response to differences in land-use change outcomes across scenarios. This choice emphasizes aspects of biodiversity outcomes that are more directly comparable across multiple models and means comparisons are less impacted by model-specific differences and biases. We also used the most recent versions of BDMs that are still developing – for example, the PREDICTS implementation of BII used here[21] better captures compositional turnover caused by land-use change than did an earlier implementation[22]. All BDMs remain affected by uncertainty in the initial land-use distribution, especially the spatial distribution of current forest and grassland management, which varies across IAMs and causes estimates of all BDIs for the year 2010 to differ significantly among IAMs. Because these initial differences between IAMs persist across time horizons and scenarios, the direction and amplitude of projected relative changes in indicator values are more informative than their absolute values across the ensemble.

Third, we used bootstrap resampling with replacement to obtain confidence intervals of ensemble statistics and limit the influence of any particular model on the key results (**Methods**). However, our approach does not cover part of the overall uncertainty, stemming from either individual models (e.g., related to input parameter uncertainty) or limitations common to most models implemented in this study, such as the rudimentary representation of relationships between biodiversity and land-use intensity (see **Supp. discussion *2***, and **Methods** for more information on the evaluation of individual BDMs).

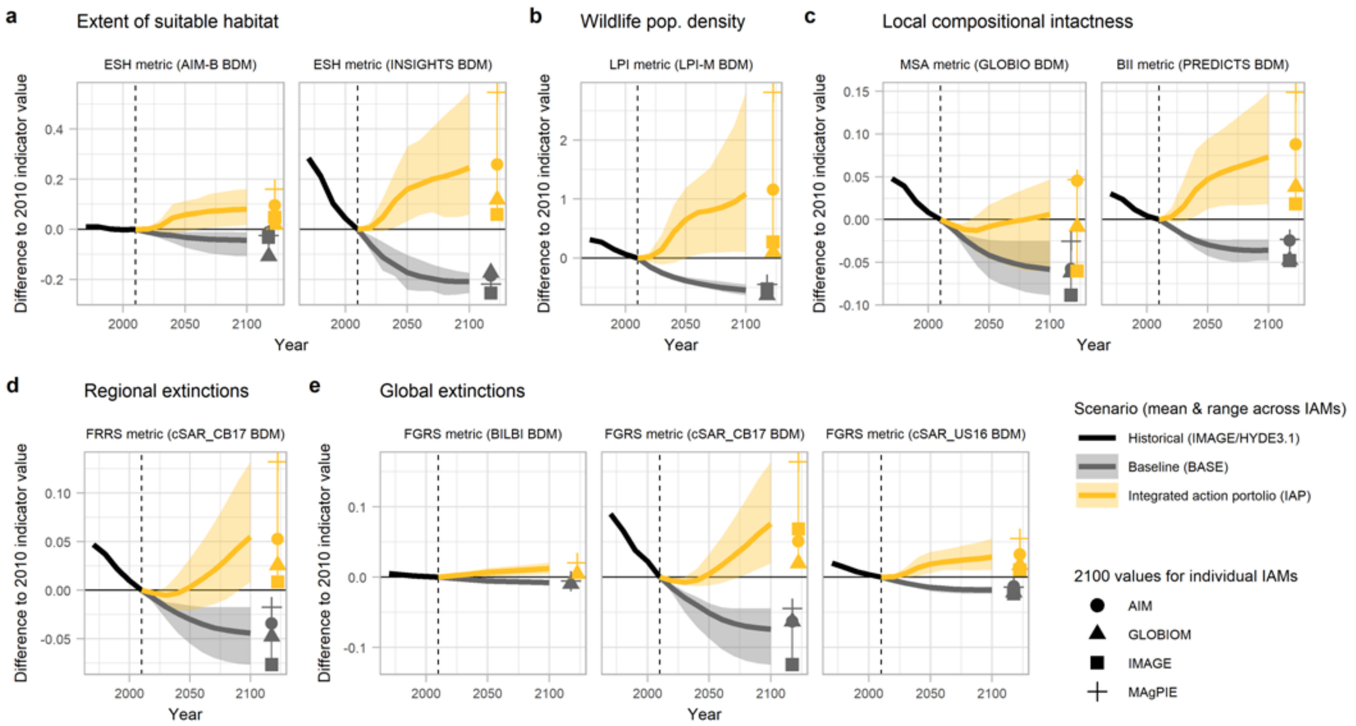

Fig. 1 | Estimated recent and future global biodiversity trends resulting from land-use change, with and without coordinated efforts to reverse trends*. Panels a-e depict the trends for the five aspects of biodiversity, resulting from changes in nine biodiversity indicators (BDIs; individual sub-panels, see* ***Table 2****). BDI values are shown as differences from the 2010 value (=1); a value of -0.01 means a 1% loss in: the extent of suitable habitat (panel a), the wildlife population density (panel b), the local compositional intactness (panel c), the regional number of species (panel d) or the global number of species (panel e). BDI values are projected in response to land-use change derived from one source over the historical period (1970-2010, black line; 2010 is indicated with a vertical dashed line) and from four Integrated Assessment Models (IAMs: AIM, GLOBIOM, IMAGE and MAgPIE; thick lines display the mean across models while ribbons display the range across models) for the baseline BASE scenario (grey) and Integrated Action Portfolio IAP scenario (yellow, see* ***Table 1****) over the future period (2010-2100).*

Contribution of different interventions

To understand the contribution of different strategies, we analyzed the BDI trends projected for all seven scenarios (see **Table 1**) for an ensemble of 28 BDI and IAM combinations, as shown in **Fig. 2a** for the MSA BDI and **Extended Data Fig. 6** for other BDIs. We focused on ensemble statistics for three outcomes (**Fig. 2b; Extended Data Table 2**): the date of peak loss (date at which the BDI value reached its minimum over the 2010-2100 period); the share of future peak loss that could be avoided, compared to the BASE scenario; and the speed of recovery after the peak loss (the recovery rate after peak loss, relative to the rate of decline over the historical period, see **Methods**).

Our analysis shows that a bold conservation plan is crucial for halting biodiversity declines and setting ecosystems onto a recovery path[3]. Increased conservation efforts (C scenario) was the only single bundle of action scenario leading on average across the ensemble to both a peak in future biodiversity losses before the last quarter of the 21st century (mean and 95% CI of the average date of peak loss ≤ 2075) and large reductions in future losses (mean and 95% CI of the average reductions ≥ 50%). On average across the ensemble, the speed of biodiversity recovery after peak loss was slow in Supply-Side (SS) and Demand-Side (DS) scenarios, but much faster when also combining increased conservation and restoration (in C, C+SS, C+DS and IAP scenarios), with a larger amount of reclaimed managed land (**Extended Data Fig. 4**). Our IAP scenario involve restoring 4.3-14.6 million km^2 of land by 2050, requiring the Bonn Challenge target (3.5 million km^2 by 2030) to be augmented by higher targets for 2050.

However, efforts to increase both the management and the extent of protected areas – to 40% of terrestrial area, based on wilderness areas and Key Biodiversity Areas – and to increase landscape-level conservation planning efforts in all terrestrial areas (C scenario; **Methods**) were insufficient on average to avoid >50% of the losses projected in the BASE scenario in many biodiversity-rich regions (**Extended Data Fig. 7**). Furthermore, the slight decrease in the global crop price index projected on average across IAMs in the BASE scenario was reversed in the C scenario (**Extended Data Fig. 8**). Without transformation of the food system, bolder conservation efforts would be conflict with future food provision, given the projected technological developments in agricultural productivity across models (**Supp. discussion 3**).

In contrast, a deeper food system transformation, relying on feasible supply-side and demand-side efforts as well as increased conservation efforts (IAP scenario; **Supp. discussion 3**), would greatly facilitate the reversal of biodiversity trends, reduce the trade-offs emerging from siloed policies, and offer broader benefits. On average across the ensemble, ≥67% of future peak losses were avoided for 96% (95% CI: 89-100%) of IAM and BDI combinations in the IAP scenario, in contrast to 43% (95% CI: 25-61%) in the C scenario (see **Extended Data Table 2**). Similarly, across the ensemble, biodiversity trends were reversed by 2050 for 96% (95% CI: 89%-100%) of IAM and BDI combinations in the IAP scenario vs. 61% (95% CI: 43%-79%) in the C scenario. Integrated efforts thus alleviate pressures on habitats (**Extended Data Fig. 5**) and reverse biodiversity trends from habitat loss decades earlier than strategies that allow habitat losses followed by restoration (**Extended Data Fig. 7**). Integrated efforts might also mitigate the trade-offs between regions and exploit complementarities between interventions: for example, increased agricultural intensification and trade may limit agricultural land expansion at the global scale, but induce expansion at a regional scale unless complemented with conservation efforts[23,24]. We found spatially contrasted – and sometimes regionally negative – impacts of various interventions, but the number of regions in favorable status increased with integration efforts (**Extended Data Figure 7**) . Finally, integrated strategies have benefits other than just enhancing biodiversity: dietary transitions alone have significant benefits for human health[25], and integrated strategies may also increase food availability, reverse future trends in greenhouse gas emissions from land use, and limit increases in the impact of land use on the water and nutrient cycles (**Extended Data Fig. 8**; **Supp. discussion *4***).

