Towards pathways bending the curve of terrestrial biodiversity trends within the 21st century

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Abstract: Unless actions are taken to reduce multiple anthropogenic pressures, biodiversity is expected to continue declining at an alarming rate. Models and scenarios can be used to help design the pathways that sustain a thriving nature and its ability to contribute to people. This approach has so far been hampered by the complexity associated with combining projections of pressures on, and subsequent responses from, biodiversity. Most previous assessments have projected continuous biodiversity declines and very few have identified pathways for reversing the loss of biodiversity without jeopardizing other objectives such as development or climate mitigation. The *Bending The Curve* initiative set out to advance quantitative modelling techniques towards ambitious scenarios for biodiversity. In this proof-of-concept analysis, we developed a modelling approach that demonstrates how global land use and biodiversity models can be combined to can shed light on pathways able to bend the curve of biodiversity trends as affected by land-use change, the biggest current threat to biodiversity. In order to address the uncertainties associated with such pathways we used a multi-model framework and relied on the Shared Socioeconomic Pathway/Representative Concentration Pathway scenario framework. This report describes the details of this modelling approach.

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1 Introduction

Biodiversity is decreasing at an alarming rate, as measured through rates of species extinction (Pimm *et al* 2014, Ceballos *et al* 2015), local changes in community composition (Dornelas *et al* 2014), declines in population abundance (Ceballos *et al* 2017, McRae *et al* 2017) and reduced biodiversity intactness (Newbold *et al* 2016). Direct human pressures are responsible for the main threats to biodiversity (Maxwell *et al* 2016, Joppa *et al* 2016), such as the conversion of habitats to agricultural and urban areas, and the overexploitation of natural and semi-natural habitats through hunting, logging and fishing. Indirect anthropogenic pressures like climate change (Scheffers *et al* 2016) are also high and a large proportion of threatened species are affected by multiple threats reinforcing one another (Brook *et al* 2008).

Biodiversity losses area expected to continue throughout the 21st century (Sala *et al* 2000, van Vuuren *et al* 2006, Newbold *et al* 2015). Human population and its impacts on land resources are expected to increase until 2050s (Popp *et al* 2017). Unless addressed, global trends in habitat degradation will continue at rates similar to that of the second half of the 20th century (if not higher). The fastest rates of habitat degradation are expected in Africa, Latin America and Asia. In addition, without ambitious mitigation, increasing and pervasive threats such as climate change could dramatically strengthen (Pecl *et al* 2017, Bellard *et al* 2012). At the same time, ambitious efforts to mitigate future global warming could inflate habitat degradations through large-scale development of bioenergy (Heck *et al* 2018, Turner *et al* 2018).

Yet, continued biodiversity decline is not inevitable (Van Vuuren *et al* 2015). Conservation to date has prevented extinctions and slowed declines (Hoffmann *et al* 2010, Butchart *et al* 2006), and increased conservation efforts might preserve biodiversity (Visconti *et al* 2015) and crucial ecosystem contributions (Watson *et al* 2018), while a significant portion of the Earth's degraded ecosystems could be restored (Johnson *et al* 2017). Through the promotion of more healthy diets, education, or gender equality, future human pressures could also be significantly lessened while yielding large co-benefits (Crist *et al* 2017, Tilman and Clark 2014). Further efforts towards more sustainable production practices and food supply chains might also largely reduce future pressures (Tilman *et al* 2017, Mueller *et al* 2012, Godfray *et al* 2010). The challenge is to identify potential pathways that will allow us to restore nature, limit climate change and feed the still growing population – all to be achieved under accelerating effects of climate change.

Recent efforts to halt biodiversity loss have been insufficient (Tittensor *et al* 2014, Tollefson and Gilbert 2012) and we currently lack any roadmap charting pathways that reverse biodiversity trends without jeopardizing the chances of reaching other desirable objectives (Obersteiner *et al* 2016, Steffen *et al* 2015). Such a roadmap would be highly relevant for driving a far more integrated and unified approach to securing the biosphere integrity needed to deliver the 2030 Sustainable Development Agenda. The next few years present a number of policy opportunities across the United Nations Framework Convention on Climate Change (UNFCCC), the Convention on Biological Diversity (CBD) and United Nations Convention on Combating Desertification (UNCCD) to drive an integrated approach to land use that delivers climate, biodiversity and land-degradation-neutrality objectives.

Models and scenarios can help in designing such a roadmap (IPBES 2016), but this has so far been hampered by the complexity associated with projections of pressures and subsequent biodiversity responses (Rosa *et al* 2017). In a pioneering contribution, the IMAGE/GLOBIO modeling framework was used to design and quantify so-called 'target-seeking' or 'backcasting' scenarios aiming to reach particular targets (Van Vuuren *et al* 2015, Kok *et al* 2018, Netherlands Environmental Assessment Agency 2010), defined among others as halting the loss of biodiversity. However, several aspects need to be further explored in order to derive roadmaps for future action. First, although the scenarios included a comprehensive set of biodiversity drivers, they did not capture sufficiently ambitious biodiversity targets (halting loss rather than reversing trends) and the biodiversity outcomes were limited (only about half of the future losses in the counterfactual scenario could be avoided). Second, this work relied on only one modelling framework, combining one model of drivers of biodiversity change and one model of how one measure of biodiversity responds to drivers. It did not evaluate the considerable uncertainties due to the various assumptions made, contrasting for example with the particularly wide uncertainty for current and future land use (Popp *et al* 2017, Prestele *et al* 2016). Capturing such uncertainties requires a multi-model setup. Finally, uncertainties related to the assumptions defining the counterfactual scenario (leading to continuation of biodiversity losses) were not quantified: relying on the recent scenario framework defined by the Shared Socioeconomic Pathways (Riahi *et al* 2017) and Representative Concentration Pathways could enable such quantification (van Vuuren *et al* 2011).

In this report we detail the recent methodological developments undertaken under the *Bending The Curve* initiative, aiming at improving modeling techniques for science-based targets and conservation planning. This proof-of-concept analysis produced a set of scenarios for ambitious policy targets, aiming to reverse within the 21st century the current declining trends in biodiversity as affected by land use, and evaluated them with multiple models and multiple measures of biodiversity. The goals were to:

- develop new and ambitious scenarios in which the curve of recent and expected future biodiversity trends (as affected by land use) is bent upwards within the 21st century,
- explore new methods to develop narratives and provide quantification of such scenarios
- allow exploring how various options - or "action wedges" - could contribute to the target of "bending the curve"
- allow assessing synergies and trade-offs between sustainable development goals
- allow for controlled exploration of uncertainties by using multiple models to quantify land-use scenarios and evaluate biodiversity outcomes, while driving the models with a common scenario framework (the Shared Socioeconomic Pathways and Representative Concentration Pathways)

2 Overview of the approach

In order to generate future scenarios leading to more positive biodiversity conservation outcomes, we developed a new approach that combines current knowledge – i.e., existing data, models and scenarios – from the land-use and biodiversity modelling communities. It relies on three steps (see Figure 1):

I. Gathering existing storylines of future land use and datasets for quantifying ambitious conservation measures. The assumptions of the Shared Socioeconomic Pathways (SSPs) and Representative Concentration Pathways (RCPs) concerning future land use were reviewed and datasets were collated to allow the quantification of more ambitious protection and restoration efforts. These datasets of land use, biodiversity and modelled impacts of land use on biodiversity were used to inform where increased protection efforts would likely be targeted and where the biodiversity value of additional restoration land would be highest. This information was used to guide land-use decisions in a subset of the scenarios developed in step II. The SSP and RCP scenarios are detailed in Section 3, while the processing of spatially explicit datasets of biodiversity is detailed in Section 4.

II. Generating and quantifying scenarios of likely future trends in land use with and without additional actions to bend the curve of biodiversity trends. We designed two *reference* scenarios and 18 *wedges* scenarios in which various biodiversity action wedges are implemented. Those scenarios in which all wedges are combined are referred to as *bending* scenarios. We used the land-use component of four Integrated Assessment Models (IAMs) to generate spatially explicit land-use projections for all scenarios. In some scenarios, the land-use allocation in IAMs was guided by spatially explicit information on biodiversity and its response to land use. The scenarios generated are described in Section 3.3 while the IAMs, the implementation of scenarios in IAMs and the IAM simulations and outputs are described in Section 5.

III. Estimating the impacts of quantified land-use projections on a range of biodiversity indicators. We used eight biodiversity models (BDMs) to assess the impacts of land-use changes simulated for the various scenarios by the four IAMs over the 21st century. The models involved, their use of the spatially explicit land-use projection input and the reported outputs are detailed in Section 6.

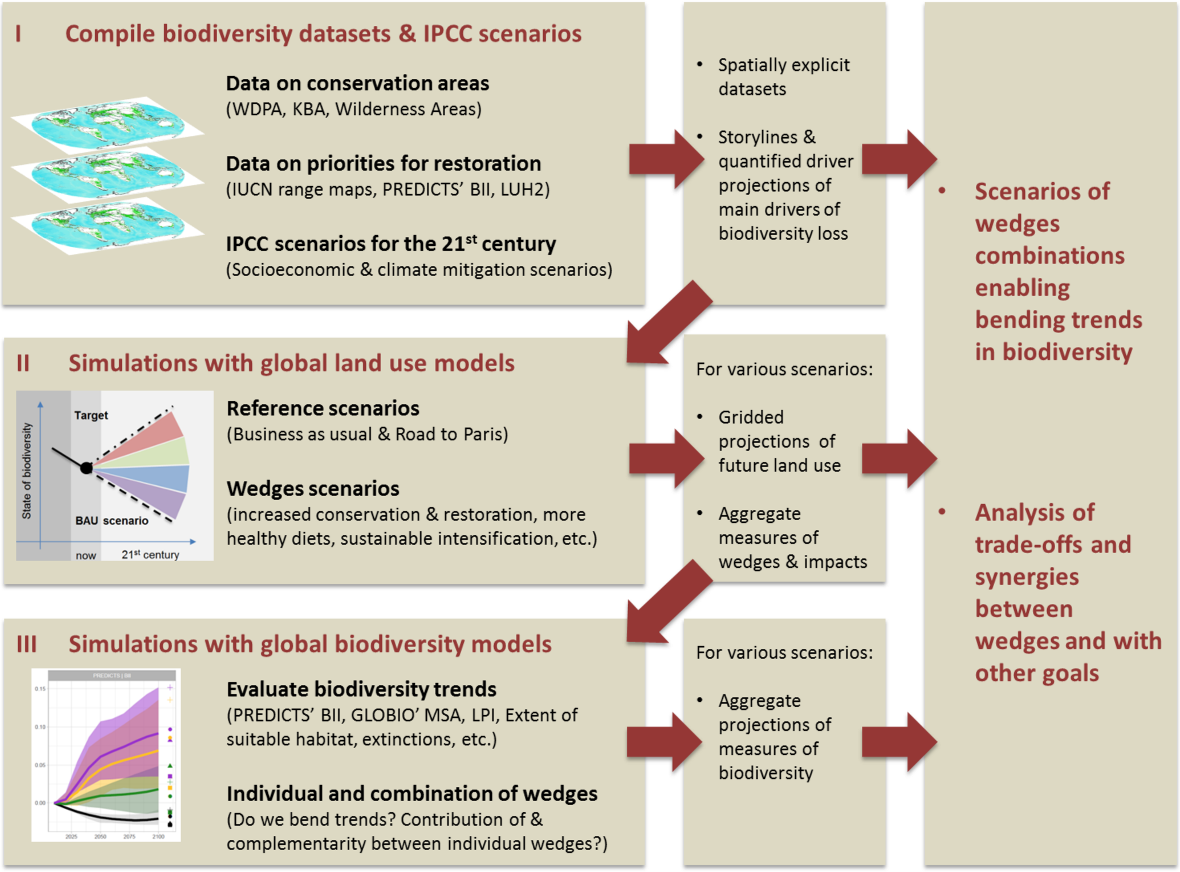


Figure 1 - Illustration of the overall approach to generating land-use projections able to bend the curve of biodiversity trends as affected by human land use.

Although our approach accounts for the impact of land-use change on biodiversity and consider scenarios of ambitious climate change mitigation, our proof-of-concept analysis did not account for the impacts of climate change on biodiversity.

3 Scenarios

3.1 Land-use drivers of biodiversity in the SSP and RCP scenario framework

Our scenarios rely to a large extent on the Shared Socioeconomic Pathways (SSPs) and the Representative Concentration Pathways (RCPs) scenario framework (Moss *et al* 2010, van Vuuren *et al* 2014). This framework has recently been developed by multiple stakeholders to facilitate coordinated climate-change analysis, with a large contribution from the Integrated Assessment Modelling Consortium (IAMC). The scenarios can also be used for analysis of long-term global environmental change and constitute the most developed set of global long-term scenarios that provide both storylines and quantified projections of the main drivers of future land use.

