

Transforming biodiversity governance through improving evidence and diversifying values of nature in scenarios and models

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Abstract

The Kunming-Montreal Global Biodiversity Framework (KM-GBF) sets ambitious 2030 targets and 2050 goals but lacks the scenario and modelling infrastructure needed to link national actions to global outcomes. Tracing the evolution of biodiversity scenarios and models, from Limits to Growth, the Millennium Ecosystem Assessment and the SSP-RCP framework to the Nature Futures Framework (NFF), we review 65 modelling resources spanning biodiversity, ecosystems, ecosystem services, drivers and integrated systems across terrestrial, freshwater and marine realms. We assess their capacity to integrate the state of nature relevant to KM-GBF Goals and the drivers and interventions of the 2030 action targets to assess whether models can inform the National Biodiversity Strategies and Action Plans and National Reports for progress tracking and policy evaluation. We also analyse scenario analysis capabilities and how models reflect diverse values of nature from global to subnational scales with policy-relevant applications. We find that substantial technical capacity exists in the reviewed models to inform KM-GBF using the NFF. However, models have limited capacity in detecting changes in nature and attributing those changes to specific drivers or interventions. We identify three priorities for building a coherent evidence infrastructure: (1) integrating scenario analysis across the full KM-GBF policy cycle across scales; (2) standardizing causally informed monitoring and modelling to generate conservation evidence; and (3) strengthening cross-sectoral, multilevel coordination among scientific and policy communities. Coordinated, interoperable model development alongside continued innovation, sustained by institutional commitment and capacity-building, can transform the KM-GBF from an aspiration into implementation mechanisms for realizing equitable nature-positive futures.

Keywords: biodiversity governance, scenarios, models, indicators, Global Biodiversity Framework, Nature Futures Framework, detection-and-attribution, multiscale, intersectoral, interoperability

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Frameworks, typologies, and glossary

Kunming-Montreal Global Biodiversity Framework (KM-GBF)

- **Goals:** The 2050 Vision of ‘Living in Harmony with Nature’ is operationalised through four 2050 ‘outcome’ goals. Successful implementation will result in halting and reversing ecosystem loss and species extinction (Goal A), ensuring biodiversity’s sustainable use so that nature’s contributions to people are maintained (Goal B), promoting fair and equitable sharing of benefits from genetic resources (Goal C), and securing sufficient financial, technical, and capacity-building means to implement the framework (Goal D). (CBD Secretariat, 2022)
- **Targets:** Twenty-three short-term action targets have been formulated to be achieved by 2030, grouped around three themes of addressing biodiversity loss through reducing direct threats to biodiversity (T1-8), human-centred management (T9-13), and enabling conditions including finance, knowledge, and governance (T14-23). (CBD Secretariat, 2022)
- **Monitoring Framework:** In the KM-GBF, the Monitoring Framework is the official set of indicators adopted to track progress toward the KM-GBF’s Goals and Targets. (CBD Secretariat, 2022)

Modelling: Qualitative or quantitative representation of key components of a system and of relationships between these components. (IPBES, 2026)

- **Explanatory model:** A data analysis method that uses existing observations of a biodiversity response variable and relevant predictor variables to generate or fit a relationship. (Ferrier et al., 2017)
- **Predictive model:** An activity that presumes the relationship between variables is already known and combines it with observed or estimated predictor values to forecast unknown values of the response variable. (Ferrier et al., 2017)

Prediction: A projection is branded “most likely” to become a forecast prediction, often obtained using deterministic models, outputs of which can enable some level of confidence to be attached to projections. (IPBES, 2026)

Projection: A projection is a potential future evolution of a quantity or set of quantities, often computed with the aid of a model. Unlike predictions, projections are conditional on assumptions concerning, for example, future socio-economic and technological developments that may or may not be realised. (IPCC, 2026)

Measures

- **Variables:** Standardized environmental, climatic, and biological measurements that help characterise their conditions across time, space and level. (Pereira et al., 2013)
- **Indicator:** A quantitative or qualitative factor or variable that provides a simple, measurable and quantifiable characteristic or attribute responding in a known and communicable way to a changing environmental condition, to a changing ecological process or function, or to a changing element of biodiversity. (IPBES, 2026)

Detection: A process of demonstrating that a biodiversity measure has changed relative to an undisturbed baseline or statistical model-derived expectation. (Gonzalez et al., 2023a)

Attribution: Evaluating the relative contributions of multiple potential causal factors to a detected biodiversity change, assigning statistical confidence to the causal models used. (Gonzalez et al., 2023a)

Detection and attribution framework: Detection and attribution framework operates through an iterative five-step workflow comprising causal modelling, observation, estimation, detection, and attribution. (Gonzalez et al., 2023a)

Counterfactual analyses: Counterfactual analysis aims to establish the difference between the (intended or unintended) outcomes of an intervention and the outcomes if no action had been taken. (Coetzee and Gaston, 2021)