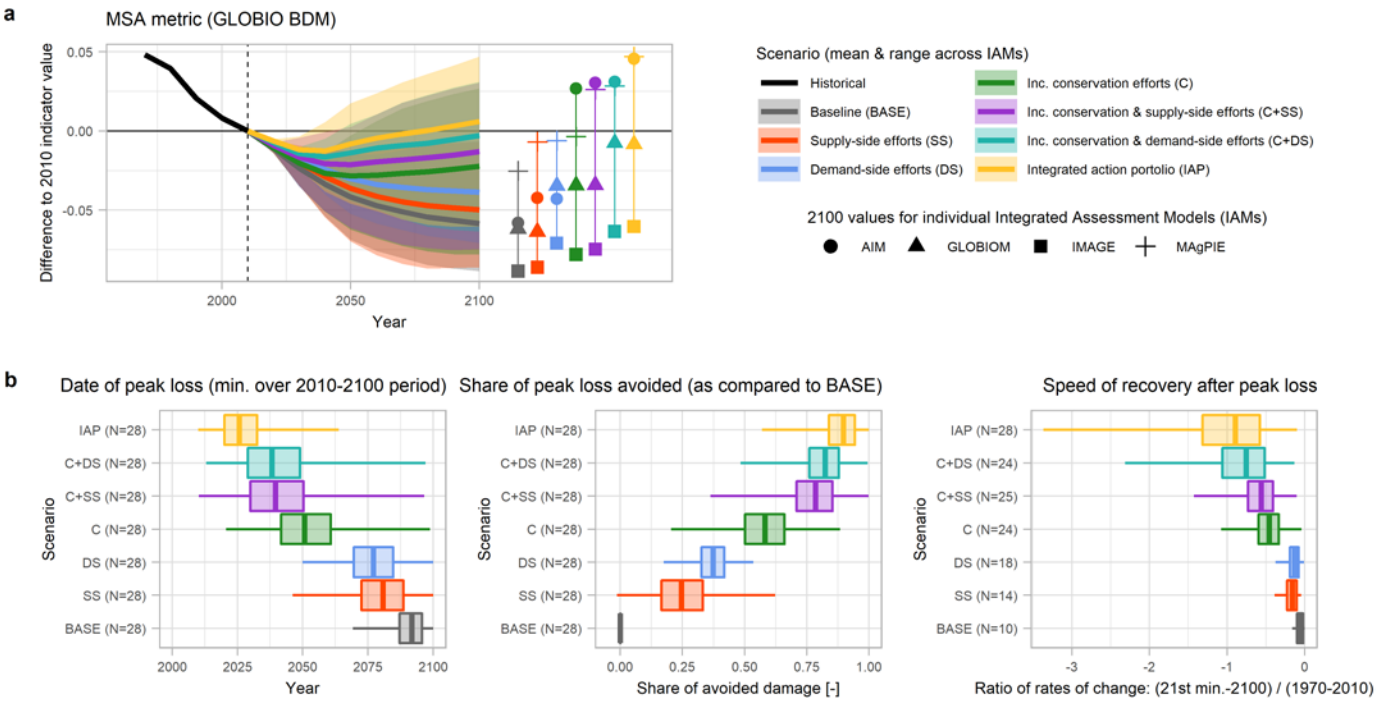

Fig. 2 | Contributions of various efforts to reverse land-use change-induced biodiversity trends. *Future actions towards reversing biodiversity trends vary across seven scenarios (BASE, SS, DS, C, C+SS, C+DS and IAP), indicated by different colors. In panel a, the line for each future scenario represents the mean across four IAMs and the ribbon represents the range across four IAMs of future changes (compared to 2010) for one illustrative biodiversity metric (MSA) estimated by one biodiversity model (GLOBIO). For the historical period, the black line represents the changes projected in the same biodiversity metric for the single land-use dataset considered over this period. Symbols display the estimated changes by 2100 for individual IAMs. Panel b displays estimates of the distribution across combinations of BDIs and IAMs, for each scenario, of: the date of the 21st century minimum (date of peak loss, left sub-panel); the proportion of peak biodiversity losses that could be avoided compared to the BASE scenario (middle sub-panel); and the speed of recovery after the minimum has been reached (right sub-panel, normalized by the historical speed of change, so that a value of -1 means recovery at the speed at which biodiversity losses took place in 1970-2010, and values lower than -1 indicate a recovery faster than the 1970-2010 loss). Values are estimated from 10,000 bootstrap samples from the original combination of BDIs and IAMs: in each boxplot, the thick vertical bar indicates the mean estimate (across bootstrap samples) of the mean value (across BDI and IAM combinations), the box indicates the 95% confidence interval of the mean value, and the horizontal lines indicate the mean estimates (across bootstrap samples) of the 2.5th and 97.5th quantiles (across BDI and IAM combinations). In each boxplot, the estimates are based on bootstrap samples with N=28 (7 BDIs x 4 IAMs), except for the right sub-panel, in which N ≤ 28, as the speed of recovery after peak loss is not defined if the peak loss is not reached before 2100.*

Discussion and conclusions

Our study suggests ways of resolving key trade-offs associated with bold actions for terrestrial biodiversity[4,26]. Actions in our IAP scenario address the largest threat to biodiversity – habitat loss and degradation – and are projected to reverse declines for five aspects of biodiversity. These actions may be technically possible, economically feasible and consistent with broader sustainability goals, but designing and implementing policies that enables such efforts will be challenging and will demand concerted leadership (**Supp. discussion 3**). In addition, reversing declines in other biodiversity aspects (e.g., phylogenetic and functional diversity) might require different spatial allocation of conservation and restoration actions, and possibly higher areal increase (**Supp. discussion 5**). Similarly, other threats (e.g., climate change, biological invasions) currently affect two to three times fewer species than land-use change at the global scale[5], but can be more important locally, can have synergistic effects, and will increase in global importance in the future. Therefore, a full reversal of biodiversity declines will require additional interventions, such as ambitious climate change mitigation that exploits synergies with biodiversity rather than further eroding biodiversity. Nevertheless, even if the actions explored in this study are insufficient, they will remain essential for reversing terrestrial biodiversity trends.

The need for transformative change and responses that simultaneously address a nexus of sustainability goals was recently documented by the Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services[1,2]. Our study complements that assessment by shedding light on the nature, ambition and complementarity of actions required to reverse the decline of global biodiversity trends from habitat loss, with direct implications for the international post-2020 biodiversity strategy. Reversing biodiversity trends – an interpretation of the 2050 Vision of the Convention on Biological Diversity – requires the urgent adoption of a conservation plan that retains the remaining biodiversity and restores degraded areas. Our scenarios feature an expansion to up to 40% of terrestrial areas with effective management for biodiversity, restoration efforts beyond the targets of the Bonn Challenge, and a generalization of land-use planning and landscape approaches. Such a bold conservation plan will conflict with other societal demands from land, unless transformations for sustainable food production and consumption are simultaneously considered. For a successful post-2020 biodiversity strategy, ambitious conservation must be combined with action on drivers of biodiversity loss, especially in the land use sectors. Without an integrated approach that exploits synergies with the Sustainable Development agenda, future habitat losses will at best take decades to restore, and further irreversible biodiversity losses are likely.

Models and scenarios can help to further outline integrated strategies that build upon contributions from nature to achieve sustainable development. This will however necessitate further research and the development of appropriate practices at the science-policy interface. Future assessments should seek to better represent land-management practices as well as additional pressures on land and biodiversity, such as climate change impact and mitigation, overexploitation, pollution and biological invasions. The upscaling of novel modeling approaches might facilitate such improvements, although it currently faces data and technical challenges[18]. In addition to innovative model developments and multi-model assessments, efforts are needed to evaluate and report on the uncertainty and performance of individual models. Such efforts however remain constrained by the complexity of natural and human systems and data limitations: for example, the models used in this analysis lack validation, not least because a thorough validation effort would face data and conceptual limitations[27]. . In such a context, both improved modeling practices (e.g., open source and FAIR principles[28], community-wide modeling standards[29]) and participatory approaches to validation might play a key role in enhancing the usefulness of models and scenarios[30].

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Methods

Qualitative and quantitative elements of scenarios

The Shared Socioeconomic Pathway (SSP) scenario framework[31] provides qualitative narratives and model-based quantifications of the future evolution of human demographics, economic development and lifestyle, policies and institutions, technology, and the use of natural resources. Our baseline assumption (BASE scenario) for the future evolution of drivers of habitat loss and degradation followed the *Middle Of The Road* SSP2 scenario[32], extending historical trends in population, dietary preferences, trade and agricultural productivity. SSP2 describes a world in which human population peaks at 9.4 billion by 2070 and economic growth is moderate and uneven, while globalization continues with slow socioeconomic convergence between countries.

In six additional scenarios (see **Table 1**), we assumed that additional actions are implemented in either single or combined bundles with an intensity that increases gradually from 2020 to 2050. The three bundles we consider are: *increased conservation efforts* (termed C), specifically increases in the extent and management of protected areas (PAs), restoration, and landscape-level conservation planning; *supply-side efforts* (SS), namely further increases in agricultural land productivity and trade of agricultural goods; and *demand-side efforts* (DS), namely waste reduction in the food system and a shift in human diets towards a halving of animal product consumption where it is currently high. The additional scenarios correspond to each bundle separately (single bundle of action scenarios: C, SS and DS) and to combined bundle of action scenarios, in which actions are paired (C+SS and C+DS) and combined as the integrated action portfolio of all three bundles (IAP scenario). The scenarios correspond to the following scenarios described in the methodological report[33] available at http://dare.iiasa.ac.at/57/: BASE = RCPref_SSP2_NOBIOD, SS = RCPref_SSP1pTECHTADE_NOBIOD, DS = RCPref_SSP1pDEM_NOBIOD, C = RCPref_SSP2_BIOD, C+SS = RCPref_SSP1pTECHTADE_BIOD, C+DS = RCPref_SSP1pDEM_BIOD, IAP = RCPref_SSP1p_BIOD.

The supply-side and demand-side efforts are based on assumptions from the *Green Growth* SSP1 scenario[16,34], or more ambitious. For the supply-side measures, we followed the SSP1 assumptions strictly, with faster closing of yield gaps leading to higher convergence towards the level of high-yielding countries, and trade in agricultural goods developing more easily in a more globalized economy with reduced trade barriers. Our assumed demand-side efforts are more ambitious than SSP1 and involve a progressive transition from 2020 onwards, reaching by 2050: i) a substitution of 50% of animal calories in human diets with plant-derived calories, except in regions where the share of animal products in diets is already estimated to be low (Middle East, Sub-Saharan Africa, India, South-east Asia and other Pacific Islands) and ii) a 50% reduction in total waste throughout the food supply chain, compared to the baseline scenario. See **Supp. discussion *3*** for a discussion of the feasibility of these options.

We generated new qualitative and quantitative elements depicting increased conservation efforts that were more ambitious than in the SSPs. Qualitatively, they relied on two pillars. Firstly, protection efforts are increased at once in 2020 in their extent to all land areas (hereafter referred to as 'expanded protected area') that are either currently under protection or identified as conservation priority areas through agreed international processes or based on wilderness assessment. Land management efforts also mean that land-use change leading to further habitat degradation is not allowed within the expanded protected areas from 2020 onwards. Secondly, we assume ambitious efforts – starting low in 2020 and progressively increasing over time – both to restore degraded land and to make landscape-level conservation planning a more central feature of land-use decisions, with the aim to reclaim space for biodiversity outside of expanded protected areas, while considering spatial gradients in biodiversity and seeking synergies with agriculture and forestry production.

To provide quantification of the increased conservation efforts narrative, we compiled spatially explicit datasets (**Extended Data Fig. 1**) used as inputs by the IAMs, as follows:

(i) For the first pillar (increased protection efforts), we generated 30-arcmin resolution rasters of a) the extent of expanded protected areas and b) land-use change restrictions within these protected areas. We estimated a plausible realization of expanded protected areas by overlaying the World Database of Protected Areas[35] (i.e., currently protected areas), the World Database on Key Biodiversity Areas[36] (i.e., agreed priorities for conservation) and the 2009 Wilderness Areas[37] (i.e., proposed priorities based on wilderness assessment) at 5-arcmin resolution before aggregating the result to 30-arcmin resolution to provide, on a 30-arcmin raster, the proportion of land under expanded protected areas (**Extended Data Fig. 1 a**). To estimate land-use change restrictions within expanded protected areas, we allowed a given land-use transition only if the implied biodiversity impact was estimated as positive by the impacts of land use on the Biodiversity Intactness Index (BII[20,38]) modeled from the PREDICTS database[39] (**Extended Data Fig. 1 c**). The BII estimates are global, but vary depending on spatially explicit features for the level of land-use aggregation considered in IAMs (whether the background potential ecosystem is forested or not and whether the managed grassland is pasture or rangeland), so we used the 2010 land-use distribution from the LUH2 dataset[40] to estimate spatially explicit land-use change restrictions. These layers were used as input in the modeling of future land-use change, to constrain possible land-use changes in related scenarios.

(ii) For the second pillar (increased restoration and landscape-level conservation planning efforts), we generated, on a 30-arcmin resolution, a set of coefficients allowing the estimation of a relative biodiversity stock *BV(p)* score for any land-use configuration in any pixel *p*. To calculate the score (see [Equ. 1]), we associated a pixel-specific regional relative range-rarity weighted species richness score *RRRWSR(p)* (**Extended Data Fig. 1 b**) with land-use class *LU* and pixel *p* specific modeled impacts of land uses on the intactness of ecological assemblages[20] *BII(LU,p)* (**Extended Data Fig. 1 c**) and the modeled proportion of pixel terrestrial area occupied by each land use in each pixel *a(LU,p)*. The *RRRWSR(p)* score was estimated from range maps of comprehensively assessed groups (amphibians, chameleons, conifers, freshwater crabs and crayfish, magnolias and mammals) from the IUCN Red List[41] and birds from the Handbook of the Birds[42] and gave an indication of the relative contribution of each pixel in representing the biodiversity of the region. This spatially-explicit information was used as an input for modeling future land-use change to quantify spatial and land-use-specific priorities for biodiversity outside protected areas (including restoring degraded land).

$$BV(p) = \sum_{LU=1}^{N} [BII(LU,p) \cdot RRRWSR(LU,p) \cdot a(LU,p)] \qquad \text{[Equ. 1]}$$

Projections of recent past and future habitat loss and degradation

To project future habitat loss and degradation, we used the land-use component of four Integrated Assessment Models (IAMs) to generate spatially and temporally explicit projections of land-use change for each scenario. IAMs are simplified representations of the various sectors and regions of the global economy. Their land-use components can be used to provide quantified estimates of future land-use patterns for given assumptions about their drivers, allowing the projection of biodiversity metrics into the future[43]. The IAM land-use components were: AIM (from AIM/CGE[44,45]), GLOBIOM (from MESSAGE-GLOBIOM[46]), IMAGE (from IMAGE/MAGNET[47,48]) and MAgPIE (from

REMIND-MAgPIE[49]) – see Section 5.1 of the methodological report[33] for details. All have global coverage (excluding Antarctica), and model demand, production and trade at the scale of 10 to 37 world regions. Land-use changes are modelled at the pixel scale in all IAMs except for AIM, for which regional model outputs are downscaled. For the GLOBIOM model, high-resolution land-use change model outputs were refined by downscaling from the regional to the pixel scale.