The SSPs describe five alternative futures (SSP1 to SSP5) for societal development. Each SSP consists of a qualitative narrative as well as model-based quantification, together providing detailed information on demographics, human development, economy and lifestyle, policies and institutions, technology, and environment and natural resources (O'Neill *et al* 2015, Riahi *et al* 2017). While SSP2 depicts a *Middle Of The Road* scenario extending historical trends with slow and limited climate mitigation, SSP1 depicts a more sustainable world with fewer challenges for climate mitigation and adaptation. By contrast, the other SSPs describe futures with further challenges stemming from e.g., high population growth, high use of fossil fuel, conflicts and lack of regulation. The quantification by various IAMs have been described in general (Riahi *et al* 2017) and in terms of land-use developments (Popp *et al* 2017). The SSPs provide the global land-use and biodiversity modelling communities with a set of detailed and quantified scenarios concerning many of the determinants of future habitat degradation. Assumptions about human population, diets, waste and mitigation allow for exploring alternative developments of global and regional demands for food, feed and bioenergy. Assumptions about globalization, trade, land regulation and productivity allow the exploration of alternative developments of the intensification of managed lands and conversion of intact ecosystems required for meeting a particular level of demand for food, feed and bioenergy.

Combining SSPs with the RCPs provides additional details about the amplitude and timing of climate mitigation efforts throughout the 21st century to reach particular levels of anthropogenic forcing on the climate system. RCPs relate to the amplitude of anthropogenic forcing to the climate system, and can be linked to simulations from Earth System Models to provide quantified estimates of future changes in climates for various scenarios. They range from a low perturbation (RCP2.6) to a high perturbation (RCP8.5) of the climate system, leading in 2100 to likely levels of global mean temperature increase (as compared to pre-industrial period) by 0.9 to 2.5 °C (mean 1.6°C) and 3.2 to 5.4°C (mean 4.3°C), respectively.

The amplitude of efforts needed to reach a particular RCP depends on the SSP and these efforts have various implications for habitat destruction and degradation, sometimes in opposite direction. For example, limiting global greenhouse gas emissions can be achieved through a reduced production of meat and dairy products and an intensification of agricultural production, altogether limiting the conversion of unmanaged land. Such a pathway may also promote land-use changes that minimize releases of the carbon stored in the vegetation and soils, thereby potentially preserving some biodiversity-rich areas. However, mitigation scenarios may also rely on the development of short rotation bioenergy plantations, increasing pressure to convert unmanaged land, and the afforestation of non-forested areas for both carbon sequestration and extractive use. The biodiversity impacts of afforestation will depend on where such changes take place and how the resulting plantations and forests are managed.

3.2 Additional assumptions concerning conservation

Increasing conservation efforts is a crucial component of interventions towards better future for ecosystems and a healthy planet (Johnson *et al* 2017, Watson *et al* 2014, 2018). Although the SSPs and RCPs contain many features related to degradation of habitats, conservation efforts are not evident in either SSP narratives or quantified land-use projections (Popp *et al* 2017). The narratives for land-use regulation vary with respect to the level (from low to high) of assumed regulation of land-use change, in relation to the pace of deforestation and its variation across broad regions. For some models, the implementation of these narratives in IAMs translated in assumptions about the extent of protected areas: while in SSP3 they stay constant at their 2010 level, they are extended by 2050 to 17% and 30% of the terrestrial area in SSP2 and SSP1, respectively. The implementation of the narratives across models was however not harmonized. In addition, these scenarios do not cover the range of possible biodiversity outcomes as they remain below ambitious proposals put forward (Wilson 2016) and do not cover important aspects such as restoration of previously managed land.

In order to develop assumptions concerning ambitious protection and restoration efforts, and to implement these assumptions within the IAMs, we compiled various datasets:

a) A spatially explicit **potential protected areas layer** indicating, for a regular 0.5° x 0.5° latitude-longitude grid, the share of terrestrial area that could potentially be protected in the future based on current protected areas, sites identified as important for biodiversity and remaining pristine areas. See Section 4.1 for the compilation of the layer and Section 5.2 for the implementation in IAMs.
b) A spatially explicit **regional restoration priority layer** providing for each pixel of a regular 0.5° x 0.5° latitude-longitude grid a restoration priority score taking continuous values between 0 (lowest priority) and 1 (highest priority). This layer is a spatially explicit indicator of the regional relative range-rarity weighted species richness. It indicates the places holding more species and/or species of smaller range than other places in the same biome and continent. See Section 4.3 for compilation and Section 5.2 for implementation in the IAMs.
c) A dataset of **modelled impacts of various land uses on biodiversity intactness *BII(LUC,E(p))***, providing for each type of land use *LUC* and type of ecosystem *E(p)* (potentially forested versus not potentially forested, specified for each pixel *p* from a regular 0.5° x 0.5° latitude-longitude grid) a Biodiversity Intactness Index (BII: Scholes and Biggs 2005, Newbold *et al* 2016) score as compared to pristine conditions, estimated from the PREDICTS database (Hudson *et al* 2017). See Section 4.2 for data compilation and Section 5.2 for implementation in IAMs.

These different datasets are used to design two scenario elements additional to those of the SSPs (see 5.2 for more precise details on their implementation into IAMs):

- Increased protection efforts after 2020: in places identified by the potential protected areas layer we assume that from 2020 onwards, land-use change that is detrimental to biodiversity (as estimated by the related difference in BII) is not allowed. This rule represents an ambitious protection effort in which both the management of currently protected areas is improved and the extent of protected areas is increased.
- Increased restoration efforts after 2020: we assume that from 2020 onwards, ambitious restoration efforts occur everywhere, through which financial incentives are put in place to regionally guide land-use change decisions towards net biodiversity gains. This includes setting aside for restoration land previously devoted to agriculture or intensive forestry. The net biodiversity impact of any land-use change is measured in a pixel by the BII and across pixels by the regional restoration priority layer.

3.3 Reference, bending and wedges scenarios

We designed a set of 20 scenarios in order to evaluate likely 21st century land-use changes (reference scenarios), land-use changes predicted if instead many efforts to bend the biodiversity curve are combined (bending scenarios) and finally land-use changes predicted if only a subset of these efforts are implemented (wedges scenarios).

Reference scenarios

As detailed in Table 1, we consider two reference scenarios (*RFref_SSP2_NOBIOD* and *RF1p9_SSP2_NOBIOD*), which are both based on central socioeconomic projections but differentiated by the extent of climate mitigation efforts. Our reference scenarios build on the *Middle Of The Road* scenario (SSP2, Fricko *et al* 2017), which roughly extends recent trends into the future. It broadly describes a world in which human population peaks at 9.4 billion individuals by 2070, economic growth is moderate and uneven, while globalization continues with slow socioeconomic convergence between countries. For SSP2 the various IAMs used indicate that global demand for land-based production will increase by more than 70% over the century (Popp *et al* 2017) thereby increasing threats to biodiversity. Despite increases in overall land productivity of about 60% at the global scale by 2100, cropland and pasture expands by more than 400 million hectares, mostly at the expense of forest in Latin America and other natural lands in Africa.

Overall, in our *RFref_SSP2_NOBIOD* scenario the climate mitigation efforts are assumed to be limited, with a level of radiative forcing (RF) in 2100 leading to global mean temperature increase of about +4°C, as compared to pre-industrial times (assuming a median climate sensitivity). However, according to the long-term goal of the Paris Agreement, the global mean temperature increase should be maintained well below +2° C: this would require a strong and global mitigation effort, to reach a level of radiative forcing of about 1.9 $W.m^{-2}$ in 2100. Such climate mitigation efforts could negatively impact biodiversity if extensive biofuels and afforestation for carbon sequestration projects are enacted without careful consideration of biodiversity. Such a scenario is available from the IAMC database (Rogelj *et al* 2018), and we created a second reference scenario (*RF1p9_SSP2_NOBIOD*) to evaluate how such an ambitious mitigation effort could affect possibilities to bend the curve of biodiversity loss. Overall, *RFref_SSP2_NOBIOD* scenario contains the reference SSP2 without explicit climate mitigation effort, while the *RF1p9_SSP2_NOBIOD* scenario assumes aggressive mitigation efforts in order to maintain global mean temperature increase around +1.5°C.

We remind that the proof-of-concept analysis did not account for climate change impacts on biodiversity. Therefore, it can estimate the biodiversity cost of climate mitigation actions, but not the benefits for biodiversity of climate mitigation, through avoided climate change-driven biodiversity loss.

Bending scenarios

As detailed in Table 1, we consider two bending scenarios (*RFref_SSP1p_BIOD* & *RF1p9_SSP1p_BIOD*, one for each reference scenario). As compared to the reference scenarios, the bending scenarios are characterized by the following assumptions:

- <u>increasing protection efforts</u>: any change in land use estimated as detrimental to biodiversity (according to PREDICTS' BII coefficient) is not allowed from 2020 onwards for all areas identified by the potential protected areas layer (see Section 4.1 for compilation and Section 5.2 for details on the implementation in IAMs);
- <u>increasing restoration efforts</u>: over the entire land area, incentives are gradually put in place to favor land-use changes resulting in biodiversity improvements from 2020 onwards. The net

impact on biodiversity (gain or loss) of a particular land-use change transition is measured by the difference between the PREDICTS' BII coefficients for the two land uses, while the relative importance (for biodiversity) of one pixel as compared to another is measured by the regional restoration priority layer (see Section 4.3 for compilation and Section 5.2 for details on the implementation in IAMs);

- shifting towards healthier diets: dietary preferences evolve towards 50% less meat compared to the reference scenario, linearly between 2020 and 2050 (the corresponding animal calories are replaced by vegetal calories) except for regions with low share of meat in diets like Middle-East, Sub-Saharan Africa, India, Southeast Asia and other Pacific islands (where dietary preferences follow the reference scenarios). This goes beyond assumptions of SSP1 on similar matters;
- reducing waste throughout the food supply chain: we assume that total waste (losses in harvest, processing, distribution and final household consumption) decrease by 50% by 2050 compared to the baseline, linearly between 2020 and 2050. This goes beyond assumptions of SSP1 on similar matters;
- sustainably increasing productivity: we assume that crop yields develop following SSP1, assuming in particular a rapid convergence of land productivity in developing countries to that of developed countries.
- increasing trade in the agricultural sector: we assume that trade of agricultural goods develops according to SSP1, with a more globalized economy and reduced trade barriers.
- reducing the impact of climate mitigation on land resource (for RF1p9 scenarios only): when considering scenarios compatible with maintaining global warming below +2° Celsius, we consider that some of the pressure on the land-use sector from climate mitigation is redistributed to other sectors. In particular, we assume that although GHG emissions remain taxed, there is no additional demand for biofuels and no additional afforestation for carbon sequestration (i.e., beyond restoration for biodiversity).

Wedges scenarios

As detailed in Table 1, we tested 16 additional scenarios in which only a subset of the above-mentioned efforts to bend biodiversity trends are assumed.