Scenario implementation was done according to previous work[16], with the exception of assumptions on increased conservation efforts (see Section 5.2 of the methodological report[33] for details). For all IAMs, the increased protection efforts were implemented within the economic optimization problem as spatially explicit land-use change restrictions within the expanded protected areas from 2020 onwards. The expanded protected areas reached 40% of terrestrial area (compared to 15.5% assumed for 2010), and >87% of additionally protected areas were solely identified as wilderness areas. The increased restoration and landscape-level conservation planning efforts were implemented in the economic optimization problem as spatially explicit priorities for land-use change from 2020 onwards. A relative preference for biodiversity conservation over production objectives, increasing over time, was implemented through a tax on changes in the biodiversity stock or increased scarcity of land available for production.

For each scenario, the IAMs projected the proportion of land occupied by each of twelve different land-use classes (built-up area, cropland other than short-rotation bioenergy plantations, cropland dedicated to short-rotation bioenergy plantations, managed grassland, managed forest, unmanaged forest, other natural vegetation, restoration land, abandoned cropland previously dedicated to crops other than short-rotation bioenergy plantations, abandoned cropland previously dedicated to short-rotation bioenergy plantations, abandoned managed grassland, abandoned managed forest) in pixels over the terrestrial area (excluding Antarctica) of a 30-arcmin raster, in 10-year time steps from 2010 to 2100. Abandoned land was treated differently according to the scenarios: in scenarios with increased conservation efforts (C, C+SS, C+DS & IAP) it was systematically considered to be restored and entered the 'restoration land' land-use class. In other scenarios it was placed in one of the four abandoned land-use classes for thirty years, after which it was moved to the 'restoration land' land-use class, unless it had been reconverted into productive land.

This led to the generation of 3,360 individual raster layers depicting, at the global scale and 30-arcmin resolution, the proportion of pixel area occupied by each land-use class (12 in total) at each time horizon (10 in total), as estimated

by each IAM (4 in total) for each scenario (7 in total). As the spatial and thematic coverage of the four IAMs differed slightly, further harmonization was conducted, leading to the identification of 111 terrestrial ecoregions that were excluded from the analysis due to inconsistent coverage across IAMs. For analysis, the land-use projections were also aggregated at the scale of IPBES sub-regions[50]. More details on the outputs, including a definition of land-use classes and the specifications of each IAM, can be found in the methodological report[33].
In order to estimate the biodiversity impacts of recent past trends in habitat losses and degradation, we used the spatially explicit reconstructions of the IMAGE model, estimated from the HYDE 3.1 database[51] for the period from 1970 to 2010, for the same land-use classes and with the same spatial and temporal resolution as used for future projections.

Projections of recent past and future biodiversity trends

We estimated the impacts of the projected future changes in land use on nine biodiversity indicators (BDIs), providing information on six biodiversity metrics (see **Table 2**) indicative of five aspects of biodiversity: the extent of suitable habitat (ESH metric), the wildlife population density (LPI metric), the compositional intactness of local communities (MSA and BII metrics), the regional extinction of species (FRRS metric) and the global extinction of species (FGRS metric). Each BDI is defined as a combination of one of six biodiversity metrics and of one of eight biodiversity models (BDMs) we used: AIM-B[52], INSIGHTS[53,54], LPI-M[19,55], BILBI[56–58], cSAR_CB17[59], cSAR_US16[60,61], GLOBIO[62], PREDICTS[63–65]. These models were selected for their ability to project biodiversity metrics regionally and globally under various scenarios of spatially explicit future changes in land use. Their projections considered only the impact of future changes in land use, and did not account for future changes in other threats to biodiversity (e.g., climate change, biological invasions, hunting).

Estimating future trends in biodiversity for all seven scenarios, ten time horizons and four IAMs was not possible for all BDMs. We therefore adopted a tiered approach (see Section 6 of the methodological report[33]): for the two extreme scenarios (BASE and IAP), trends were estimated for all IAMs and time horizons for all BDIs except FGRS x BILBI BDM, for which trends were estimated for only two IAMs (GLOBIOM and MAgPIE) and three time horizons (2010, 2050 and 2100). For the other five scenarios (C, SS, DS, C+SS, C+DS), trends were estimated for all IAMs and time horizons for seven BDIs (MSA metric x GLOBIO BDM, BII metric x PREDICTS BDM, ESH metric x INSIGHTS BDM, LPI metric x LPI-M BDM, FRRS metric x cSAR_CB17, FGRS metric x cSAR_CB17 and FGRS metric x cSAR_US16 BDM). Values of each indicator were reported at the global level and for the 17 IPBES sub-regions[50] for all BDIs except for FGRS metric x cSAR_US16 BDM (reported only at the global level).

The BDMs differ in key features affecting the projected trends (see Section 6 of the methodological report[33]). For example, the two models projecting changes in the extent of suitable habitat rely on the same type of model (Habitat Suitability Models) but have different taxonomic coverage (mammals for INSIGHTS vs. vascular plants, amphibians, reptiles, birds, and mammals for AIM-B), different species-level distribution modeling principles (expert-driven for INSIGHTS vs. species distribution model for AIM), and different granularity in their representation of land use and land cover (12 classes for INSIGHTS vs. 5 classes for AIM-B). While all BDMs implicitly account for the current intensity of cropland, only one (GLOBIO) accounts for the impact on biodiversity of future changes in cropland intensity. Similarly, temporal lags in the response of biodiversity to restoration of managed land differed across models, often leading to different biodiversity recovery rates within restored land (**Supp. discussion *2***). As detailed in the section 6.5 of the methodological report[33], the individual BDMs have been subject to various forms of model evaluation.

Further calculations on projected biodiversity trends

To facilitate the comparison with the literature and the comparison of baseline trends between time periods and BDIs, we estimated the linear rate of change per decade in the indicator value for all BDI and IAM combinations in two time periods (1970-2010, 2010-2050), as the percentage change per decade (see **Extended Data Table 1**). The linear rate of change per decade for each period and BDI x IAM combination was derived by dividing the total change projected over the period by the number of decades.

We also estimated the date $D_{PeakLoss}$ and value $V_{PeakLoss}$ of the peak loss over the 2010-2100 period for each BDI, IAM and scenario combination for which all time steps were available. The date of peak loss is defined as the date when the minimum indicator value estimated over the 2010-2100 period is reached, and the value of peak loss is defined as the corresponding absolute BDI value difference from the 2010 level (=1). For the 28 concerned BDI x IAM combinations, we then defined the share of future losses that could be avoided in each scenario *S* (compared to the BASE scenario) as [1-$V_{PeakLoss}$(S)/$V_{PeakLoss}$(BASE)]. For BDI x BDI combinations for which the date of the peak loss was earlier than 2100, we defined the period between the date of peak loss and 2100 as the recovery period, and estimated the relative speed of BDI recovery as the average linear rate of change over the recovery period, relative to the average rate of decline in the historical period (1970-2010). The date of peak loss, share of avoided losses and relative speed of recovery were also estimated at the scale of IPBES subregions, for the 24 BDI and IAM combinations available at such a scale.

To estimate more robust estimates of the summary statistics (mean, median, standard deviation, 2.5^{th} and 97.5^{th} quantile) across the ensemble of IAM and BDM combinations (28 at global scale and 24 at regional scale) for the above-mentioned values (date of peak loss, share of future losses that could be avoided, speed of recovery) in each scenario, we performed bootstrap resampling with replacement for 10,000 samples. This allowed us to estimate a mean, a standard deviation and a confidence interval (CI: defined as the range between the 2.5^{th} and 97.5^{th} quantile) for each ensemble statistic (mean, median, standard deviation, 2.5^{th} and 97.5^{th} quantile) at global and regional scales (see **Extended Data Table 2**). No weighting of individual IAM and BDI combinations was applied. Analysis was done with the version 3.6.1 of the R software [66].

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Data availability

The 30-arcmin resolution raster layers (extent of expanded protected areas, land-use change rules in expanded protected areas, coefficients allowing the estimation of the pixel-specific and land-use change transition-specific biodiversity impact of land-use change) used by the IAMs to model increased conservation efforts cannot be made freely available due to the terms of use of their source, but will be made available upon direct request to the authors. The 30-arcmin resolution raster layers providing the proportion of land cover for each of the twelve land-use classes, four IAMs, seven scenarios and ten time horizons are publicly available from a data repository under a CC-BY-NC license (http://dare.iiasa.ac.at/57/), together with the IAM outputs underpinning the global scale results of **Extended Data Fig. 3** and **Extended Data Fig. 8** (for all time horizons), the global and IPBES subregion-specific results of **Extended Data Fig. 4** and **Extended Data Fig. 5**, and the BDM outputs underpinning the global and IPBES subregion-specific results depicted in **Fig. 1**, **Fig. 2**, **Extended Data Fig. 2**, **Extended Data Fig. 6**, **Extended Data Fig. 7**, **Extended Data Table 1** and **Extended Data Table 2** (for all available time horizons, BDIs, IAMs and scenarios).

Code availability

The code and data used to generate the BDM outputs is publicly available from a data repository under a CC-BY-NC license (http://dare.iiasa.ac.at/57/) for all BDMs. The code and data used to analyze IAM and BDM outputs and generate figures is publicly available from a data repository under a CC-BY-NC license (http://dare.iiasa.ac.at/57/).

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Author contributions

DL and MO lead the study. DL coordinated the modeling, performed the analysis, coordinated the writing of the preliminary draft and performed the writing of later drafts. DL, MB, SHMB, AC, AD, FAJD, MDM, JCD, MD, RF, MH, TH, SH, JPH, SLLH, FH, NJ, TKri, GMM, HO, APo, APu, AMS, AT, HV, HvM, WJvZ and PV were involved in the core modeling and writing. RAlk, RAlm, GB, NDB, SEC, FDF, SFe, SFr, SFu, MG, TH, PH, MH, AJH, MJ, TKra, HLC, TM, CM, DN, TN, GST, ES, BS, DPvV, CW, JEMW, WW and LY contributed through several iterations on the study design, result analysis and article writing.

Competing interests

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Additional information

Supplementary information is available for this paper at DOI-link.

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Extended data

Extended Data Table 1

Extended Data Table 1 | Prolongation of historical biodiversity trends in the baseline scenario. *Summary metrics (mean linear rate of indicator change in the periods 1970-2010 and 2010-2050, peak loss – i.e., minimum value of indicator change – over 2010-2100) for each biodiversity indicator (1970-2010 linear change rate, mean and range across IAMs for 2010-2050 linear change rate and peak loss in the BASE scenario) and biodiversity aspect (mean across BDIs for 1970-2010 linear change rate, mean and range across IAMs and BDIs for 2010-2050 linear change rate and 2010-2100 minimum change in the BASE scenario).*

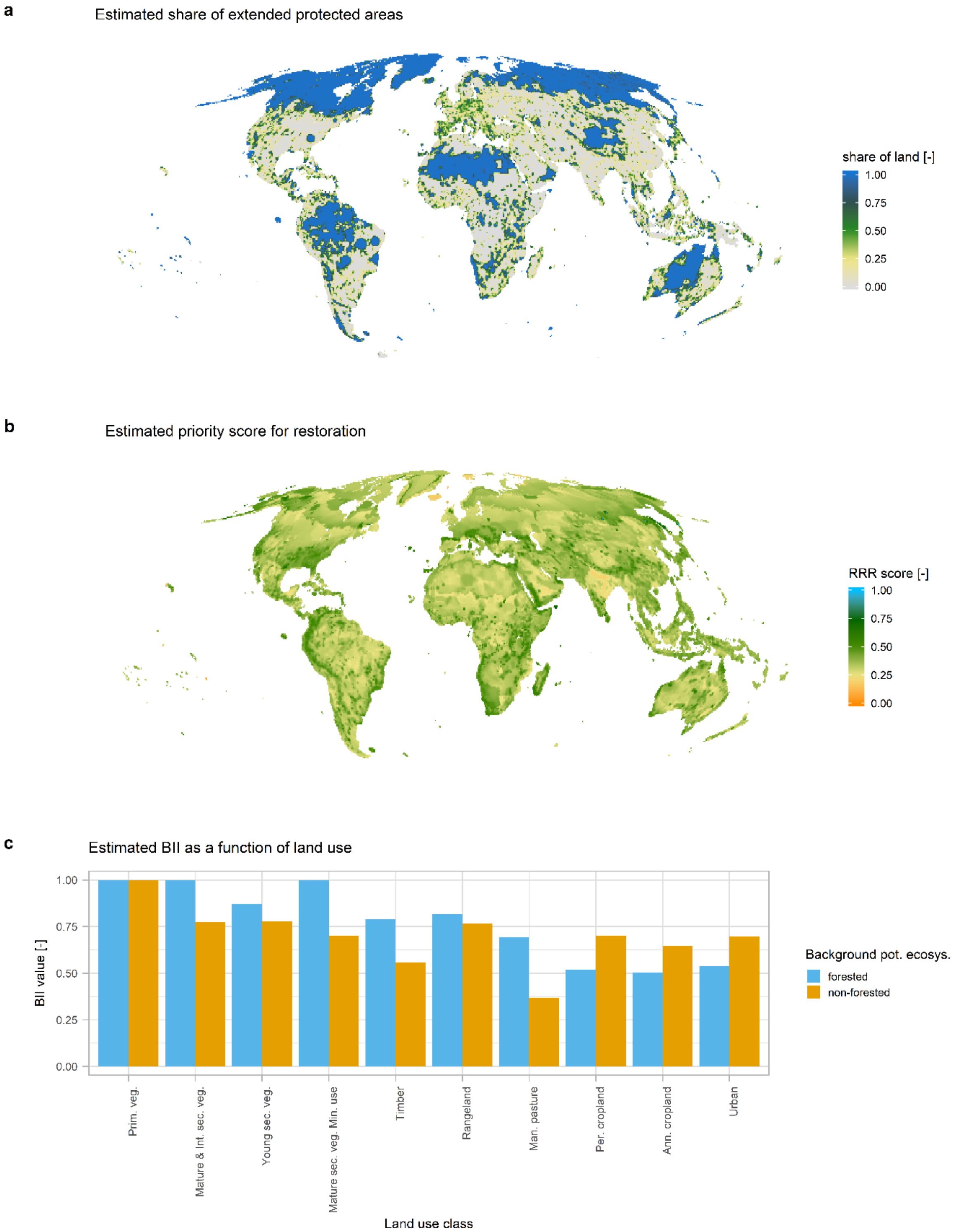
Biodiversity indicator	Mean linear rate of change		Peak loss	Biodiversity aspect	Mean linear rate of change rate		Peak loss
	1970-2010	2010-2050 (BASE scenario)	2010-2100 (BASE scenario)		1970-2010	2010-2050 (BASE scenario)	2010-2100 (BASE scenario)
	[%/decade]	[%/decade] mean (range) across IAMs	[%] mean (range) across IAMs		[%/decade] mean (range) across BDIs	[%/decade] mean (range) across BDIs & IAMs	[%] mean (range) across BDIs & IAMs
ESH metric (AIM-B BDM)	-0.26	-0.79 (-1.81; -0.21)	-4.61 (-10.76; -1.18)	Extent of suitable habitat	-2.90 (-5.54; -0.26)	-2.55 (-6.03; -0.21)	-12.91 (-26.29; -1.18)
ESH metric (INSIGHTS BDM)	-5.54	-4.30 (-6.03; -2.57)	-21.20 (-26.29; -17.30)				
LPI metric (LPI-M BDM)	-5.94	-9.68 (-10.25; -7.98)	-54.16 (-62.97; -44.59)	Wildlife population density	-5.94 (-)	-9.68 (-10.25; -7.98)	-54.16 (-62.97; -44.59)
MSA metric (GLOBIO BDM)	-1.15	-1.04 (-1.72; -0.60)	-5.84 (-8.85; -2.52)	Local compositional intactness	-0.94 (-1.15; -0.74)	-0.89 (-1.72; -0.57)	-4.77 (-8.85; -2.38)
BII metric (PREDICTS BDM)	-0.74	-0.73 (-1.06; -0.57)	-3.71 (-4.95; -2.38)				
FRRS metric (cSAR_CB17 BDM)	-1.12	-0.75 (-1.37; --0.40)	-4.4- (-7.66; -1.75)	Regional extinctions	-1.12 (-)	-0.75 (-1.37; -0.40)	-4.40 (-7.66; -1.75)
FGRS metric (BILBI BDM)	-0.13	-0.14 (-0.14; -0.13)	-0.75 (-0.95; -0.54)	Global extinctions	-0.90 (-2.07; -0.13)	-0.68 (-2.18; -0.13)	-3.84 (-12.44; -0.54)
FGRS metric (cSAR_CB17 BDM)	-2.07	-1.27 (-2.18; -0.93)	-7.38 (-12.44; -4.46)				
FGRS metric (cSAR_US16 BDM)	-0.49	-0.36 (-0.50; -0.28)	-1.83 (-2.37; -1.40)				

Extended Data Table 2

Extended Data Table 2 | Key statistics of the data supporting Figure 2. Summary statistics for the date of peak loss, the share of avoided future peak loss as compared to the BASE scenario and the relative speed of recovery after peak loss, by scenario (rows). For each scenario, whether looking at the mean, median or 2.5th and 97.5th quantiles of each quantity (groups of columns), the statistics across BDIs and IAMs combinations (columns) are estimated from samples of size N (between 10 and 28) either directly from the unique sample of BDM outputs (simulated) or from the 10,000 bootstrapped samples (with replacement) for which we present estimates across samples of mean, median and quantiles (q025 and q975 for respectively 2.5th and 97.5th percentiles, defining 95% confidence intervals CI95 = [q025,q975]).

			mean				median				2.5th quantile				97.5th quantile			
			simulated	est. from bootstrap resampling			simulated	est. from bootstrap resampling			simulated	est. from bootstrap resampling			simulated	est. from bootstrap resampling		
metric	scenario	N		mean	q025	q975		mean	q025	q975		mean	q025	q975		mean	q025	q975
Date of peak loss	BASE	28	2091.8	2091.8	2087.1	2095.7	2100.0	2098.7	2080.0	2100.0	2066.8	2069.2	2060.0	2080.0	2100.0	2100.0	2100.0	2100.0
	SS	28	2080.7	2080.7	2072.5	2088.6	2095.0	2090.1	2065.0	2100.0	2046.8	2046.2	2040.0	2050.0	2100.0	2100.0	2100.0	2100.0
	DS	28	2077.1	2077.1	2069.6	2084.6	2075.0	2078.4	2060.0	2100.0	2050.0	2050.0	2050.0	2050.0	2100.0	2100.0	2100.0	2100.0
	C	28	2050.7	2050.8	2041.8	2060.7	2040.0	2044.2	2030.0	2060.0	2020.0	2020.6	2020.0	2026.8	2100.0	2098.8	2086.5	2100.0
	C+SS	28	2039.6	2039.6	2030.0	2050.4	2035.0	2034.0	2020.0	2045.0	2010.0	2010.2	2010.0	2016.8	2100.0	2096.6	2066.3	2100.0
	C+DS	28	2038.2	2038.1	2028.9	2048.9	2030.0	2029.6	2020.0	2035.0	2010.0	2013.0	2010.0	2020.0	2100.0	2097.1	2066.3	2100.0
	IAP	28	2025.7	2025.7	2020.0	2032.5	2020.0	2021.2	2020.0	2030.0	2010.0	2010.0	2010.0	2010.0	2063.0	2063.7	2040.0	2090.0
Share of avoided future peak loss	BASE	28	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	SS	28	0.25	0.25	0.17	0.33	0.20	0.20	0.06	0.30	-0.02	-0.01	-0.03	0.02	0.64	0.62	0.58	0.65
	DS	28	0.37	0.37	0.33	0.42	0.39	0.38	0.31	0.46	0.17	0.17	0.15	0.22	0.54	0.54	0.51	0.54
	C	28	0.58	0.58	0.50	0.66	0.60	0.60	0.47	0.73	0.19	0.20	0.12	0.35	0.89	0.88	0.81	0.90
	C+SS	28	0.79	0.79	0.71	0.85	0.81	0.81	0.74	0.88	0.35	0.36	0.15	0.60	1.00	1.00	0.99	1.00
	C+DS	28	0.82	0.82	0.76	0.88	0.85	0.86	0.77	0.93	0.49	0.48	0.28	0.67	1.00	1.00	0.98	1.00
	IAP	28	0.90	0.90	0.84	0.94	0.95	0.94	0.88	1.00	0.58	0.57	0.32	0.79	1.00	1.00	1.00	1.00
Relative recovery speed	BASE	10	-0.06	-0.06	-0.10	-0.02	-0.03	-0.04	-0.10	-0.01	-0.19	-0.16	-0.21	-0.08	0.00	0.00	-0.01	0.00
	SS	14	-0.16	-0.16	-0.23	-0.11	-0.11	-0.13	-0.21	-0.08	-0.44	-0.39	-0.49	-0.22	-0.04	-0.05	-0.07	-0.04
	DS	18	-0.13	-0.13	-0.19	-0.08	-0.12	-0.11	-0.14	-0.05	-0.41	-0.37	-0.42	-0.21	0.00	-0.01	-0.03	0.00
	C	24	-0.46	-0.46	-0.60	-0.34	-0.44	-0.41	-0.62	-0.24	-1.13	-1.08	-1.18	-0.79	-0.03	-0.04	-0.12	-0.02
	C+SS	25	-0.56	-0.56	-0.73	-0.41	-0.46	-0.45	-0.62	-0.31	-1.50	-1.43	-1.56	-1.02	-0.09	-0.10	-0.19	-0.04
	C+DS	24	-0.76	-0.75	-1.06	-0.52	-0.52	-0.55	-0.81	-0.40	-2.48	-2.31	-3.44	-1.16	-0.11	-0.13	-0.28	-0.05
	IAP	28	-0.89	-0.90	-1.32	-0.58	-0.56	-0.58	-0.73	-0.47	-3.36	-3.36	-5.26	-1.38	-0.08	-0.10	-0.27	0.00
share of BDI x IAM combinations with (date of peak loss ≤ 2050)	BASE	28	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
	SS	28	0.21	0.21	0.07	0.39	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	1.00	0.99	1.00	1.00
	DS	28	0.25	0.25	0.11	0.43	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	1.00	1.00	1.00	1.00
	C	28	0.61	0.61	0.43	0.79	1.00	0.87	0.00	1.00	0.00	0.00	0.00	0.00	1.00	1.00	1.00	1.00
	C+SS	28	0.82	0.82	0.68	0.96	1.00	1.00	1.00	1.00	0.00	0.02	0.00	0.68	1.00	1.00	1.00	1.00
	C+DS	28	0.86	0.86	0.71	0.96	1.00	1.00	1.00	1.00	0.00	0.06	0.00	0.68	1.00	1.00	1.00	1.00
	IAP	28	0.96	0.96	0.89	1.00	1.00	1.00	1.00	1.00	0.68	0.62	0.00	1.00	1.00	1.00	1.00	1.00
share of BDI x IAM combinations with (share of avoided future losses ≥ 67%)	BASE	28	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
	SS	28	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
	DS	28	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
	C	28	0.43	0.43	0.25	0.61	0.00	0.23	0.00	1.00	0.00	0.00	0.00	0.00	1.00	1.00	1.00	1.00
	C+SS	28	0.82	0.82	0.68	0.96	1.00	1.00	1.00	1.00	0.00	0.02	0.00	0.68	1.00	1.00	1.00	1.00
	C+DS	28	0.82	0.82	0.68	0.96	1.00	1.00	1.00	1.00	0.00	0.02	0.00	0.68	1.00	1.00	1.00	1.00
	IAP	28	0.96	0.96	0.89	1.00	1.00	1.00	1.00	1.00	0.68	0.61	0.00	1.00	1.00	1.00	1.00	1.00