		Assumptions																	
		Diets		*Waste*		*Technology*		*Trade*		*Bioenergy*			*Afforestation*			*protection*		*Restoration*	
		SSP2	Healthier diets	SSP2	Reduced waste	SSP2	Inc. productivity	SSP2	Inc. trade	RFref	RF1.9	no biofuels	RFref	RF1.9	Only restoration	no	yes	no	yes
scenarios	**Reference scenarios**																		
	RFref_SSP2_NOBIOD	x		x		x		x		x			x			x		x	
	RF1p9_SSP2_NOBIOD	x		x		x		x			x			x		x		x	
	Bending scenarios																		
	RFref_SSP1p_BIOD		x		x		x		x	x			x				x		x
	RF1p9p_SSP1p_BIOD		x		x		x		x			x			x		x		x
	Wedges scenarios																		
	Only restoration & protection																		
	RFref_SSP2_BIOD	x		x		x		x		x			x				x		x
	RF1p9_SSP2_BIOD	x		x		x		x			x			x			x		x
	Only healthier diet & reduced waste																		
	RFref_SSP1pDEM_NOBIOD		x		x		x	x		x			x			x		x	
	RF1p9_SSP1pDEM_NOBIOD		x		x	x		x			x			x		x		x	
	Only increased productivity & trade																		
	RFref_SSP1pTECHTRADE_NOBIOD	x		x			x		x	x			x			x		x	
	RF1p9_SSP1pTECHTRADE_NOBIOD	x		x			x		x		x			x		x		x	
	Only reduced reliance on land for climate mitigation																		
	RF1p9p_SSP2_NOBIOD	x		x		x		x				x			x	x		x	
	Inc. restoration & protection + healthier diets & reduced waste																		
	RFref_SSP1pDEM_BIOD		x		x	x		x		x			x				x		x
	RF1p9_SSP1pDEM_BIOD		x		x	x		x			x			x			x		x
	Inc. restoration & protection + reduced reliance on land for climate mitigation																		
	RF1p9p_SSP2_BIOD	x		x		x		x				x			x		x		x
	All wedges but healthier diets & reduced waste (and reduced reliance on land for climate mitigation)																		
	RFref_SSP1pTECHTRADE_BIOD	x		x			x		x	x			x				x		x
	RF1p9_SSP1pTECHTRADE_BIOD	x		x			x		x		x			x			x		x
	All wedges but reduced reliance on land for climate mitigation																		
	RF1p9_SSP1pTECHTRADEDEM_BIOD		x		x	x			x		x			x			x		x
	All wedges but increased restoration & protection																		
	RFref_SSP1p_NOBIOD		x		x		x		x	x			x			x		x	
	RF1p9p_SSP1p_NOBIOD		x		x		x		x			x			x	x		x	
	All wedges but increased restoration & protection and reduced mitigation reliance on the agricultural sector																		
	RF1p9_SSP1pTECHTRADEDEM_NOBIOD		x		x		x		x		x			x		x		x	

Table 1 - List of scenarios and corresponding assumptions

4 Spatially explicit datasets for biodiversity conservation

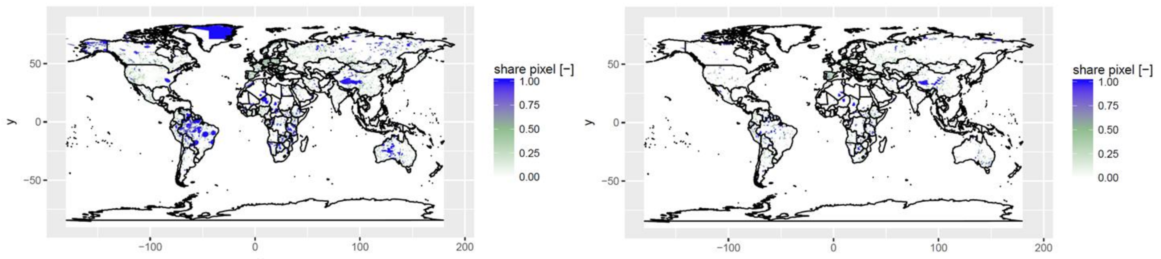
4.1 Potential protected areas layer

The goal of the spatially explicit potential protected areas layer is to inform the IAMs on areas that could potentially be protected in the future if protection efforts were to increase. This covers locations currently subject to protection, and locations identified as important for future protection efforts. In order to estimate this layer, we overlaid three global datasets (while ensuring no double counting of areas in case of overlapping), as illustrated in Figure 2:

- Protected Areas from the *World Database of Protected Areas* (IUCN and UNEP-WCMC 2017), including protected areas in all categories (Ia, Ib, II, III, IV, V, VI and Not Reported), using polygons as well as point data (except when no area is reported). For point data a circular shape was assumed, with an area defined by the REP AREA field. The resulting shapefile was re-projected to a WGS84 lat-lon projection.
- Key Biodiversity Areas from the *World Database of Key Biodiversity Areas* (BirdLife International 2017), using both polygons and points (assuming a circular shape with an area defined by the SitArea field). The resulting shapefile was re-projected to a WGS84 lat-lon projection.
- The 2009 Wilderness Areas (Watson *et al* 2016), which utilized the latest version of the Human Footprint dataset (Venter *et al* 2016) and has then been transformed in readily available wilderness maps (Allan *et al* 2017). These maps report the proportional extent of wilderness areas in 5 arcmin raster in a WGS84 lat-long projection. The raster value was transformed into a raster of binary information (1 for pixels with any wilderness, 0 eslewhere) for overlaying with other shapefiles.

a) WDPAs

b) KBAs



c) Wilderness areas

d) Potential protected areas

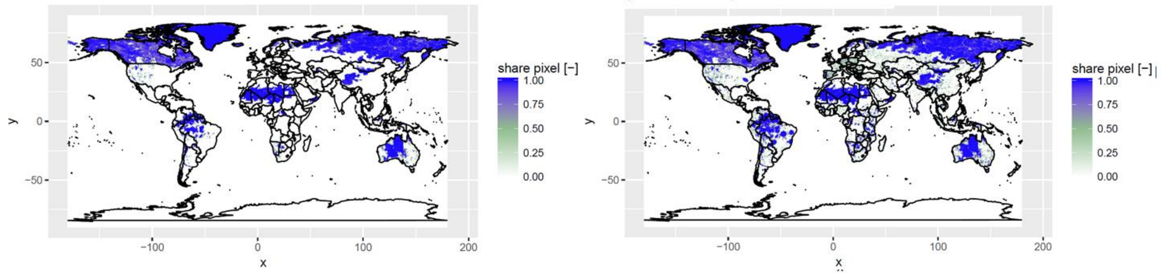


Figure 2 - Illustration of the construction of the potential protected areas layer. We combined a) the World Database of Protected Areas (IUCN and UNEP-WCMC 2017), b) the World Database of Key Biodiversity Areas (BirdLife International 2017), and c) the 2009 Wilderness Areas (Watson *et al* 2016) into d) a single potential protected areas layer. Colours on the map display the share of land under any of the respective layer.

The three shapefiles were overlaid into a shingle shapefile of potential protected areas, and then overlaid with a land mask at 5 arcminutes (based on GLC2000) to estimate the land area under potential protected areas. The result was overlaid with a shapefile of a regular 0.5° x 0.5° latitude-longitude grid to aggregate the share of land potentially protected at half-degree resolution, referred to in other parts of the manuscript as the **potential protected areas layer (*PP(p)*)**. The total of the potential protected areas layer represents 38% of the total terrestrial area.

4.2 Modelled impact of different land uses on biodiversity

In order to inform IAMs on the local biodiversity impacts of land use (as compared to pristine state), we used the PREDICTS implementation of Scholes & Biggs' (2005) Biodiversity Intactness Index (BII, Newbold *et al* 2016, Purvis *et al* 2018), estimated from the PREDICTS database (Hudson *et al* 2017). BII is defined as the average abundance of originally-present species (i.e., excluding introduced species) relative to their abundances in an intact assemblage, and estimates the impact land use has had on the integrity of ecological assemblages (the lower the value, the higher the impact).

For each type of land-use class (*LUC*, 10 classes) and type of ecosystem (*E*) (potentially forested versus not potentially forested), statistical models of organismal abundance and compositional similarity to a minimally-impacted assemblage, using sites in primary vegetation as the baseline, were combined to provide an empirical estimate of the *BII(LU,E)*. The classification *E(p)* of each pixel *p* from a regular 0.5° x 0.5° latitude-longitude grid was sourced from the LUH2 dataset, which provides fractional coverage of land-use classes within each pixel (Hurtt *et al*, in prep.). While more details on how the models are fitted can be found elsewhere (De Palma *et al* 2018, Hill *et al* 2018), a refined classification of land use, better adapted to the IAMs, was used in this study. The obtained *BII(LU,E)* values are displayed in Figure 3.

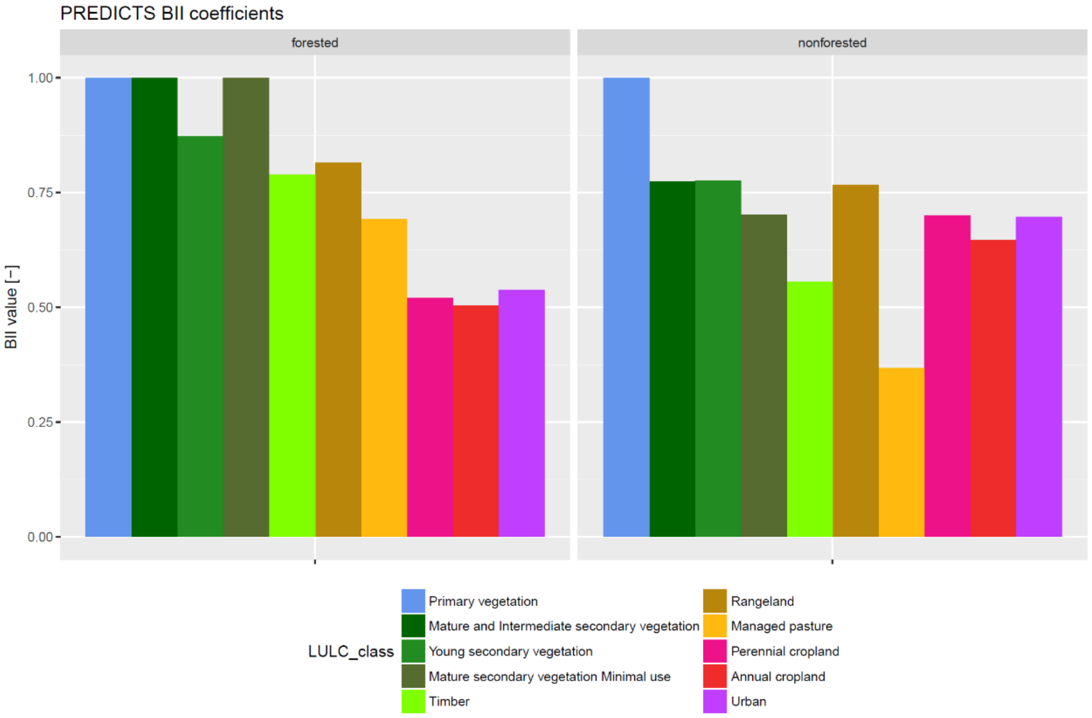


Figure 3 – Illustration of the BII coefficients estimated from the PREDICTS database, providing a measure of the relative impact of 10 land-use classes on the integrity of ecological assemblages (as compared to pristine conditions).

These BII values are combined with the spatially explicit mask of ecosystem type (potentially forested or not) from the LUH2 dataset (Hurtt *et al,* in prep.). The resulting product is termed the **modelled**

impacts of various land uses on biodiversity intactness *BII(LU,p)*, providing in each pixel *p* of a regular 0.5° x 0.5° latitude-longitude grid the BII value of each land-use class (*LU*).

4.3 Regional restoration prioritization layers

In order to allow IAMs to incorporate the effect of incentives towards land-use changes that improve biodiversity, we compiled a layer of regional restoration priority (*RR(p)*). This provides on a regular 0.5° x 0.5° latitude-longitude grid a raster derived from the range size rarity relative to all pixels in the same biome and continent. Taking values ranging from 0 to 1, the indicator has higher values for pixels that contain a higher number of species (irrespective of their taxonomic group) or in which species have a higher degree of endemism than the average for the same biome and continent. It therefore takes into consideration both broad scale (e.g., extinction risk) and local biodiversity (species richness) concerns. It was calculated from the range maps of the species in the IUCN Red List (IUCN 2017) and (BirdLife International and Handbook of the Birds of the World 2017) in several steps:

a) First we estimated the pixel *p* specific range size rarity index by summing over each and every species present in the grid cell the proportion of their total range size contained in that pixel (the more species and the smaller their ranges, the higher the value).
b) Then, we normalized this score relative to that of all pixels in the same continent and biome by taking the difference to mean pixel value for the continent and biome, divided by the standard deviation of pixel values for the continent and biome. The resulting values express the number of standard deviations that each pixel lies away from the mean pixel value for same biome and continent.
c) The normalized range size rarity value of pixels outside of endemism hotspots varied over several orders of magnitude as result of differences in species richness and range rarity of occupying species. Despite this variation, values in these pixels were typically two orders of magnitude lower than those for pixels in endemism hotspots, containing many range-restricted species. To correct for this tendency of the index to reflect relative endemism more strongly than relative species richness, we took the log transformation of these values (shifted so that all values are strictly positive). The log-transformed values are finally rescaled to the [0-1] range, with a median value across pixels of 0.36, and 95% of pixels having a value within the [0.25;0.51] interval (see map in Figure 4).

Figure 4 illustrates the unweighted range size rarity layer (step a), upper panel) and the final **regional restoration priority layer *RR(p)*** (lower panel).