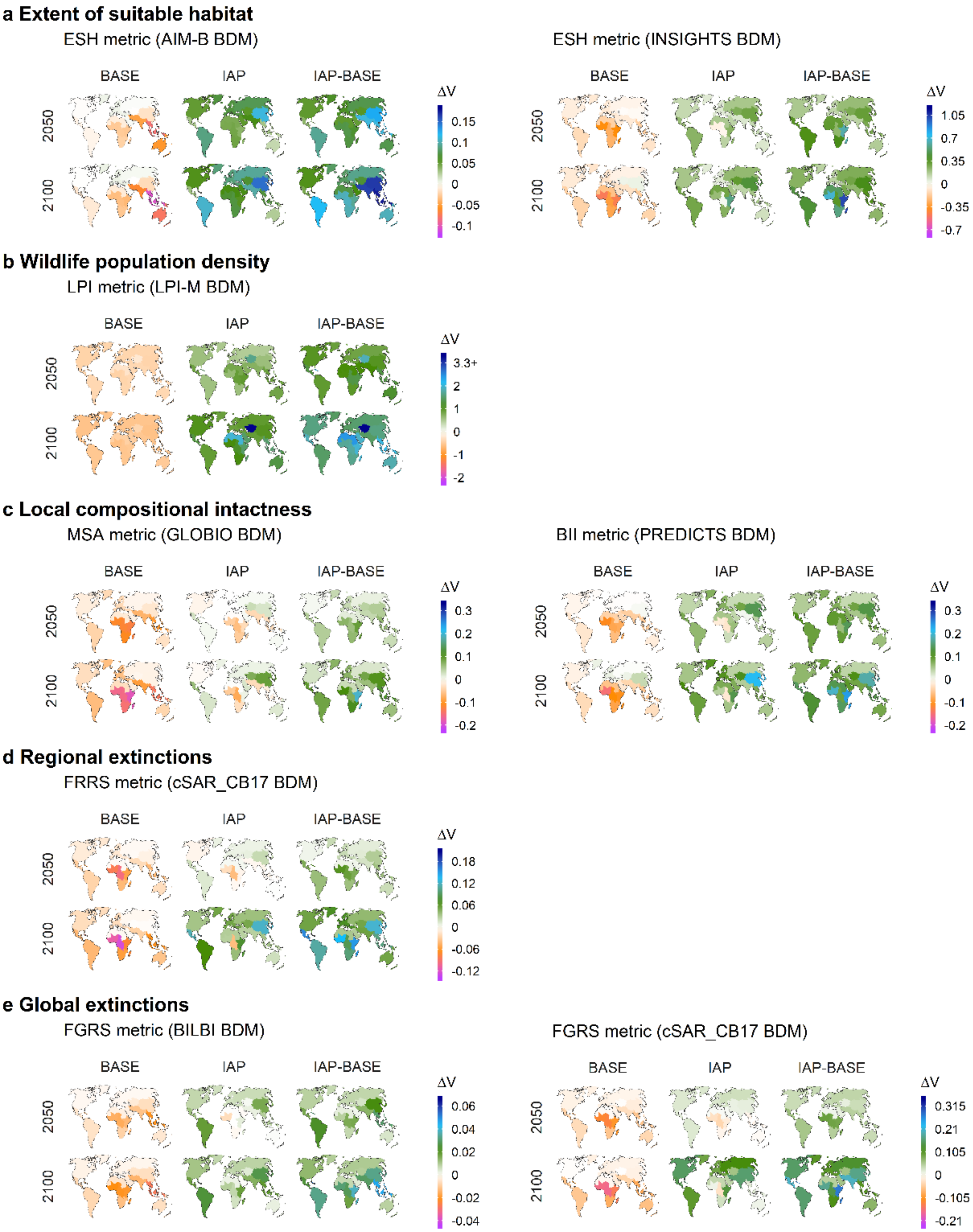
Extended Data Figure 1



Extended Data Fig. 1 | Datasets used to provide spatially explicit input for modeling increased conservation efforts into the land-use models. *The figure presents at 30 arcmin-resolution the proportion of land under the assumed expanded protected areas (panel a, based on all areas from the World Database on Protected areas[35] and areas from Key Biodiversity Areas[36] and Wilderness Areas[37]) and the value of the assumed spatial priority score for restoration (panel b, Relative Range Rarity-Weighted Species Richness score RRRWSR, based on species range maps from the ICUN Red List[41] and the Handbook of the Birds of the World[42]), as well as the impact of various land uses on the Biodiversity Intactness*

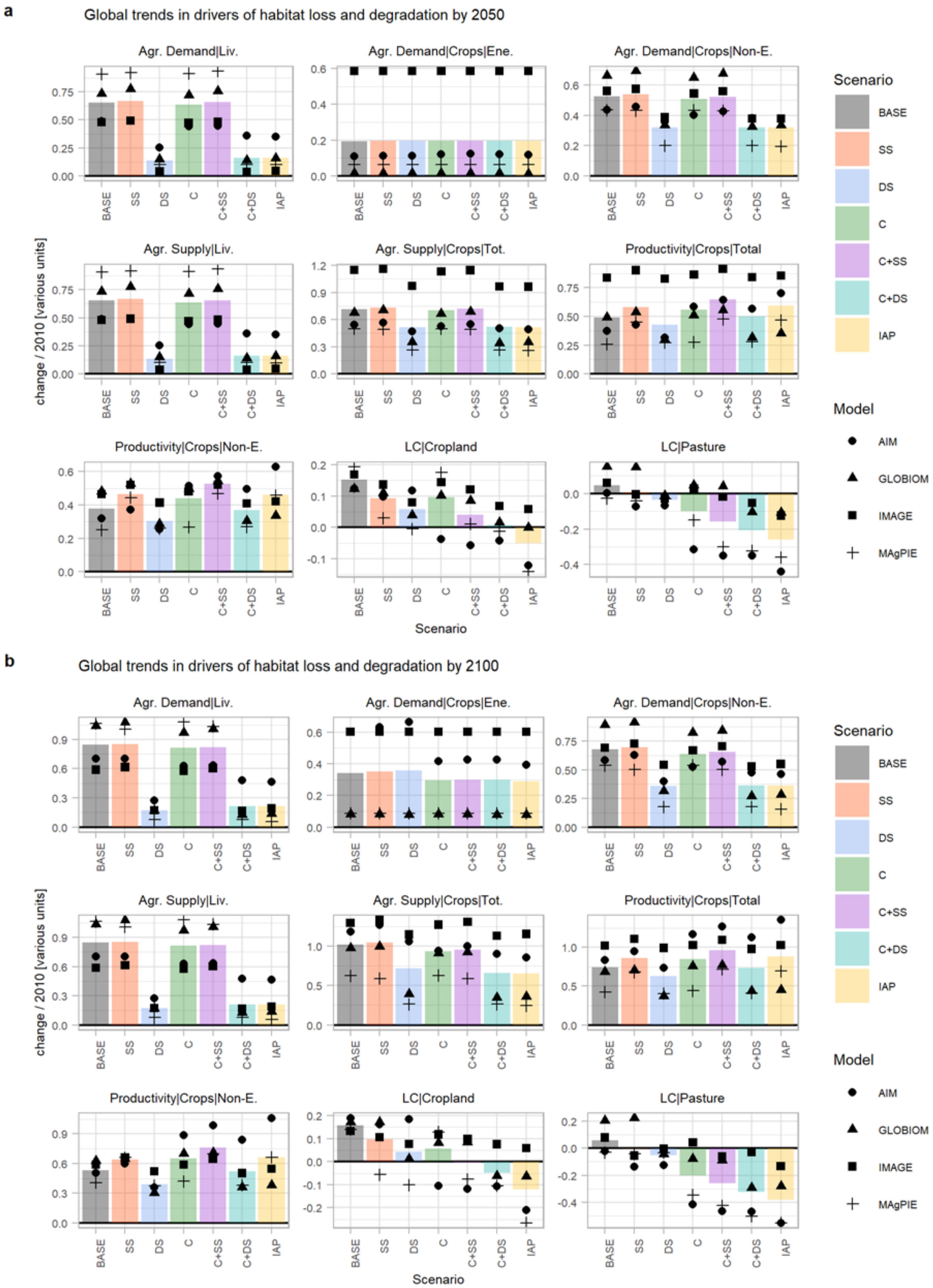
Index (BII[38]) of various land-use classes (panel c, estimated from assemblage data for 21702 distinct sites worldwide from the PREDICTS database[20], 11534 from naturally forested biomes and 10168 from naturally non-forest biomes). Datasets from panels a and c were used to implement spatially explicit restrictions to land-use change within land-use models (from 2020 onwards); datasets from panels b and c were used to implement spatially explicit priorities for restoration and landscape-level conservation planning (from 2020 onwards) in the scenarios were increased conservation efforts are assumed (see ***Methods****).*

Extended Data Figure 2



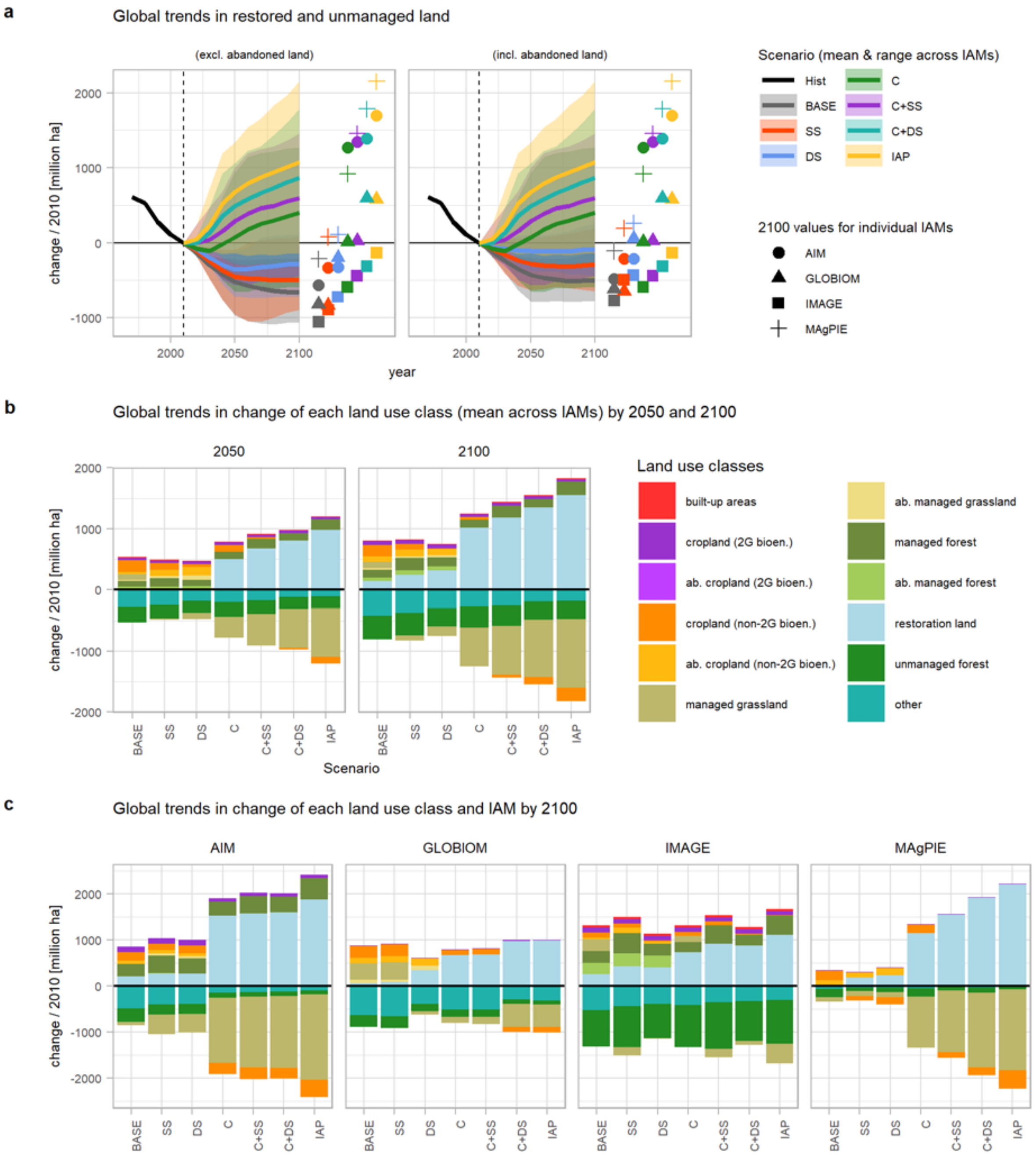
***Extended Data Fig. 2 | Spatial patterns in projected changes in the value of biodiversity indicators for BASE and IAP scenarios** (and the difference between the IAP and BASE scenarios) for the 17 IPBES subregions, by 2050 and 2100 (as compared to 2010 value). The figure displays the projected changes (mean across IAMs) for each of the eight combinations of biodiversity indicators (BDIs) and biodiversity models (BDMs, see **Table 2**) for which values at the scale of the IPBES subregions are available, grouped in five aspects of biodiversity (panels a-e). The FGRS indicator was estimated by the cSAR_US16 model only at the global scale.*

Extended Data Figure 3



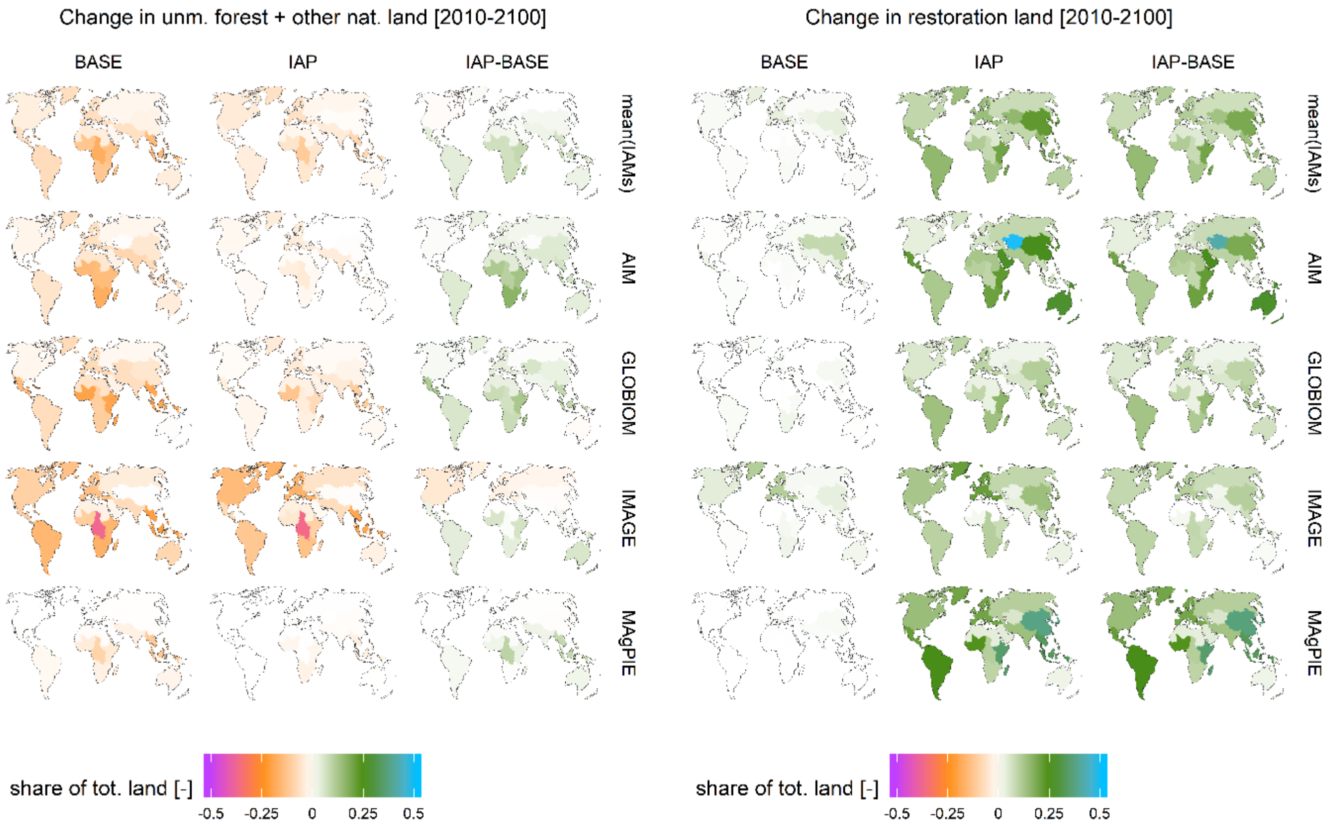
Extended Data Fig. 3 | Projected future global trends in drivers of habitat loss and degradation. Bars indicate for each scenario (colors, mean across all four IAMs) relative change from 2010 to 2050 (upper panel) and 2100 (lower panel) in nine variables (sub-panels). The symbols indicate the IAM-specific values. The variables displayed from the upper left right sub-panel to bottom right sub-panel are: agricultural demand *for livestock products (Agr. Demand|Liv.), agricultural demand for short-rotation bioenergy crops (Agr. Demand|Crops|Ene.), agricultural demand for crops other than short-rotation bioenergy crops (Agr. Demand|Crops|Non-E.), agricultural supply of livestock products (Agr. Supply|Liv.), agricultural supply of all crop products (Agr. Supply|Crops|Tot.), average yield of crops other than short-rotation bioenergy crops (in metric tonnes dry matter per hectare, Productivity|Crops|Non-E.), and the land dedicated cropland (LC|Cropland) and pasture (LC|Pasture).Values displayed for each variable are change relative to the value of the same variable simulated for 2010, except for two variables (Agr. Demand|Crops|Ene. And Agr. Demand|Crops|Ene.) for which the change in each of these variables is normalized by the sum of values simulated in 2010 for the two variables (i.e., normalization to total demand for crops).*

Extended Data Figure 4



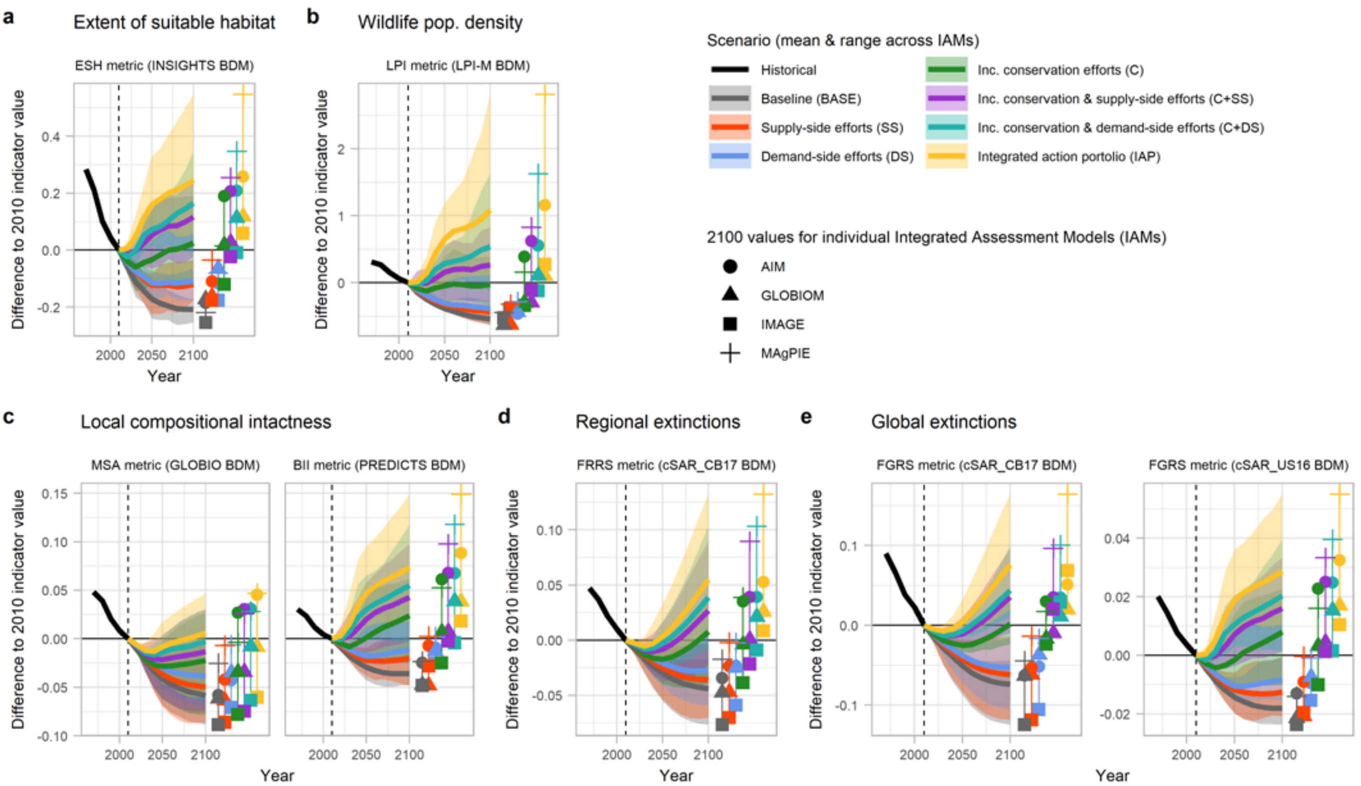
Extended Data Fig. 4 | Projected global trends in land-use change across all scenarios. *a) Global trends in the sum of restored land, unmanaged forest and other natural land classes as compared to 2010 (with and without excluding the land abandoned and not yet in restoration – different only for scenarios without increased conservation efforts, see* ***Methods****), with thick lines displaying average values across all four IAMs, and ribbons displaying the range across IAMs. Global changes projected in the area of each of the 12 land-use classes (as compared to 2010) for the seven scenarios b) averaged across the four IAMs by 2050 and 2100, and c) for each individual IAM by 2100.*

Extended Data Figure 5



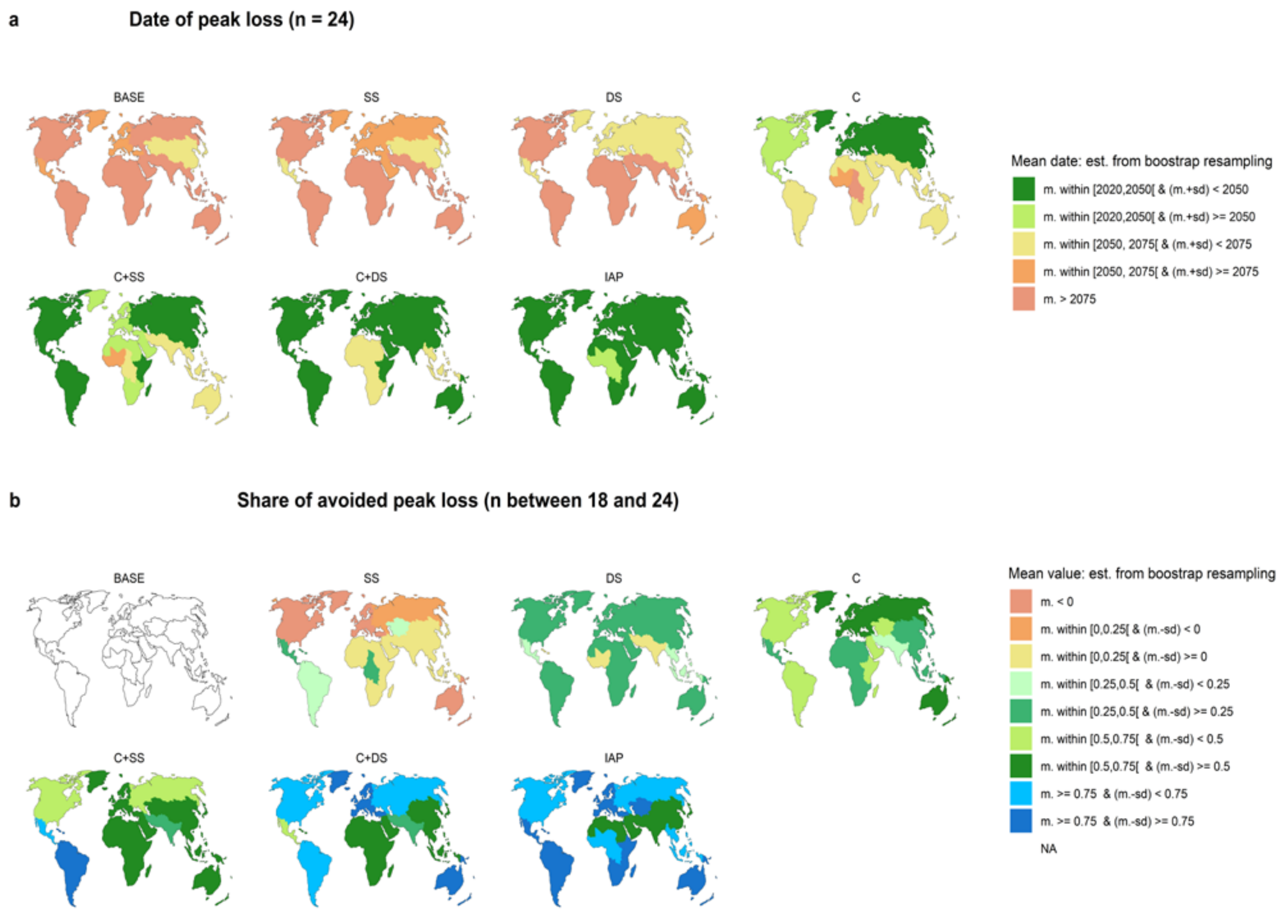
Extended Data Fig. 5 | Spatial patterns of projected habitat loss and restoration by 2100 *for the BASE and IAP scenarios and the difference (IAP-BASE), shown as the mean across IAMs (top row) and for each of the four IAMs.*