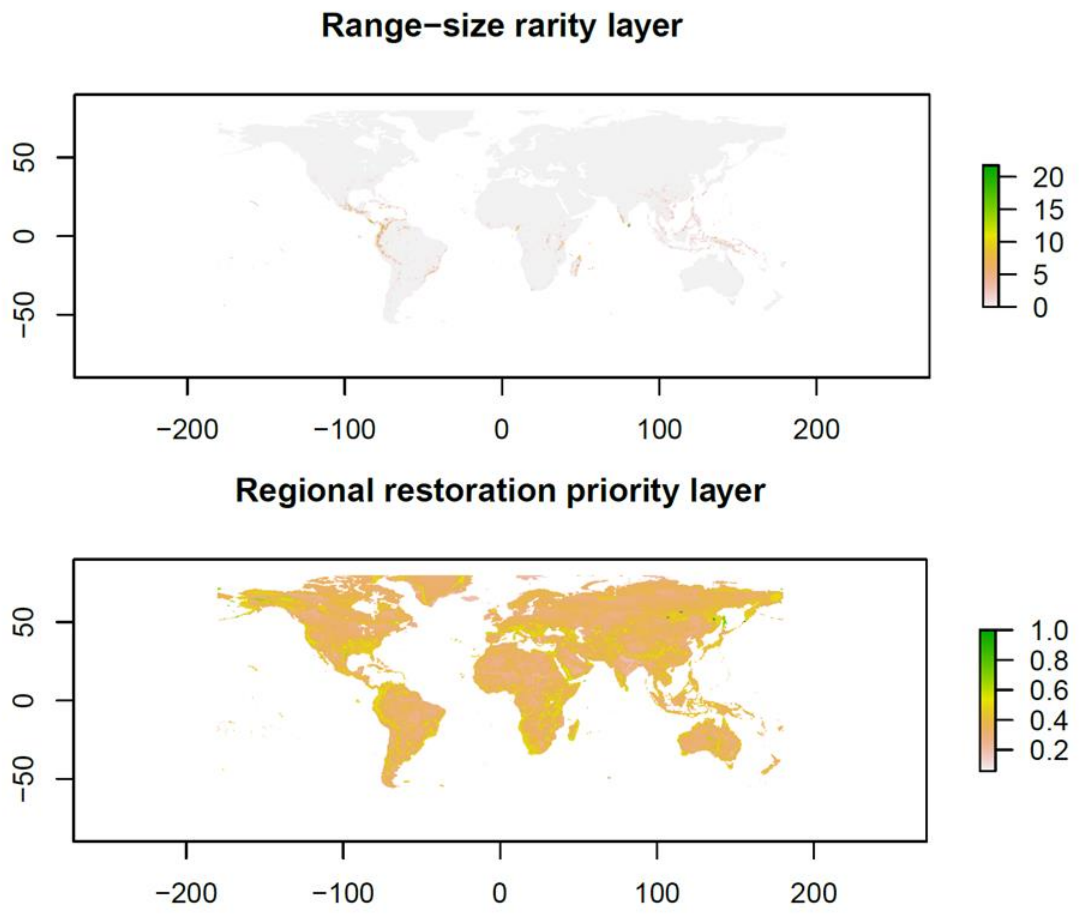


Figure 4 – Illustration of the original input (range size rarity based on IUCN range maps, upper panel) and of the final regional restoration priority layer (after normalization by biome and continent combination, log transformation and rescaling to [0-1]).

5 Projections from global land-use models

5.1 Brief description of the global land-use models used

IAMs are simplified representations of the various sectors and regions of the global economy and their link to the environment. They are widely used to explore and formulate targets and policy options, in particular in the area of climate change mitigation. They can be used to provide quantified estimates of how the various endogenously modelled aspects can evolve in the future, given assumptions about future drivers of the economy (e.g., population, economic convergence between regions, education, efforts to reduce impact on the environment and other preferences, etc.) and the environment (e.g., land and water resources as affected by climate, pollution, overexploitation etc.). As such, they can provide very useful information for projecting biodiversity into the future (Harfoot *et al* 2014b).

In order to quantify future trajectories of land-use change for the various scenarios considered, we used four different IAMs (and more particularly their land-use modules, see Table 2). The four models used (AIM, GLOBIOM/MESSAGE, IMAGE/MAGNET and MAgPIE/REMIND) have been chosen for their ability to project future land-use change under various scenarios. In the past few years, they all contributed to model inter-comparison initiatives, in which model responses were compared under harmonized set of assumptions (Schmitz *et al* 2014, Nelson and Shively 2014, Nelson *et al* 2013) or in a broader context (Alexander *et al* 2016, Prestele *et al* 2016). They were also extensively used for designing and providing quantifications to the SSP and RCP scenarios (Riahi *et al* 2017) and their land-use trajectories (Popp *et al* 2017). As further detailed in the supplementary information of (Popp *et al* 2017), the four models considered differ in their modelling of land-use decisions and their connection to agricultural, forestry and energy markets and available resources.

Land-use model name (Land-use model;IAM)	**Institution**	**Key reference**
Asia-Pacific Integrated Model (AIM/PLUM;AIM)	National Institute for Environmental Studies (NIES, Japan)	(Fujimori *et al* 2012, Hasegawa *et al* 2017)
Global Biosphere Management Model (GLOBIOM;MESSAGE)	International Institute of Applied System Analysis (IIASA, Austria)	(Havlík *et al* 2014)
Integrated Model to Assess the Global Environment (IMAGE;MAGNET)	Netherlands Environmental Assessment Agency (PBL, Netherlands)	(Stehfest *et al* 2014)
Model of Agricultural Production and its Impact on the Environment (MAgPIE;REMIND)	Potsdam Institute for Climate impact Research (PIK, Germany)	(Popp *et al* 2014)

Table 2 – List of global land-use models used in the proof-of-concept analysis of the Bending the Curve initiative, and their related IAMs

AIM (Fujimori *et al* 2012, Hasegawa *et al* 2017) is an integrated assessment modelling framework which couples several components describing economy, energy, agriculture, land-use, emissions and climate. The core of the scenario quantification is done by AIM/CGE which is a computable general equilibrium model, representing the entire economy. In the model, supply, demand, investment, and trade are described by individual behavioural functions that respond to changes in the prices of production factors and commodities, as well as changes in technology and preference parameters on the basis of assumed population, GDP, and consumer preferences. Land is represented as part of the production functions, formulated as multi-nested constant elasticity substitution functions. The allocation of land by sector for 17 regions is formulated as a multi-nominal logit function to reflect differences in substitutability across land categories, and regional land use is further downscaled to high spatial resolution with the AIM/PLUM downscaling model (Hasegawa *et al* 2017) based on spatially explicit attainable yields. The spatially explicit yields are aggregated and fed back to AIM/CGE. The spatially explicit land-use projections are derived from the land use downscaled with AIM/PLUM to a regular 0.5° x 0.5° latitude-longitude grid. In this specific exercise, new simulations with AIM/CGE coupled with AIM/PLUM were done for all scenarios.

GLOBIOM (Havlík *et al* 2014) is a bottom-up partial-equilibrium model which represents various land-use based activities, including agriculture, forestry and bioenergy sectors. It incorporates grid-cell information on the biophysical and technical cost information from various models, including the EPIC crop model (Balkovič *et al* 2014). Its spatial equilibrium modelling approach estimates jointly grid-level land-use decisions and regional level consumption, supply and bilateral trade based on cost competitiveness for 30 regions. It is coupled with the G4M model (Kindermann *et al* 2006) to better represent the forest management decisions and associated carbon fluxes, and the GLOBIOM-G4M cluster is coupled with the MESSAGE energy model (Messner and Strubegger 1995, Riahi *et al* 2012) to estimate the competitive mitigation efforts. Land-use decisions are modelled on a regular 2° x 2 ° latitude-longitude grid intersected with country boundaries, and the spatially explicit land-use projections are derived from simulated land-use change projections at regional scale further downscaled to a regular 0.5° x 0.5° latitude-longitude grid. In this specific exercise, new simulations from the GLOBIOM model were done for all scenarios, while the coupling to the MESSAGE model (resulting in trajectories of bioenergy demand and carbon prices through time, used as input for GLOBIOM) and to the G4M model (resulting in spatially explicit projections of the forestry sector and GHG emissions from land*use change) were done using the already available simulations from the SSP & RCP scenario (Fricko *et al* 2017, Rogelj *et al* 2018), i.e., no new simulations from G4M or MESSAGE were done.

The **IMAGE** framework (Stehfest *et al* 2014) describes various global environmental change issues using a set of linked models describing the energy system, the agricultural economy and land use, natural vegetation and the climate system. Food demand, production and trade is modelled via the MAGNET global general equilibrium model (Woltjer *et al* 2014) at the scale of 26 world regions, while land use is allocated on the grid level within IMAGE, based on spatially explicit attainable yields (including inputs from LPJmL, Bondeau *et al* 2007) and suitability as well as modelled cost competitiveness and competition between agricultural and energy end uses. Land*use allocation is simulated on grid cells of a size varying between 5 arcminutes and 0.5°, and re-aggregated to spatially explicit land*use projections on a regular 0.5° x 0.5° latitude-longitude grid. The energy system (including bio-energy) and mitigation action is determined in IMAGE using an energy-system and climate policy model. This can lead to demand for bio-energy, reduction of deforestation and reforestation. In this specific exercise, new simulations with IMAGE were done for all scenarios, including coupling with the MAGNET model (regional agro-economic impact on land use and intensification) and the LPJmL gridded crop model.

MagPIE (Popp *et al* 2014) is a global multi-regional partial equilibrium model of the land-use sector, which accounts for spatially explicit constraints derived by the vegetation, hydrology and crop growth model LPJmL (Bondeau *et al* 2007, Mueller and Robertson 2014). Land-use decisions in MAgPIE are modelled at a spatially explicit level (Lotze-Campen *et al* 2008) on a regular 0.5° x 0.5° latitude-longitude grid and simulated values are directly used as spatially explicit land-use projections. REMIND (Luderer *et al* 2015) is a global multi-regional energy-economy general equilibrium model linking a macro-economic growth model with a bottom-up engineering-based energy model. MAgPIE and REMIND can be coupled by exchange of price and quantity information on bioenergy and GHG emissions (Popp *et al* 2011, Kriegler *et al* 2017). In this specific exercise, new simulations with the MAgPIE model were done for all scenarios, while the trajectories of bioenergy demand and carbon prices from REMIND (used as input in MAgPIE) were taken from the existing SSP & RCP scenario simulations (i.e., no new simulations from REMIND).

5.2 Implementation of the scenario assumptions

On the one hand, as indicated in Section 3.3, most scenarios are based on rather classical scenario types (e.g., healthier dietary preferences and waste reduction) or directly on variations of SSP and RCP scenarios (in particular, SSP2, SSP1, RFref or RF1p9). The implementation details of these scenarios can be found in overview papers (Riahi *et al* 2017, Popp *et al* 2017) and papers specific to each IAM (Fujimori *et al* 2017, Fricko *et al* 2017, van Vuuren *et al* 2017, Kriegler *et al* 2017). The related assumptions will not be detailed here. On the other hand, a number of scenarios relied on action wedges that are not adequately represented in the SSP and RCP framework: their implementation in IAMs is detailed in the rest of this Section.

Increased protection efforts

In all four global land-use models, this action wedge was implemented by restricting the possible land-use changes at the pixel level. The potential protected areas layer was used to identify pixels in which land-use changes leading to reduced biodiversity were restricted from 2020 onwards (as a result of conservation actions). Although increased protection affected the spatial allocation and reduced the amount of land available in all IAMs (leading to intensification of agricultural areas and price increase), the implementation details varied across IAMs:

- For AIM, the protection was introduced only after the first AIM/CGE run. Consequently, in AIM/PLUM the grid cells for which the potential area subject to protection is larger than 50% of total land area (summing to 33% of total terrestrial area, out of a total potential protected area summing to 38% of total terrestrial area), cropland and pasture cannot expand from 2020 onwards. The result was fed back into AIM/CGE for a second run, leading to price increases. Although this resulted in prices changes as well as regional scale different spatial land-use allocation and intensification, this did not lead to redistribution of agricultural land across regions. A low sensitivity was reported, with respect to the choice of the threshold used to delineate pixels under protection.
- For GLOBIOM and MAgPIE, in pixels for which the potential area subject to protection is larger than 50% of total land area (summing to 33% of total terrestrial area), no land-use transition was allowed from 2020 onwards if leading to a decrease in BII. This limited the land available for expanding cropland, pasture of forestry in the economic modeling, leading to intensification, price increases and redistribution of agricultural land with and across regions. In addition, for GLOBIOM the demand also reacts to the price changes. A low sensitivity was reported with respect to the choice of the threshold used to delineate pixels under protection.
- For IMAGE, within half-degree pixels, the total share of land potentially under protection (as provided by the potential protected areas layer) was used to increase protected area in 5 arcmin resolution grid cells, first in grid cells with lowest proportion of agricultural land, up to the total non-agricultural land area, and while subtracting the protected area extent already assumed in the reference scenarios. In addition, this information was used to reduce the land supply curve in the economic modelling in MAGNET, leading to intensification, price increases, demand reduction and redistribution of agricultural land with and across regions.