Extended Data Figure 6



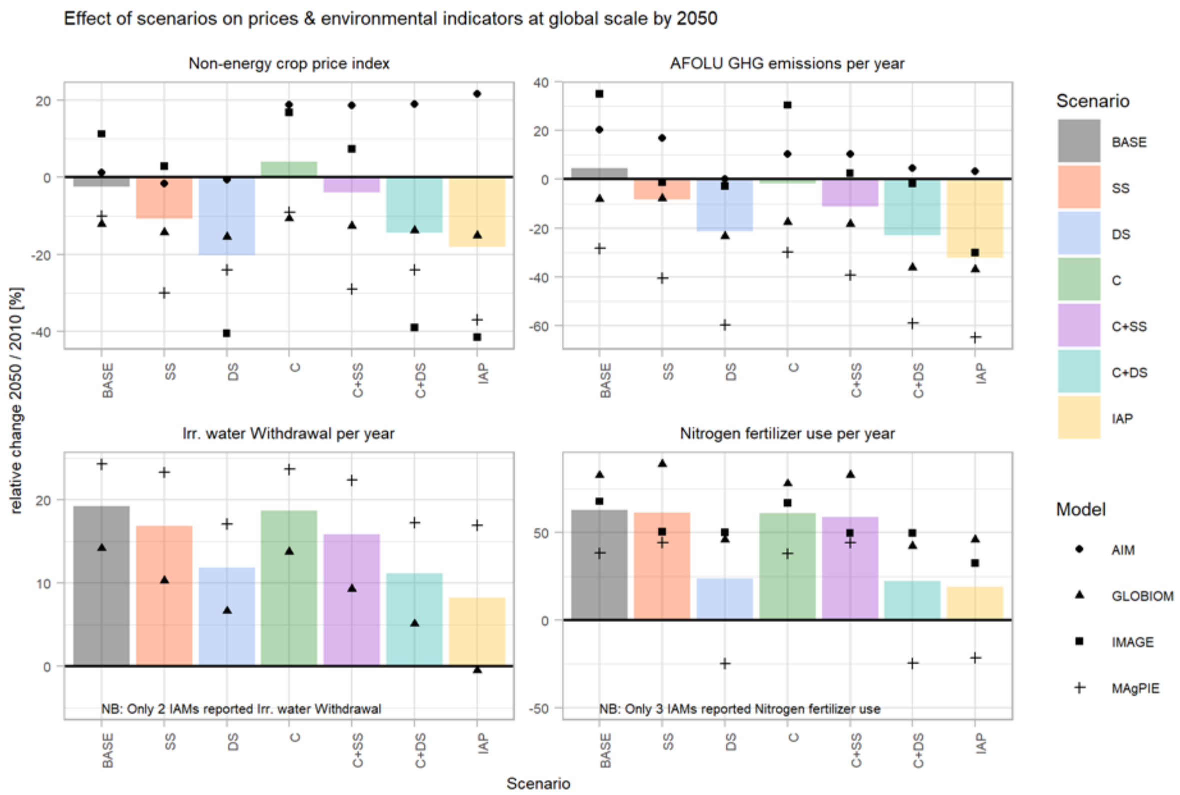
***Extended Data Fig. 6 | Estimated recent and future global biodiversity trends resulting from land-use change for all seven scenarios**. Panels a-d depict the trends, for the four different biodiversity aspects, resulting from changes in six biodiversity indicators (individual sub-panels, see **Table 2** for definitions). Indicator values are shown as differences to the 2010 value (=1); a value of of -0.01 means a loss of 1% in: the extent of suitable habitat (panel a), the wildlife population density (panel b), the local compositional intactness (panel c), the regional number of species (panel d) or the global number of species (panel e) – see **Table 2**. Indicator values are projected in response to land-use change derived from one source over the historical period (1970-2010, black line; 2010 is indicated with a vertical dashed line) and from four different Integrated Assessment Models (IAMs: AIM, GLOBIOM, IMAGE and MAgPIE; thick lines display the mean across models while ribbons display the range across models) for each of the seven future scenarios (see legend and **Table 1**).*

Extended Data Figure 7



Extended Data Fig. 7 | Spatial patterns of the date of 21st century peak loss (panel a) and the share of avoided future peak loss (panel b). *Across the 17 IPBES subregions, individual maps in each panel show, for each region and for each of the seven scenarios, the mean value, estimated from 10,000 bootstrapped samples of the simulated IAM and BDI combinations (n=24 for panel a, and n between 18 and 24 for panel b as regions and combinations for which the baseline peak loss is less than 0.1% were excluded). Color codes are based on the mean (m.) and standard deviation (sd) estimates (across the 10,000 samples for each region and scenario) of the sample mean value.*

Extended Data Figure 8



Extended Data Fig. 8 | Global changes in the price index of non-energy crops (upper left panel), in total greenhouse gas emissions from agriculture, forestry and other land uses (AFOLU sector, upper right panel), total irrigation water withdrawal (lower left panel) and Nitrogen fertilizer use (bottom right panel) between 2010 and 2050*, for seven scenarios and four IAMs (average across IAMs shown as bars, individual IAMs shown as symbols). Irrigation water withdrawal was reported by only two IAMs (MAgPIE and GLOBIOM, values not reported for the other two IAMs); Nitrogen fertilizer use was reported by only three IAMs (MAgPIE, GLOBIOM and IMAGE, values not reported for AIM).*

Supplementary discussion

Supp. discussion 1 – Future trends in drivers of habitat loss and degradation in the BASE and IAP scenarios

We projected that, by 2050, global demand for crops other than short-rotation bioenergy crops will be 55% greater and global demand for livestock products 65% greater, on average across the four IAMs, than in 2010. Agricultural intensification was projected to be a major source of future increases in crop production; the global average productivity was estimated to increase by 38% from 2010 to 2050 for crops other than short-rotation bioenergy crops. However, areas occupied by agricultural and forestry activities were projected to expand at global scale by 4.2 million km^2 on average across IAMs between 2010 and 2050 (increasing to 4.8 million km^2 by 2100). Simultaneously, about 1.0 million km^2 of managed land was projected to be abandoned on average across IAMs between 2010 and 2050 (increasing to 3.1 million km^2 by 2100), pointing to a partial redistribution of managed land. Altogether, an additional 5.3 million km^2 of unmanaged forest and other natural vegetation was projected to be converted for agriculture and forestry by 2050 (increasing to 8.0 million km^2 by 2100), on average across IAMs (**Extended Data Fig. 4**). For the biodiversity-rich IPBES subregions[50] of West Africa, Central Africa, East Africa and Adjacent Islands, Caribbean, Mesoamerica and South America as well as South Asia and South Eastern Asia, projected habitat losses represent in the worst case up to 38% of the total land area of the region by 2100, and on average 11% (across all IAMs and biodiversity-rich regions; **Extended Data Fig. 5**).

In the IAP scenario, the increases in the demand of livestock products projected from 2010 to 2050 were two-thirds lower than in the BASE scenario, and increases in non-bioenergy crop products were one-third lower (**Extended Data Fig. 3**). The extent of protected areas increased to 40% of the terrestrial area and incentives for restoration are set in place (see **Methods**). As a result, areas dedicated to agriculture and forestry in this scenario were projected to decrease on average across IAMs as compared to 2010, by 6.9 million km^2 by 2050 and 10.9 million km^2 by 2100. On average across the different IAMs, an even larger amount of agricultural and forestry land – 9.8 million km^2 by 2050, 15.5 million km^2 by 2100 (i.e., respectively 8% and 12% of total land area) – was projected to be set aside for restoration. Losses of unmanaged forest and other natural vegetation are mitigated but not canceled out: on average across IAMs, by 2100 these losses were almost halved in the IAP scenario as compared to the BASE scenario at the global scale (**Extended Data Fig. 4-5**), and were halved on average in biodiversity-rich regions.

Supp. discussion 2 – Sources of uncertainties in future projections

Using four IAMs made it possible to account explicitly for some of the uncertainty in projected future changes in land use, stemming from differences in model features (such as initial land-use distribution and land-use change dynamics) and from differences in the strategies used to implement the various scenario features in the models. For example, both the residual losses of unmanaged forest and other natural land in biodiversity-rich regions and the increase in restoration land differed significantly between IAMs for the IAP scenario: GLOBIOM and IMAGE projected less optimistic trends than AIM and MAgPIE (**Extended Data Fig. 5**). The disparity stems from differences between IAMs in the amount of managed grassland that can be restored (lower in GLOBIOM than in other IAMs), the amplitude of preferences towards restoration (lower in IMAGE than in other IAMs) and the amount of deforestation not directly related to the expansion of managed land (higher in IMAGE than in other IAMs). These differences often resulted in greater variation in biodiversity outcome between the IAP and BASE scenarios for AIM and MAgPIE than for the other two IAMs (**Fig. 1**), and highlight the importance of assessments based on multi-model ensembles, to cover related uncertainties in projected future habitat trends.

Similarly, using eight BDMs allowed us to account for some uncertainties relating to biodiversity model features (**Methods**). For example, temporal lags in the response of biodiversity to the restoration of managed land differed between models, often leading to different biodiversity recovery rates within restored land at the global scale for the IAP scenario. Three metrics estimated by three models (ESH metric x AIM-B BDM, FGRS metric x cSAR_US16 BDM and LPI metric x LPI-M BDM) assumed that restored areas are as good as pristine areas for biodiversity, and that the positive impact occurs immediately after shifting to restoration. They therefore provide an upper (optimistic) boundary of biodiversity recovery under restoration. For all other BDIs, restored areas recover to a level of biodiversity that is not always equivalent to that in pristine areas, and for three metrics estimated by two models (MSA x GLOBIO, FRGS x cSAR_CB17 and FRRS x cSAR_CB17), only after several decades. These BDIs provide a more conservative assessment of biodiversity trends – some, such as cSAR_CB17, assumed a linear rate of recovery over

70 years, which might be viewed as pessimistic. In addition, BDMs estimating the same metric can project different amplitudes of absolute and relative change through time, due to differences in taxonomic coverage, input data and detail in land-use classes. For example, the two BDMs estimating the extent of suitable habitat do so for different sets of taxa and using different land-use classification and input data: AIM-B considers vascular plants, amphibians, reptiles, birds and mammals based on occurrence data, whereas INSIGHTS models only mammals, based on range maps and reported land-use and elevation preferences. Similarly, the difference in the amplitude of projected future relative changes between LPI on the one hand and BII and MSA on the other hand arises from several sources: differences in input data, taxonomic coverage (e.g., birds and mammals for LPI, vs. vertebrates, invertebrates and plants for BII and MSA), whether models rely on observed site- and population-level temporal changes in relative abundance (as for LPI) or on observed differences in sites' relative abundance (as for BII and MSA), whether they represent the sole impact of land-use change over the entire land area covered by IAMs (as for BII and MSA) or the impacts of both land-use change and other threats (with assumed constant effect across scenarios and time horizons) over a restricted number of grid-cells corresponding to matched sites within the observational record (as for LPI), differences in how species- and site-level data are processed (e.g., truncation to 1 of relative abundances greater than 1 for BII and MSA), and differences in the aggregation of model outputs across grid-cells (e.g., weighting by potential density for BII). Finally, LPI combines species trends using geometric means, which (if declines tend to be concentrated in the less abundant species) has the consequence that LPI declines much more steeply than the average population size; whereas MSA is more directly proportional to average population size, and BII completely so.