These mild differences in implementation and model features imply that relatively moderate differences across IAMs are expected in the simulated broad response of land use to the increased protection action wedge. Most of the channels of impact of the increased restoration action wedge are similar across IAMs: as compared to scenarios without this action wedge activated, the increased protection efforts will trigger in all IAMs a redistribution of agricultural area expansion to grid cells not protected (however, for AIM, only within the same region). It will also limit the expansion and trigger an intensification of the agricultural areas, potentially leading to an overall increase in the price of agricultural products. In addition, for all IAMs but AIM, agricultural production and trade will also be potentially redistributed across regions (towards regions with less protected areas), and for some models (GLOBIOM and IMAGE) the demand for agricultural products will decrease to buffer increased prices.

Increased restoration efforts

This action wedge consists in putting in place incentives over the entire land area to favor land-use changes resulting in biodiversity improvements, from 2020 onwards. This includes the possibility to set aside land for restoration. For all models, the net biodiversity impact of a particular land-use change in a given grid cell is estimated from the resulting change in a biodiversity stock variable, and incorporated into the land-use optimization from 2020 onwards. For a given land use in a given grid cell, the biodiversity stock was calculated as the corresponding occupied area (in hectares) multiplied by the land-use and grid cell-specific PREDICTS' BII coefficient (dimensionless) and the grid cell-specific value the regional restoration priority layer (dimensionless). Its sum over all land uses and grid cells in a region can be interpreted as a measure of how intact and biodiversity rich the total area is, given a land-use distribution. There were differences across models in how the land optimization accounted for implied net biodiversity impacts, leading to differences in the channels of impact of increased restoration efforts, from spatial allocation to land scarcity or mitigation potentials:

- For AIM, increased restoration efforts constrained spatial allocation and altered the cost of the land resource. The net biodiversity stock gain (resp. loss) of any land-use change decision in any pixel is subsidized (resp. taxed) within the optimization, with a value that increases over time (from 1 $/ha in 2020 to 1000 $/ha in 2100 with an S-shape curve assuming a progressive increase at the beginning, a peak rate of increase by 2060, and stabilization to high values in 2100). While the possibilities to abandon cropland or pasture already existed in the model, abandonment is assumed to be for restoration purposes and allocated where ultimate gains for biodiversity would be highest. The land put into restoration at any time step can be used again for production use in later time steps, but at high cost. The carbon sequestration resulting from the restoration of land is not accounted for and not valorized in scenarios including a carbon tax.
- For GLOBIOM, increased restoration efforts constrained spatial allocation and altered the cost of the land resource. The net biodiversity stock gain (resp. loss) of any land-use change decision in any pixel is subsidized (resp. taxed) within the optimization, with a value that increases over time (from 10 $/ha in 2020 to 1000 $/ha in 2100 with an S-shape curve assuming a progressive increase at the beginning, a peak rate of increase by 2060, and stabilization to high values in 2100). The land put into restoration at any time step can be used again for production use in later time steps, but at high cost. The carbon sequestration resulting from the restoration of land is accounted for (one-time sequestration flux when put to restoration) and valorized upon conversion in scenarios including a carbon tax.
- For IMAGE, increased restoration efforts only constrained spatial allocation and did not reduce the amount of land available. While the possibilities to abandon cropland or pasture already exist in the model, here they are assumed to be for the purpose of restoration and allocated where ultimate gains for biodiversity would be highest. Symmetrically, expansion of cropland or pasture is reprioritized to places with lower biodiversity. However, at the

difference to other IAMs, there is no economic incentive to further re-arrange land-use (through e.g., intensification of existing agricultural areas to set aside more land) towards configurations better for biodiversity. The land put into restoration at any time step is not explicitly excluded from productive use, but highly discouraged. Carbon sequestreted in restoration areas is accounted for but not further incentivized by a carbon tax in the RF1p9 climate mitigation scenario as the latter relies on the protection of carbon-rich forests (REDD protection of all forest with carbon density > 100 tC/ha) and the restoration of degraded forests (forest degradation due to reasons other than agricultural expansion or forestry is reduced to zero by 2030, and degraded forest areas are restored from 2030-2060 - see Doelman *et al* 2018).

- For MAgPIE, the assumed increased restoration efforts constrained spatial allocation and altered the cost of the land resource. The net biodiversity stock gain (resp. loss) of any land-use change decision in any pixel is subsidized (resp. taxed) within the optimization, with an value that increases over time (from 10 $/ha in 2020 to 100 $/ha in 2100 with a S-shape curve assuming a progressive increase at the beginning, a peak rate of increase by 2060, and stabilization to high values in 2100). While the possibilities to abandon cropland or pasture already existed in the model, they are assumed to be done for restoration and allocated where ultimate gains for biodiversity would be highest. The land put into restoration at any time step can be used again for production use in later time steps, but at high cost. The carbon sequestration resulting from the restoration of land is accounted for (natural vegetation regrowth over time with sigmoid growth curves) but is not valorized in scenarios including a carbon tax.

These differences have two main implications for the simulated land-use projections:

- Although the channels of impact of the increased restoration action wedge are relatively similar across IAMs (towards spatial configurations better for biodiversity), the amount of restoration land simulated by the IMAGE model should be lower than for other IAMs, especially if land sparing wedges (such as sustainable yield intensification, reduced waste, healthier diets, or increased trade) are not activated. For all IAMs, as compared to scenarios without this action wedge activated, the increased restoration efforts will lead to both a redistribution of the agricultural expansion (towards grid cells with lower priority score) and a reduced expansion, compensated by intensification of agricultural areas and leading to price increases. Also, in all IAMs, the abandonment of agricultural land will also be spatially re-allocated (towards grid cells of higher priority score), as a restoration action. In addition, for all IAMs but IMAGE, the amount of agricultural land put aside for restoration will be larger than in scenarios in which this action wedge is not activated, with a difference increasing over time. By contrast, for IMAGE, the amount of land set aside for restoration will increase only in scenarios considering both increased restoration and land sparing action wedges.
- Although the benefits for climate change mitigation of setting land aside for restoration (through carbon sequestration) is calculated by most IAMs (all except AIM), scenarios with strong climate mitigation will not lead to more land set aside for restoration as compared to scenarios with limited climate mitigation (except for GLOBIOM). For all IAMs except AIM, the carbon sequestrated in the land set aside for restoration is however estimated with different assumptions about the time profile of carbon accumulation. For all IAMs except GLOBIOM, this carbon sequestration is not included in the mitigation portfolio, and therefore not incentivized in the strong climate mitigation policy assumptions. By contrast, for the GLOBIOM model, more land could be put into restoration in scenarios in which a strong climate mitigation policy is assumed, as compared to scenarios without strong mitigation.

Reduced reliance on land for mitigation efforts

In some scenarios (tagged by 'RF1p9p', i.e., RF1p9p_SSP1p_BIOD, RF1p9p_SSP1p_NOBIOD, RF1p9p_SSP2_BIOD and RF1p9p_SSP2_NOBIOD) compatible with maintaining global warming below +2° C, we considered that some of the pressures from climate mitigation on land are strongly reduced. In particular, although GHG emissions remain taxed (or caped, for IMAGE) in all mitigation scenarios, the following assumptions were implemented:

- we assumed no additional demand for biofuels (as compared to RFref scenario). For all IAMs, additional demand in biofuels (as compared to the RFref scenario) was removed. Although strong reductions in the land pressure from biofuel development while still being able to achieve the same climate mitigation target seems a strong assumption, the large-scale development of 3rd generation biofuels could provide a significant step in that direction and mitigation efforts could be for part redistributed to other sectors.
- we assumed no afforestation (for carbon sequestration) beyond afforestation as a response to incentives for restoring biodiversity. However, this was implemented differently across IAMs and no afforestation (at all) was assumed for all IAMs except IMAGE, in which no reduction of afforestation was assumed. For the GLOBIOM model, afforestation is derived from the G4M simulations (which was not re-run for this exercise) and a scenario without afforestation was taken (i.e., similar to RFref), thus differing from RF1p9 scenarios. For the MAgPIE model, afforestation is not considered in any scenario, therefore the assumption has no impact on land-use projections. For the AIM model, no afforestation was also assumed. For the IMAGE model, afforestation remains the same as under RF1p9 since it is assumed to be based on protection and restoration policies, and therefore beneficial to biodiversity. The sensitivity of land-use projections to this assumption wedge should therefore highly depend on the IAM.

5.3 Simulations and outputs

We ran simulations from the global land-use models, from their starting date (from 1970 for IMAGE to 2005 for AIM) and with their resolution (from 1 year for IMAGE to 10 years for GLOBIOM) up to the year 2100 for all 20 scenarios. They reported two types of output for time steps of 10 years (or higher frequency), starting from the year 2010.

Aggregated outputs

Each IAM generated outputs aggregated at the scale of a few regions (AgMIP regions if possible, and two different sets of regions splitting the World in 5 regions[1]), with 10-year time steps from 2010 to 2100 and for all 20 scenarios. These outputs cover a few key input or output variables concerning population, the demand, supply and prices for food, feed and bioenergy commodities, nitrogen fertilizer use and the land cover and use. A few additional variables were delivered for some of the IAMs: non-CO_2 GHG emissions from land use (except for AIM), irrigation water withdrawal (except for AIM) and forestry production (except for MAgPIE).

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[1] The two sets of five regions were the 5 five regions reported in (Popp et al 2017) (OECD, REF, ASIA, MAF & LAM) as well as a slight re-work of 5 regions spatially better grouped and closer to the IPBES regions (ASIAPAC, EUMENA, SSA, OAM, NAM). For further details please have a look at the Appendix.

Spatially explicit land-use outputs

Each IAM generated land-use projections over a regular 0.5° x 0.5° latitude-longitude grid for at least every 10 years from 2010 onwards and for all 20 scenarios. This was the primary and only driver of biodiversity change as evaluated by the biodiversity models (see Section 6), and the thematic resolution of the land-use projections was harmonized across IAMs to facilitate use by the biodiversity modeling teams. We reported the share of total grid cell area occupied by eight different land-use/cover classes: cropland other than 2nd generation biofuel perennial crops; 2nd generation biofuel perennial crops; grassland (used for livestock); unmanaged forest; managed forest (for both extractive and non-extractive use – e.g., carbon sequestration); restored land; other (vegetated and non-vegetated), and built-up areas. As detailed in Table 3, there were notable differences across IAMs in the initial extent and dynamics of these land covers. More notable differences include:

- GLOBIOM has less grassland and more other natural land as compared to other models, because many areas identified as grassland from FAO are not needed for livestock and reclassified in the model as other natural land.
- Some land cover/use classes (e.g., managed forests, perennial crops for bioenergy), are not well constrained by observations and their spatial location can differ substantially across models.
- Managed forests encompass afforestation (for both extraction and carbon sequestration), which can increase substantially under the climate mitigation scenarios. However, unlike other models, MAgPIE was run without afforestation in this study: managed forests should increase less than other models under the RF1p9 scenarios.
- Built-up areas are static for all models except IMAGE.
- Restored land is present in BIOD scenarios for all models (only after 2020) but can also be present in NOBIOD scenarios for MAGPIE and IMAGE (as abandoned agricultural land). The restored land can only come from land previously used for agriculture (e.g., cropland or grassland) and is allocated to restoration based on its potential biodiversity value after full recovery. For GLOBIOM, it cannot decrease in further time steps and therefore the land allocated to restoration in a time step is obtained from the model outputs. For the other IAMs, under high pressure for land conversion, some of the land previously set aside for restoration could be put into production again. This means splitting ‘restored’ land output from IAMs by age class in each pixel is straightforward for GLOBIOM (the difference between time steps allow keeping track of the age) but for other IAMs additional assumptions are required (e.g., if the area of ‘restored’ land decreases, either take the youngest restored area first, or take equally from all age classes).
- While the spatially explicit information with respect to the biodiversity value of restoration is based on the same data layer (the range-rarity layer provided by IUCN, weighted by biome and continent combination) for all models, the spatially explicit details of the restoration rationale also depends on where agricultural land is and what the opportunity costs are. Since the two later layers can differ widely across models, the projections of restoration areas can differ widely across models.
- The ‘other’ land cover/use category includes inland water for AIM and GLOBIOM, but excludes it for IMAGE and MAgPIE.

Table 3 – Definition of the land-use classes of spatially explicit land-use projections generated by IAMs.

land-use classes		**standard def.**		**model specific differences to standard def.**			
ID	*LU_class_name*	*definition of class*	*dynamics and initialization*	*AIM*	*GLOBIOM*	*IMAGE*	*MAGPIE*
1	cropland_other	cropland area; excluding 2nd. generation bioenergy plantations (but includes 1st generation bioenergy crops); both n-fixing and not; both perennial (e.g., oil palm) and annual	can expand on the account of forest, other or grassland; can decrease if not used; initialized with a dataset of spatial distribution at pixel level (different for each model) and further harmonization with FAO stats art regional scale	-	-	-	-
2	cropland_bioenergySRP	cropland dedicated to 2nd generation bioenergy short rotation plantations (perennial cropland)	dynamics similar to cropland; often initialized to 0 in base year (patterns can largely differ across models)	-	-	-	-
3	grassland	grassland used for feeding livestock, can be both rangeland or pasture, both temporary or permanent grassland	can expand on the account of forest or 'other', and of cropland for some models; can decrease if not used or converted to cropland; initialized with a dataset of spatial distribution at pixel level (widely different for each model)	-	only 'used' grassland (given productivity and spatial distribution assumptions; rest is rebalanced to other), amounts to only half of FAO grassland globally	permanent grassland only; only pasture can change while rangeland is fixed (split based on productivity assumption)	permanent grassland only
4	forest_unmanaged	forests areas not managed, can be both primary or secondary, was present in year 2000 and excludes new forest (afforestation)	can only decrease; initialized with a dataset of spatial distribution at pixel level (differs widely across models) with different types of harmonization	-	-	-	primary forest only

Table 3 (continued)

land-use classes		**standard def.**		**model specific differences to standard def.**			
ID	*LU_class_name*	*definition of class*	*dynamics and initialization*	*AIM*	*GLOBIOM*	*IMAGE*	*MAGPIE*
5	forest_managed	forests areas managed (for extractive use or carbon sequestration), includes both forest present in year 2000 and new forest (e.g., afforestation)	can increase (of primary forest or other) or decrease (from deforestation); initialized with a dataset of spatial distribution at pixel level (differs widely across models) with different types of harmonization	-	-	for extractive use only	-
6	restored	land that was used as grassland or cropland and set aside for restoration (only from 2020 onwards)	never before 2020; only in BIOD scenarios (except for IMAGE and MAGPIE), and cannot decrease (except MAGPIE and AIM); where to restore is based on the range-rarity layer, but also on the initial occupation of land (which can differ widely for e.g., grassland)	Can decrease under high pressure on land	-	Can decrease under high pressure on land; also present in NOBIOD scenario	Can decrease under high pressure on land; also present in NOBIOD scenario
7	other	other vegetated (primary or secondary non-forest and non-agricultural vegetation, including shrubland, tundra, wetlands), and non-vegetated (bare land, deserts, water, ice or permanent snow) areas	can increase as a result cropland or grassland abandonment (in all time steps for NOBIOD scenarios, before 2020 in BIOD scenarios); can decrease due to conversion to cropland or pasture	-	-	excludes inland water	excludes inland water; cannot increase from 2020 onwards as it goes to restored layer, also for NOBIOD scenarios
8	built_up_areas	built-up areas	static to year initial year (except for IMAGE); initialized with a dataset of spatial distribution at pixel level (differs widely across models)	-	-	increases over time dependent on SSP-specific population growth and rates of urbanization	-

6 Projections from global biodiversity models

6.1 Brief description of the biodiversity models used

In order to estimate the biodiversity impacts of the future trajectories of land-use change for the various scenarios considered, we used 11 different global biodiversity indicators coming from various global biodiversity models (see Table 4). The models used have been chosen for their ability to project spatially explicit changes in biodiversity at a global scale under various scenarios of future land use. They cover various aspects of biodiversity such as the extent of suitable habitat, abundance of organisms, measures of species loss, and measures of integrity of the ecological assemblages.

Biodiversity model	**Indicator**	**Biodiversity aspect**	**Key references**
Living Planet Index (LPI-M) model	Living Planet Index (LPI-M | LPI)	abundance of birds and mammals	(McRae *et al* 2017, Collen *et al* 2009)
INtegrated ScenarIos of Global HabiTat for Species (INSIGHTS) model	Extent of Suitable Habitat (INSIGHTS | ESH)	extent of suitable habitat of mammals	(Visconti *et al* 2016)
Asia-Pacific Integrated Model (AIM-biodiversity)	Extent of Suitable Habitat (AIM-B | ESH)	extent of suitable habitat for vascular plants, amphibians, reptiles, birds, and mammals	(Ohashi *et al*, in prep.)
Projecting Responses of Ecological Diversity In Changing Terrestrial Systems (PREDICTS) model	Biodiversity Intactness Index (PREDICTS | BII)	compositional integrity of ecological assemblages (based on abundance of original species)	(Purvis *et al* 2018, De Palma *et al* 2018, Hill *et al* 2018)
Global Biodiversity (GLOBIO) model	Mean Species Abundance (GLOBIO | MSA) Index	compositional integrity of ecological assemblages (based on abundance of original species)	(Alkemade *et al* 2009)
Countryside Species-Area Relationship (cSAR) model	Fraction of remaining regional species (cSAR | FRRS_CB17), Fraction of remaining endemic species (cSAR | FRES_CB17)	long-term extirpation (for FRRS_CB17) and extinction of species (for FRES_CB17) of mammal, bird and amphibian species	(Chaudhary and Brooks 2017)
	Extirpation index (cSAR | ETPI_US16), Extinction index (cSAR | EXCI_US16)	long-term extirpation (for ETPI_US16) and potential long-term extinction (for EXCI_US16) of species of mammals, birds, amphibians, reptiles and vascular plants	(UNEP and SETAC 2016, Chaudhary *et al* 2015)
Biogeographic modelling Infrastructure for Large-scale Biodiversity Indicators (BILBI)	Fraction of remaining plant species (BILBI | FRPS)	long-term extinction of vascular plants	(Ferrier *et al* 2007, Hoskins *et al* 2018)
Madingley model	Abundance density index (Madingley | ADI)	abundance of all organisms	(Harfoot *et al* 2014a)

Table 4 - List of the various BDMs used in the proof-of-concept analysis of the Bending the curve initiative, and related biodiversity metrics estimated by models.

The **LPI-M model** provides an estimated index of relative abundance (LPI-M | LPI) as a function of the rate of land-use change. The model is based on a statistical (mixed-effects) model estimating rates of population change from the Living Planet Index Database (Collen *et al* 2009, McRae *et al* 2017) of vertebrate population records and the ESA-CCI land cover time series product (ESA 2017). This modelled response is then projected for each future scenario presented here.

INSIGHTS' ESH index (INSIGHTS | ESH) is a measure of the size of suitable habitat for mammals, relative to a point in time (2010 in this case). It is based on species level modelling using Habitat Suitability Models and the global range maps of 4466 terrestrial mammals obtained from the IUCN Red List database. . The HSMs were parameterized with habitat preferences coded by IUCN Red List assessors (Visconti *et al* 2016). The output, for each species, year and scenario, is a map of suitable habitat within the current range. In this exercise, species with a range lower than 150 km2 were excluded from the analysis as their range was considered too small compared to the resolution of the land-use projections. The ESH index for year *t* is obtained by computing the geometric mean of the ration ESH(*t*)/ESH(2010) over all species modelled.

AIM-Biodiversity's ESH index (AIM-B | ESH) also provides an index of relative suitable habitat size. As detailed in (Ohashi *et al,* in prep.), it is also based on Habitat Suitability modelling of individual species for 8,928 species from the GBIF database, covering several taxonomic groups (vascular plants, amphibians, reptiles, birds, and mammals). In this exercise, only species for which built-up area and agricultural land are unfavourable habitats were considered (1,907 species). The modelling was done assuming full dispersion, meaning that a species could reach all geographical areas that are predicted to be suitable in their native range.

PREDICTS' BII (PREDICTS | BII) provides a measure of the intactness of the local communities within a pixel/region (Newbold *et al* 2016, Purvis *et al* 2018, De Palma *et al* 2018, Hill *et al* 2018). The index value gives the average community abundance of the originally present species, as affected by the land use and land-use intensity in the pixel/region (relative to the original state, assuming a pristine cover). BII is calculated through linear mixed-effects models based on records from the PREDICTS database (Hudson *et al* 2017).

GLOBIO's **MSA** (GLOBIO | MSA) provides an estimate of the intactness of local communities within a pixel/region (Alkemade *et al* 2009, Schipper *et al* 2016). It represents the mean abundances of original species in a disturbed situation relative to their abundances in the original, undisturbed state. If the abundance of a given species is higher in the disturbed situation than in the reference, its abundance ratio is truncated at 1. For secondary/restored vegetation, MSA is calculated as function of the age (A) of the secondary vegetation, as MSA(A) = 0.23 + 0.081*ln(A) for MSA < 0.9, else MSA = 0.9.

The **cSAR model** provide estimates of species richness, based on Species-Area relationship type of model, in which species have different affinities for various land-use classes (Pereira and Daily 2006). The model used in this exercise (Chaudhary *et al* 2015) estimates species loss at the scale of WWF terrestrial ecoregions (Olson *et al* 2001) and for a long-term 'steady-state' posterior to the land-use change. If lost species are endemic to an ecoregion, this corresponds to species *extinctions* (i.e., irreversible loss at global scale) - otherwise, this corresponds to species *extirpations*. We use four different indicators estimated from two implementations of the cSAR model from Chaudhary *et al* (2015):

- The Extirpation (cSAR | ETPI_US16) and the Extinction (cSAR | EXCI_US16) indices estimate the amplitude of long-term extirpations and extinctions relative to their amplitude in 2010. The indices were derived for the PSLglo ($EXCI\_US16(t) = -1 \cdot PSL_{glo}(t)/PSL_{glo}(2010)$) and PSLreg ($ETPI\_US16(t) = -1 \cdot PSL_{reg}(t)/PSL_{reg}(2010)$) metrics described in (UNEP and SETAC 2016), and their value decrease when the extirpations / extinctions increase. They use the cSAR model coefficients described in (Chaudhary *et al* 2015) for five taxonomic groups and the differentiation between extirpations and extinctions involves an ecoregion-specific probability score that lost species are actually endemic.

- The Fraction of Remaining Regional Species (cSAR | FRRS_CB17, estimating extirpation) and Fraction of Remaining Endemic Species (cSAR | FRES_CB17, estimating extinctions) were derived from the extinctions and extirpations calculated following (Chaudhary and Brooks 2017), and normalized by the number of endemic species *NS* and total number of species *NES* ($FRRS_{CB17(t)} = 1 - extirp.(t)/NS$; $FRES_{CB17(t)} = 1 - extinc.(t)/NES$). As compared to (Chaudhary *et al* 2015), this model version covers three taxonomic groups and is based on the IUCN Habitat Classification Scheme (International Union for Conservation of Nature 2015), from which new affinity estimates are also derived. Extirpations are differentiated from extinctions by estimating within each ecoregion the number of total and endemic species from the IUCN Red List (IUCN 2016).

The **BILBI** model (Ferrier *et al* 2007, Hoskins *et al* 2018) provides the Fraction of Remaining Plant Species (BILBI | FRPS), a community-level estimate of extinction for vascular plants. The modelling couples the species-area relationship with i) correlative statistical modelling of 'compositional dissimilarity' between pairs of grid cells at ca. 1 km resolution (continuous patterns of spatial turnover in species composition between cells, as a function of their environmental attributes and geographic separation) and ii) estimates of the impact of different categories of land-use on local plant diversity using the PREDICTS' BII coefficients detailed above. While a separate model was generated for each of 61 bio-realms (unique combinations of biome and biogeographic realm; (Olson *et al* 2001)) the affinity of most plant species with a single bio-realm means that estimates of species loss derived from these models can be treated as global extinctions.

The **Madingley model**'s abundance density index (Madingley | ADI) provides a measure of the abundance of all heterotrophic organisms above 400μg within a pixel that feed on autotrophs or other living organisms. It is based on a mechanistic model of ecosystems (Harfoot *et al* 2014a), and is similar to the Living Planet index.

6.2 Processing of spatially explicit land-use input

As detailed in Table 5, the various BDMs have different representation of land use. Some models consider only broad land-use classes - like the Madingley model (3 classes) or the LPI-M model (2 classes) - while some other models consider more classes than are provided by the IAMs. For instance, GLOBIO and PREDICTS differentiate management intensity while INSIGHTS refines other natural & restored land classes into several subclasses. The modelling assumptions of each BDM and the mapping to classes of the IAM land-use projections are detailed in Table 5 (including potential use of side data).