While these differences between models highlight knowledge gaps, all models have different strengths and weaknesses. Using a multi-model ensemble allows us to quantify some of them, thereby allowing more robust conclusions to be reached. This approach is recommended 'to enable robust decision making and to account for uncertainty in the outcomes of biodiversity models' by the Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services (IPBES 2016[67], key recommendations of Chapter 4, p122). This approach is also widely used in other fields, such as climate science[14], agrology[68], hydrology[69] and marine ecosystem modeling[70]. It does not account for all types of uncertainties, however. For example, the BDMs implemented in this study, except for GLOBIO, did not differentiate management practices within cropland, and IAMs did not report this information.

Our results may therefore underestimate the future amplitude of both agricultural intensification-driven biodiversity losses, and biodiversity benefits from agroecological approaches[71]. Additionally, our approach does not characterize the uncertainty from individual land-use or biodiversity models, although this can be substantial. For example, in the context of climate change impact assessment, it has been shown that uncertainties from the parameterization of individual biodiversity models can be greater than those stemming from using different climate models, and as high as the uncertainty stemming from which emission scenario is considered[72].

Supp. discussion 3 – Feasibility of the various scenarios considered

Our baseline (BASE) scenario relied on the central *Middle of the Road* SSP2 scenario, which assumes an extension of historical trends in the future and has been extensively described in the literature[16,31,32]. We consider this scenario to be a plausible baseline, and it should not be seen as an overly pessimistic scenario. For example, greater habitat loss is expected[16] for the SSP3 scenario (*Regional Rivalry—A Rocky Road*), which assumes a human population that increases continuously over the entire 21st century, a slower increase in crop yields, and setbacks in recent globalization and land-use regulation trends.

The demand-side and supply-side efforts towards reversing the trends of biodiversity loss were based on options we consider to be feasible; we excluded assumptions such as increased consumption of artificial meat or insect-based proteins. Yet, implementing demand-side and supply-side efforts together (IAP scenario) can be viewed as a deep transformation of anthropogenic use of land, requiring large investments and new policies. For example, the increases in crop yields we projected in the IAP scenario are, at the global scale, close to estimated recent trends: depending on the IAM, +34% to +63% between 2010 and 2050, i.e. linear annual rates of increase of between 0.9 and 1.6 percentage points per year (base 2010), compared to estimates over the past 30 years of 0.9 to 1.9 percentage points per year[73,74]. Yet, this increase implies a doubling of crop yields in Sub-Saharan Africa over the same period. While significant yield gaps prevailing in this region might offer opportunities[75], closing the yield gap in a sustainable manner will require investments and innovative policies[76], and might be complicated by climate change[77]. Similarly, halving food waste by 2030 is a Sustainable Development Goal (SDG) target and many action levers have been identified[78]. Since we assumed such a target could be achieved by 2050 only, our scenario can be viewed as only moderately ambitious. The proposed efforts will still require country-specific and comprehensive intervention portfolios, including investment in agricultural and transport infrastructure, training and educational programs, and improved standards and norms for packaging, storing and recycling. Finally, we assumed a dietary shift that departs from historical trends and is more ambitious than SSP1 assumptions. However, improving human health through dietary change is an SDG target, and both evidence and awareness are accumulating that transitioning towards a 'flexitarian' diet could be instrumental in reducing both health and environmental risks[25,79]. Evidence of the nature of policy interventions required to trigger dietary transitions is also accumulating[80,81], making our assumption achievable.

Our scenarios aim at biodiversity conservation goals that have already been agreed in principle by Governments[3], but that will require new, ambitious and potentially challenging conservation efforts. Although it seems unlikely that the globally agreed target of 17% by 2020 will be met[6], protected area coverage has increased markedly in recent decades and there is potential for further increases– some argue that protection of 50% of the Earth's terrestrial surface is desirable and achievable[82]. However, the effectiveness of protected areas is declining, while pressures on protected areas are growing[83]. Our assumed increased conservation efforts are ambitious, but rely on a balanced approach: while we assume an expansion of protected areas to 40% of the terrestrial area with effective management (i.e., no land-use intensification), >87% of additionally protected areas are identified as wilderness areas that are by definition under low pressure, and the remaining 3.1% of terrestrial area to be additionally protected relies solely on priorities that have already been agreed (e.g., Key Biodiversity Areas). Furthermore, in order to deal with areas that are under pressure (both within and outside protected areas), we rely on landscape-level conservation planning strategies, which seek to increase the restoration of managed areas and to improve the spatial agency of other land uses[84,85]. In the IAMs, this is implemented as financial schemes that allow the integration of spatial preferences for conservation into the land-use decisions pertaining to all terrestrial areas (see **Methods**). Financial conservation schemes are increasing in scale and scope, but have been criticized for their poor outcomes and weak design[86]. However, such schemes can be improved[85], and remain a modeling simplification made for this analysis; in reality, many other types of tool can be mobilized to achieve landscape-level conservation planning [84,87]. Our scenarios led to the restoration of 4.3-14.6 million km^2 (i.e., 3-11% of terrestrial area) by 2050, which might be compatible with currently agreed targets and momentum towards restoration (e.g., Bonn Challenge, UNCCD's Land

Degradation Neutrality target-setting program). In the models, these efforts are assumed to have already partially started in 2020 in the most ambitious scenarios. In addition, our baseline scenario is based on SSP2, in which land-use trajectories and conservation efforts differ across models but are not aimed at accurately representing the observed land-use change and conservation efforts until 2020. This implies that differences in model projections between scenarios by 2020 and 2030 cannot be used to diagnose the impact of various assumptions about additional actions over this period in the real world.

The equity of proposed actions should be considered when assessing their feasibility. Solutions that transfer future development opportunities from biodiversity-rich regions to high-yielding and less biodiversity-rich regions, as well as foregone opportunities for producers in large production regions as a result of demand-side efforts, might not be perceived as acceptable or fair. In our view, such issues are inevitably associated with deep transformations of our land-use system, and require a more comprehensive analysis, including options of intra- and inter-national social transfers. However, we tried to avoid unnecessarily unfair solutions in two ways. First, our modeling relied partly on market-like dynamics (rather than solely on restrictive assumptions) to resolve the trade-offs arising from a progressive shift in societal preferences from production to conservation land use. Future habitat conversion in all regions was not strictly forbidden, but was made progressively less desirable through economic incentives. The expanded protected areas (where conversion was strictly forbidden) were mostly located in low-yielding and less biodiversity rich regions (see **Extended Data Fig. 1**). This left ample room for habitat conversion and exploitation of economic opportunities in biodiversity-rich regions, where projected conversion was only halved in the IAP scenario as compared to the BASE scenario (see **Extended Data Fig. 5**). Second, the biodiversity score used to inform the spatial priorities that minimize the biodiversity impacts of future land-use conversions (see **Methods**) was based on a regional relative range-rarity score, rather than a global absolute range-rarity score. This implies prioritizing spatial configurations within regions, while avoiding prioritizing one region over another based on their absolute levels of biodiversity, although this might be justified based solely on biodiversity considerations.

Supp. discussion 4 – Mapping of scenarios to the Sustainable Development Goals (SDGs)

Our analysis focuses on the trade-off between food provision and conservation, and we did not seek to quantify the extent to which our IAP scenario contributes towards achieving the broader Sustainable Development Goals (SDGs). However, our scenarios can be positioned with respect to the SDGs as evidence suggests that actions depicted in our IAP scenario could contribute significantly towards several SDGs and help reduce the food production system's pressure on planetary boundaries[25,88]. SSP2 – defining our baseline scenario – pictures a future in which the development of economic growth and inequalities, together with land-use developments, lead to reduced food insecurity[89] and poverty[90], therefore contributing towards SDGs 1 (No poverty), 2 (Zero hunger) and SDG 10 (Reduced inequalities). Our BASE scenario fully reflects related land-use developments, while our IAP scenario may achieve better outcomes for SDG2. While dietary preferences follow historical trends in the BASE scenario, the dietary shift assumed as part of demand-side efforts could allow significant progress towards SDGs 3 (Good health and well-being) and 13 (Climate action). Halving waste throughout the supply chain is an explicit target of SDG 12 (Responsible consumption and production), while the reductions in agricultural water withdrawal in the IAP scenario would facilitate achieving SDG 6 (Clean water and sanitation) and make a significant contribution to SDG 14 (Life below water). Improved conservation efforts would make a significant contribution towards SDG 15 (Life on land).

Supp. discussion 5 – Other biodiversity aspects and threats

Terrestrial biodiversity is a multifaceted concept, encompassing different aspects at various geographical and time scales, including the local diversity, abundance and uniqueness of genes, species, populations, traits and functions of living organisms across multiple taxonomic groups, as well as their variation across landscapes and biomes, and their genetic and ecological history. The models used in our study cover a broader range of biodiversity aspects and taxonomic groups than those in many previous studies [91,92], but they do not provide estimates of trends in some biodiversity aspects such as phylogenetic diversity and functional diversity – key indicators of the long-term ability of ecosystems to cope with future changes.

While it cannot be ensured that trends in these unmodelled terrestrial biodiversity aspects would be reversed in our most ambitious scenario, we can clarify the anticipated implications of our results for these biodiversity aspects. For example, it has been shown for mammals that conserving functional and phylogenetic diversity on top of taxonomic diversity might require a substantially larger amount of protected area[93]. This suggests that our results may be optimistic if extended to terrestrial biodiversity in general; greater effort may be required to ensure a reversal of trends across additional aspects of biodiversity. However, priorities may not be simply cumulative, and there may be overlap and synergies between strategies to conserve multiple aspects of biodiversity[94]. In our study, the assumed increased conservation efforts were already designed to balance different conservation priorities: for example, the restoration priority score (based on relative range rarity) incorporates both local richness and endemism. In addition, the expanded protected areas encompass identified biodiversity hotspots (e.g., current WDPAs and KBAs) but also intact ecosystems, expected to host high levels of functional diversity[95]. In addition, the level of ambition in our increased conservation effort scenarios is high: an addition of 25% of land to the 15% already protected (resulting in 40% of land protected) while spatial synergies between strategies to conserve multiple aspects of biodiversity were already found when investigating a smaller addition of 15% of land[94]. Overall, we believe that our scenarios may have the ambition needed to reverse additional terrestrial biodiversity aspects (as affected by land-use change), although tackling additional aspects may require adjustments in spatial priorities.

We account only for the effects on biodiversity of habitat loss due to land-use change, but in reality, biodiversity faces multiple threats. According to IUCN Red List data, the expansion and intensification of agriculture is imperiling 5,407 species (62% of species listed as threatened or near-threatened), but half as many species (2,700) are adversely affected by hunting or fishing, 2,298 species are adversely affected by biological invasions and diseases, and 1,688 by climate change[5]. Land-use change is currently the largest single threat to biodiversity[5], but other threats will increase in importance in the future, in particular climate change[96,97]. Our scenarios are focused on the largest threat, so our most ambitious scenario provides a strong indication of the actions required, but as threats intensify and shift, these actions may not be sufficient to reverse terrestrial biodiversity trends fully. This reinforces that integrated strategies, in combination with bold targets, must be central to the post-2020 biodiversity strategy.

Supplementary discussion additional references

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