BDMs also differed in their assumptions concerning biodiversity recovery within restored land. Four metrics (AIM-B | ESH, cSAR | ETPI_US16, cSAR | EXCI_US16 and LPI-M | LPI) assumed that restored area was as good as pristine area for biodiversity, with the positive impact occurring immediately after the land-use conversion. They thus provide an upper (optimistic) boundary of biodiversity recovery under restoration. For all other metrics, restored area recover a level of biodiversity equivalent to pristine area only after a long time (e.g., GLOBIO | MSA, cSAR | FRRS_CB17 and cSAR | FRES_CB17) or recover only to a level equivalent to either secondary vegetation (BILBI | FRPS, Madingley | ADI, PREDICTS | BII) or to a variety of land cover sub-classes not all beneficial to biodiversity (INSIGHT | ESH). In addition, as land-use projections differ across IAMs even for 2010, the values of the indicators simulated by the BDMs showed a variation across IAMs that depends on their land-use representation.

Finally, some models used a coarser spatial resolution than the IAM land-use projections. Aggregated shares of the eight land-use classes for IPBES subregions were provided to the PREDICTS model, using a weighting based on potential NPP from (Haberl *et al* 2007). Aggregates to WWF ecoregions (while also splitting secondary and other into primary and secondary vegetation each, leading to 12 classes in total) were provided to the cSAR model.

Table 5 - Thematic land-use resolution of the BDMs and mapping to the spatially explicit land-use projections

	Biodiversity model land-use classes	Mapping to IAM land-use class	Side data used to refine the spatially explicit land-use projections
AIM-Biodiversity	The model uses five classes (cropland, pasture, built-up area, forest and other natural land)	cropland=[cropland_other + cropland_bioenergySRP]; pasture=[grassland]; built-up area=[built_up_areas]; forest=[forest_unmanaged + forest_managed + restored*is_potentially_forested)];other natural land=[other + restored *is_potentially_nonforested]	To differentiate restoration area between forest and other natural land, we used the potentially forested vs non-forested mask form LUH2 data (Hurtt *et al*, in prep.).
BILBI	The model takes into consideration directly the land-use classes from the spatially explicit land-use projections. This is done via affinities of the represented species to these different land-use classes as measured by PREDICTS' BII coefficients.	one to one mapping	-
cSAR (UNEP and SETAC 2016)	The model uses seven classes (pristine; extensively used forest; intensively used forest; pasture/meadow, cultivated areas under a rotation system; permanent crops; artificial areas)	cultivated areas under a rotation system = [cropland_other] permanent crops = [cropland_bioenergySRP]; pasture/meadows = [grassland]; extensively used forest = [forest_unmanaged * is_secondary + 0.5 * forest_managed]; intensively used forest = [0.5 * forest_managed]; pristine = [restored + other + forest_unmanaged * is_primary]; artificial areas = [built_up_areas]	To split unmanaged_forest between extensively used forest and pristine area on a regular 0.5° x 0.5° latitude-longitude grid, we used a mask of primary vs secondary based on LUH2 data (Hurtt *et al*, in prep.).
cSAR (Chaudhary and Brooks 2017)	The model is based on 5 classes (primary [i.e., pristine], secondary vegetation, pasture, cropland and urban) based on IUCN habitat classification scheme. The restored land was considered as either secondary or primary depending on its age.	pasture = [grassland]; cropland = [cropland_other + cropland_bioenergySRP]; secondary = [restored (less than 70 years old)+ unmanaged_forest * is_secondary + other * is_secondary]; primary = [restored (70 years old or more) + unmanaged_forest * is_primary + other * is_primary]; urban = [built_up_areas]	To split unmanaged_forest between extensively used forest and pristine area on a regular 0.5° x 0.5° latitude-longitude grid, we used a mask of primary vs secondary based on LUH2 data (Hurtt *et al*, in prep.).
GLOBIO	The model simulations were based on 7 main classes (primary [i.e., pristine], secondary, forestry, pasture, cropland, cropland for bioenergy, urban) with further distinction of management intensity in some classes (clear-cut forestry, selective logging, forestry plantations; rain-fed cropland, irrigated cropland; rangeland). The MSA value of restored land increases non-linearly with the age.	pasture = [grassland]; cropland = [cropland_other]; cropland for bioenergy = [cropland_bioenergySRP]; secondary = [restored]; forestry = [forest_managed]; primary = [unmanaged_forest + other]; urban = [built_up_areas]	IMAGE data from scenario RFref_SSP2_NOBIOD was used to calculate per IPBES sub-region and modelling year the proportions of different intensity/management classes, and the split of unmanaged forests into primary vs secondary forests. Other and unmanaged_forest classes were considered as entirely primary.

Table 5 - Continued

	Biodiversity model land-use classes	Mapping to IAM land-use class	Side data used to refine the spatially explicit land-use projections
INSIGHTS	The model uses 12 classes, with finer classes for non-managed areas (built-up areas, agriculture, pasture, selective logging, forest-unmanaged, natural grassland, shrubland, tundra, deserts, ice, water and wetland). The ESA-CCI data for around year 2000 was used to split the classes 'other' and 'restored' into deserts, wetland, water, ice, tundra, shrubland and natural grassland.	agriculture = [cropland_other + cropland_bioenergy]; pasture = [grassland]; built-up area=[built_up_area]; selective logging = [forest_managed]; forest-unmanaged = [forest_unmanaged]; tundra = [share of 'other' + 'restored' at each time step]; shrubland = [share of 'other' + 'restored' at each time step]; natural grassland = [share of 'other' + 'restored' at each time step]; deserts = [share of 2010 'other ', constant]; ice = [share of 2010 'other ', constant]; water = [share of 2010 'other ', constant]; wetlands = [share of 2010 'other ', constant]	The ESA-CCI dataset (ESA 2017), averaged for year 1999-2001 and aggregated to half degree and intermediate land cover classes was used to split the sum of 'other' and 'restored' into natural non-grazed grassland, shrubland, tundra, deserts, wetland, water. While tundra, shrubland and natural grassland classes can change in extent in a given pixel (as the sum of 'other' + 'restored' changes), deserts, ice, water and wetlands are assumed fixed in their 2010 value.
LPI	The model uses 2 classes (agricultural and non-agricultural, and ignores the forest management).	agriculture = [cropland_other + cropland_bioenergySRP + grassland]; non-agriculture = [forest_managed + forest_unmanaged + restored + other + built_up_areas]	-
Madingley	The model uses 3 main land cover classes (primary [i.e., pristine], secondary and impacted)	primary = [forest_unmangaged + other * is_primary]; secondary = [forest_managed + restored + other * is_secondary]; impacted = [cropland_other + cropland_bioenergySRP + grassland + built_up_areas].	To split the other class between extensively used forest and pristine area on a regular 0.5° x 0.5° latitude-longitude grid, we used a mask of primary vs secondary based on LUH2 data (Hurtt *et al*, in prep.)
PREDICTS	The model usually uses global-scale coefficients of 9 classes for land potentially forested land and 6 classes for land potentially non-forested land, but in this exercise the coefficients were aggregated to the 8 classes of the spatially explicit land-use projections, using a weighted mean of the usual coefficients based on proportions of present-day area at global scale using LUH2 dataset.	**cropland_other**: Forested Annual + Nitrogen croplands, Forested Perennial, Non-forested Annual + Nitrogen croplands, Non-forested Perennial; **cropland_bioenergySRP**: Forested Perennial croplands, Non-forested Perennial croplands; **Grassland**: Forested Pasture (rangelands + managed pastures), Non-forested Pasture (rangelands + managed pastures); **Forest_unmanaged**: Forested Primary vegetation Minimal use, Forested Mature secondary vegetation Minimal usel; **Forest_managed**: Forested Primary vegetation Light and Intense use, Forested Secondary vegetation Light and Intense use + Timber Light and Intense use; **Restored**: Forested Mature secondary vegetation Minimal use; **Other**: Non-forested Primary vegetation Minimal use, Non-forested Secondary vegetation Minimal use, Forested Young secondary vegetation Minimal use. **Built_up_areas**: Forested Urban, Non-forested Urban	To aggregate the PREDICTS coefficient to the land-use classes of the spatially explicit projections, the LUH2 data (Hurtt *et al*, in prep.) was used.

6.3 Simulations and outputs

Simulations

Using the spatially explicit projections, the various biodiversity models provided estimates of biodiversity indicators for various time horizons (10), IAMs (4) and scenarios (20). However, the biodiversity models differ significantly in their complexity and time requirement for one simulation and we adopted a tiered approach to allow each model to contribute accordingly. Therefore, the various models ran different set of simulations out of the 800 possible combinations. We imposed that for any IAM x scenario combination, at least three time horizons were run (2010, 2050 and 2100). Madingley and BILBI models could run only two out of the four IAMs (MAgPIE/REMIND and GLOBIOM/MESSAGE) for two scenarios, while all other biodiversity models ran simulations for all four IAMs for a minimum of four scenarios (see Table 6).

Reported outputs

Values of each indicator were reported at the global level and for the 17 IPBES sub-regions (see Brooks *et al* 2016), for all scenarios, IAMs and time step.

			Scenarios																						
BDM	**IAMs**	**Time horizons**	**reference scenarios**	RFref_SSP2_NOBIOD	RF1p9_SSP2_NOBIOD	**bending sceanrios scenarios**	RFref_SSP1p_BIOD	RF1p9p_SSP1p_BIOD	**wedges sceanrios scenarios**	RF1p9_SSP2_BIOD	RF1p9p_SSP1p_NOBIOD	RF1p9_SSP1pDEM_BIOD	RF1p9_SSP1pDEM_NOBIOD	RF1p9_SSP1pTECHTRADE_BIOD	RF1p9_SSP1pTECHTRADE_NOBIOD	RF1p9_SSP1pTECHTRADEDEM_BIOD	RF1p9_SSP1pTECHTRADEDEM_NOBIOD	RF1p9p_SSP2_BIOD	RF1p9p_SSP2_NOBIOD	RFref_SSP1p_NOBIOD	RFref_SSP1pDEM_BIOD	RFref_SSP1pDEM_NOBIOD	RFref_SSP1pTECHTRADE_BIOD	RFref_SSP1pTECHTRADE_NOBIOD	RFref_SSP2_BIOD
PREDICTS	all four	2010 to 2100 by 10 years		x	x		x	x		x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x
cSAR (UNEP and SETAC 2016)	all four	2010 to 2100 by 10 years		x	x		x	x		x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x
Globio	all four	2010 to 2100 by 10 years		x	x		x	x		x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x
INSIGHTS	all four	2010 to 2100 by 10 years		x	x		x	x		x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x
LPI-M	all four	2010 to 2100 by 10 years		x	x		x	x		x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x
AIM-B	all four	2010 to 2100 by 10 years		x	x		x	x		x	x									x					x
cSAR (Chaudhary and Brooks 2017)	all four	2010, 2030, 2050, 2100		x	x		x	x																	
Madingley	GLOBIOM & MAgPIE	2010 to 2100 by 10 years		x			x																		
BILBI	GLOBIOM & MAgPIE	2010, 2050, 2100		x			x																		

Table 6 - Detail of BDM simulations performed for the Bending The Curve proof-of-concept analysis

7 Discussion

Models and scenarios could be pivotal in a number of upcoming policy processes, by helping to develop an integrated approach to land use that reverses historical trends of biodiversity loss without jeopardizing chances to reach development or climate mitigation targets. However, methodological innovations are required to allow for generating robust pathways that incorporates biodiversity goals. Through the *Bending The Curve* proof-of-concept analysis, we developed an innovative use of models to produce a set of scenarios for ambitious biodiversity targets, and evaluated them with multiple models. More specifically, the goals were (i) to develop narratives and provide quantification of new and ambitious scenarios in which the curve of recent and expected future biodiversity trends (as affected by land use) is bent upwards within the 21st century, and (ii) to perform multi-model simulations to explore whether the target is achieved for different aspects of biodiversity, what the contribution of various "action wedges" to the target is, what the synergies and trade-offs with other sustainable development goals are, and how uncertain these aspects are.

We first extended the SSP/RCP scenario framework with additional elements allowing us to quantify with IAMs an ambitious conservation narrative. We then designed a set of twenty scenarios based on the *Middle Of The Road* SSP scenario and variations of SSP/RCP assumptions. We subsequently ran simulations with four IAMs to quantify the land-use trends in such scenarios, and reported projections at both regional scale and relatively high resolution (i.e., half degree) for a standardized set of variables. We finally used several BDMs to estimate the impact of the resulting land-use projections on eleven indicators of biodiversity. These developments represent important advances to the field:

- The modelling relies on innovative techniques that should facilitate the construction of target-seeking scenarios. In particular, the incorporation into the IAM optimisation of i) estimated biodiversity effects of land use and ii) a regional restoration priority score allows for better diagnosis of pathways that minimize trade-offs between biodiversity and other objectives. Such a method could easily incorporate new datasets as they become available and opens a new avenue for research and policy applications.
- The scenarios developed complement the SSP/RCP framework by including ambitious conservation assumptions, aiming to bend biodiversity trends upwards. Such an element is missing from the current RCP/SSP framework (Kim *et al* 2018) and allows researchers to design more ambitious scenarios than previous efforts, such as the Rio+20 scenarios (Van Vuuren *et al* 2015, Kok *et al* 2018). The scenarios and quantified land-use and biodiversity projections should therefore provide information that is complementary to existing scenarios.
- The approach relies on the RCP/SSP scenario framework and uses multiple IAMs and BDMs, thereby allowing for an in-depth exploration of uncertainties. For instance, while our proof-of-concept approach varied assumptions concerning some scenario elements of SSP2 and SSP1 scenarios, assumptions from other SSPs and RCPs scenarios could be used and assumptions concerning additional elements (e.g., population) could be explored.

In addition, some features of the approach could facilitate quick and wide re-use of the scenarios and the land-use projections generated. First, the scenarios were "co-generated" by a team of various stakeholders, including expertise from land-use and biodiversity modellers but also from sustainability and biodiversity policy/conservation practice, allowing a more robust and coherent representation of policy options and implementation, and a more efficient uptake by the policy arena. Second, our effort to carefully document the modelling steps and standardize the format and content of the spatially explicit land-use projections should facilitate their re-use.

We acknowledge that this proof-of-concept analysis has certain limitations. First, although we differentiated the biodiversity effects between several land-use classes, this did not capture the entire range of biodiversity impact from land use. For example, the BII coefficients used to guide the land-use allocation and most of the biodiversity models did not differentiate the effect of various land-use intensities within cropland. This implies that the land-use pathways diagnosed as able to restore biodiversity rely on land-sparing types of strategies, while in reality high land-use intensity can have various detrimental effects on local biodiversity (e.g., pesticides, eutrophication). Additionally, a more detailed modelling (in both IAMs and BDMs) of land uses like afforestation or land areas where human footprint is low (e.g., other, a mix of various land covers including primary and secondary vegetation) could lead to more realistic pathways and better inform trade-offs and synergies between climate mitigation and biodiversity conservation. Improved modelling of the development and impact of built-up areas (static for all IAMs but IMAGE) and infrastructure (not well covered in this analysis) is also important. Moreover, for some ecological processes the history of land use matters: to better estimate the biodiversity aspects of scenarios, the land-use projections need to be complemented by historical reconstructions while limiting inconsistencies between the two. Finally, interactions between land use and biodiversity are bi-directional: while we only included the impact from land use on biodiversity, feedbacks need to be accounted for (e.g., via loss of pollinators). For our approach to provide more relevant input to the policy process, improvements in the above-mentioned aspects are important. On the one hand, progress on some of these challenges - like refining land use intensity and linking historical and projected future land use (Hurtt *et al*, in prep. , Kim *et al* 2018) - have recently been made and should be linked to our approach. On the other hand, some aspects will require more developments: for example, some impacts of land use on biodiversity might feedback to land use with delays (e.g., pesticide diffusion into the environment leading to pollination loss), complicating the type of modelling required.

This proof-of-concept analysis was intended as a demonstration case of new methods for target-seeking analysis, rather than as policy-screening exercise. Therefore, the representation of conservation efforts in the various scenarios remain rather coarse as compared to some earlier approaches (Van Vuuren *et al* 2015, Kok *et al* 2018), and the inclusion of stakeholders in the design of the scenarios remained limited. For example, to guide land-use decisions in IAMs under scenarios assuming ambitious conservation efforts, we used only one layer of priority for restoration, and only one assumption concerning the extent, location and management of future protected areas. This choice prioritizes conservation actions that balance many aspects at once, from global (e.g., mitigating extinction risks) and local (e.g., restoring the integrity of local biodiversity) biodiversity concerns. More focused efficient restoration efforts could require different prioritizations for different targets (Brooks *et al* 2006). As a consequence, our analysis cannot be used to diagnose how far trends for a particular biodiversity aspect (e.g., extinction risks or biodiversity intactness) can be bent, and what the most adequate pathways are for this purpose. In addition, although IAMs have proven useful at various stages of the policy process, useful contribution of IAMs to each stage require different levels of stakeholder involvement and refinement in the modelling of policy interventions,. Ultimately, IAMs cannot address all aspects and the methods need to be tailored to the context (Rosa *et al* 2017, IPBES 2016).

In this proof-of-concept analysis, although we accounted for land use – currently the biggest threat to biodiversity –, we did not account for other threats to biodiversity. In particular, climate change, hunting and biological invasions have been driving biodiversity loss globally in the past and are projected to be strong drivers of biodiversity change in the future. Not accounting for additional threats to biodiversity limits the reach of our proof-of-concept analysis for several reasons. First, the pathways that we estimate able to bend the curve of biodiversity trends (as affected by land use only) might not be able to bend biodiversity trends in reality if other threats increases. In addition, as various threats on biodiversity can reinforce one another, the estimated biodiversity impacts from land use only could be underestimated or overestimated depending on the evolution of other threats. Moreover, threats are interlinked via their drivers and considering multiple threats could therefore lead to the promotion of different pathways. The biodiversity trade-off related to climate change and land-based climate mitigation is an obvious example that our analysis did not fully address. Another potential trade-off relates to trade: the pathways limiting the conversion of pristine tropical habitats might also increase trade, which in turn could increase biological invasions. Such linkages could also extend beyond the terrestrial realm, for example via the water cycle (e.g., eutrophication and water consumption for irrigation), or the manifold interactions between aquaculture and agriculture (feed, diets, nutrients, etc.). On the one hand, the modelling of biodiversity under multiple threats, and the inclusion of these effects within IAMs are large technical challenges. On the other hand, the approach we propose could rapidly incorporate more threats. For example, although this was beyond the scope of the proof-of-concept analysis, some of the biodiversity models (e.g., INSIGHTS, Madingley, AIM-B, BILBI) and scenarios (RCPs) we used were also recently used to estimate projections of future biodiversity under the joint evolution of climate and land use (Kim *et al* 2018). In addition, some of the modelling framework we used can account for many threats (Van Vuuren *et al* 2015). Finally, on-going developments in biodiversity modelling (Tittensor *et al* 2017) and scenarios (Maury *et al* 2017) for the marine environment put more integrated assessments at reach: although developments are required for proper integration, IAMs are suitable tools to investigate such interactions.

8 Conclusive remarks

This report details the methods of a proof-of-concept analysis illustrating the potential for innovative modeling techniques to inform robust science-based targets and conservation planning. The analysis used four global land-use models and eight global biodiversity models to shed light on socio-economic and technological changes and conservation interventions that are able to bend upwards the biodiversity trends as affected by land-use change, the biggest current threat to biodiversity. We believe the analysis to be an important step forward in mobilizing current knowledge from the land-use and terrestrial biodiversity modelling communities for more ambitious conservation targets. We believe that the approach could rapidly be improved and include additional threats to terrestrial biodiversity. This highlights the potential of the approach to deliver timely, relevant input into upcoming policy processes.

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Appendix

List of AGMIP regions and mapping to 5 SSP regions used in e.g., (Popp *et al* 2017) and to the 5 regions used in this analysis

AGMIP Code	**AGMIP Region detail**	Mapping to SSP aggregated regions	Mapping to 5 regions used in this analysis
ANZ	Australia/New Zealand	OECD	ASIAPAC
BRA	Brazil	LAM	LAM
CAN	Canada	OECD	NAM
CHN	China	ASIA	ASIAPAC
EUR	Europe (excl. Turkey)	OECD	EUMENA
FSU	Former Soviet Union (European and Asian)	REF	EUMENA
IND	India	ASIA	ASIAPAC
MEN	Middle-East / North Africa (incl. Turkey)	MAF	EUMENA
OAS	Other Asia (incl. Other Oceania)	ASIA	ASIAPAC
OSA	Other South, Central America & Caribbean (incl. Mexico)	LAM	LAM
SEA	South-East Asia (incl. Japan, Taiwan)	OECD	ASIAPAC
SSA	Sub-Saharan Africa	MAF	SSA
USA	United States of America	OECD	NAM

List of SSP regions

CODE	**Detail**
OECD	OECD 90 and EU member states and candidates
REF	Countries from the Reforming Ecomonies of Eastern Europe and the Former Soviet Union
ASIA	Asian countries with the exception of the Middle East, Japan and Former Soviet Union states
MAF	Middle East and Africa
ASIAPAC	Latin America and the Caribbean

List of 5 aggregated regions used in this analysis

CODE	**Detail**
NAM	Nothern America
LAM	Latin and Central America (incl. Mexico)
SSA	Sub-Saharan Africa
EUMENA	Europe, Former Soviet Union and Middle-East
ASIAPAC	Asia and Pacific

Mapping between AGMIP regions and Countries

AGMIP	ISO3	ISO#	AGMIP	ISO3	ISO#	AGMIP	ISO3	ISO#	AGMIP	ISO3	ISO#
ANZ	AUS	36	FSU	ARM	51	OSA	AIA	660	SSA	AGO	24
	NZL	554		AZE	31		ATG	28		BEN	204
BRA	BRA	76		BLR	112		ARG	32		BWA	72
CAN	CAN	124		GEO	268		ABW	533		BFA	854
CHN	CHN	156		KAZ	398		BHS	44		BDI	108
	HKG	344		KGZ	417		BRB	52		CMR	120
	MAC	446		MDA	498		BLZ	84		CPV	132
EUR	ALB	8		RUS	643		BMU	60		CAF	140
	AND	20		TJK	762		BOL	68		TCD	148
	AUT	40		TKM	795		VGB	92		COM	174
	BEL	56		UKR	804		CYM	136		COG	178
	BIH	70		UZB	860		CHL	152		CIV	384
	BGR	100	IND	IND	356		COL	170		COD	180
	HRV	191	MEN	DZA	12		CRI	188		DJI	262
	CYP	196		BHR	48		CUB	192		GNQ	226
	CZE	203		EGY	818		DMA	212		ERI	232
	DNK	208		IRN	364		DOM	214		ETH	231
	EST	233		IRQ	368		ECU	218		GAB	266
	FIN	246		ISR	376		SLV	222		GMB	270
	FRA	250		JOR	400		FLK	238		GHA	288
	DEU	276		KWT	414		GRD	308		GIN	324
	GIB	292		LBN	422		GLP	312		GNB	624
	GRC	300		LBY	434		GTM	320		KEN	404
	VAT	336		MAR	504		GUY	328		LSO	426
	HUN	348		OMN	512		HTI	332		LBR	430
	ISL	352		PSE	275		HND	340		MDG	450
	IRL	372		QAT	634		JAM	388		MWI	454
	ITA	380		SAU	682		MEX	484		MLI	466
	LVA	428		SYR	760		MSR	500		MRT	478
	LIE	438		TUN	788		NIC	558		MUS	480
	LTU	440		TUR	792		PAN	591		MOZ	508
	LUX	442		ARE	784		PRY	600		NAM	516
	MLT	470		YEM	887		PER	604		NER	562
	MCO	492		ESH	732		KNA	659		NGA	566
	MNE	499	OAS	AFG	4		LCA	662		REU	638
	NLD	528		BGD	50		VCT	670		RWA	646
	NOR	578		BTN	64		SUR	740		STP	678
	POL	616		COK	184		TTO	780		SEN	686
	PRT	620		FJI	242		TCA	796		SYC	690
	ROU	642		PYF	258		URY	858		SLE	694
	SMR	674		KIR	296		VEN	862		SOM	706
	SRB	688		MDV	462		GUF	254		ZAF	710
	SVK	703		MHL	584		PRI	630		SDN	729
	SVN	705		FSM	583		VIR	850		SWZ	748
	ESP	724		MNG	496	SEA	BRN	96		TGO	768
	SWE	752		NRU	520		KHM	116		UGA	800
	CHE	756		NPL	524		PRK	408		TZA	834
	MKD	807		NCL	540		IDN	360		ZMB	894
	GBR	826		NIU	570		JPN	392		ZWE	716
	GRL	304		PAK	586		LAO	418	USA	USA	840
	SJM	744		PLW	585		MYS	458			
	IMN	833		PNG	598		MMR	104			
	JEY	832		WSM	882		PHL	608			
	GGY	831		SLB	90		KOR	410			
				LKA	144		SGP	702			
				TKL	772		THA	764			
				TON	776		TLS	626			
				TUV	798		VNM	704			
				VUT	548		TWN	158			