Scenario analyses

- **Retrospective scenarios:** Retrospective scenarios assess the extent to which outcomes actually achieved by an implemented policy match those expected based on modelled projections, thereby informing policy review. (IPBES, 2026)
- **Exploratory scenarios:** Scenarios that examine a range of plausible futures, based on potential trajectories of drivers - either indirect (e.g., socio-political, economic and technological factors) or direct (e.g., habitat conversion, climate change). (IPBES, 2026)
- **Target-seeking scenarios:** Scenarios that start with the definition of a clear objective, or a set of objectives, specified either in terms of achievable targets, or as an objective function to be optimized, and then identify different pathways to achieving this outcome (e.g., through backcasting). (IPBES, 2026)
- **Policy-screening scenarios:** Scenarios used in ex-ante assessments, to forecast the effects of alternative policy or management options (interventions) on environmental outcomes. (IPBES, 2026)

Spatial planning: Spatial planning is a method or process for analysing and allocating the spatial and temporal distribution of human uses and activities in a given area, in order to achieve various social, economic and ecological objectives. (CBD Secretariat, 2022)

Nature Futures Framework (NFF) is a flexible, heuristic tool and modelling state-space developed by the IPBES Task Force on Scenarios and Models for scenario analyses.

- **Intrinsic values** ('Nature for Nature'): The value inherent to nature, independent of human experience and evaluation, and therefore beyond the scope of anthropocentric valuation approaches. (IPBES, 2026)
- **Instrumental values** ('Nature for Society'): The value attributed to something not as an end in itself but as a means of achieving a particular end. (IPBES, 2026)
- **Relational values** ('Nature as Culture'): The values that contribute to desirable relationships, such as those among people or societies, and between people and nature, as in Living in harmony with nature. (IPBES, 2026)

1. History of global biodiversity governance, assessments and scenarios

The Convention on Biological Diversity (CBD), opened for signature in June 1992 and entering into force in December 1993, established three objectives: biodiversity conservation, the sustainable use of biodiversity, and the fair and equitable sharing of benefits arising from genetic resources (United Nations, 1992). With the Global Biodiversity Framework (GBF) as its global governance framework for biodiversity, the Global Biodiversity Outlooks, now replaced by the 'Global Review of Collective Progress', have long functioned as a global-level diagnostic tool, illustrating the gap between current trends of commitment and globally agreed Convention targets (Figure 1). The implementation of GBF has relied primarily on National Biodiversity Strategies and Action Plans (NBSAPs) and National Reports (NRs).

However, critical science-policy gaps exist with the lack of formal mechanisms that link the NBSAP (or national target-setting) and the GBF (or global target-setting) development with scenario analysis or quantitative projections. These evaluations help inform national policies design by identifying where to prioritise protection, restoration, and sustainable use and trade-offs and synergies with other national goals based on the assessment of biodiversity change, ecosystem degradation, ecosystem services values, and human needs, for instance, considering projected climate change. Furthermore, there are no formal assessments within the CBD that evaluates whether the actions implemented by the Parties (i.e., nations, state-actors) are successfully contributing to halting and reversing biodiversity loss for the world to achieve the 2050 'Living in Harmony with Nature' vision.

The establishment of the Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services (IPBES) in 2012 marked an important step towards strengthening the science-policy interface for biodiversity to build rigorous evidence bases for biodiversity governance through knowledge synthesis and capacity building (Larigauderie and Mooney, 2010). The IPBES methodological assessment on scenarios and models of biodiversity and ecosystem services conducted the first comprehensive evaluation of biodiversity modelling and scenario analysis capabilities for policy support (IPBES, 2016). The assessment highlighted important advancements and limitations, including incomplete representation of drivers of biodiversity loss, limited treatment of ecological interactions, substantial uncertainties in models and scenarios, and the scarcity of scenarios exploring alternative policy and management options (Aschi et al., 2026; Rosa et al., 2017; Rounsevell et al., 2021; Weiskopf et al., 2022).

The intellectual foundations of global biodiversity scenario modelling predate the Rio Conventions by two decades. The Club of Rome's *Limits to Growth* introduced the World3 system dynamics model, an influential template for integrated, multi-variable, long-term environmental projections that later shaped major environmental scenario exercises (Meadows et al., 1974). Decades later, the integrated assessment models (IAMs) started to develop that represent multiple domains of the global system and quantify future scenarios (Rotmans, 1990). For example, in the terrestrial realm, the IMAGE modelling framework (Stehfest et al., 2014) provided a platform linking socioeconomic drivers (e.g., agricultural production, energy production) to ecosystem outcomes (e.g., mean species abundance, MSA), operationalized through GLOBIO using empirical pressure-impact relationships globally (Alkemade et al., 2009). A few complementary modelling advanced. Correlative and

empirical models, including species-area relationships (SAR, [MacArthur and Wilson, 2001](#)), species distribution (SDM, [Guisan and Thuiller, 2005](#)) models to compositional and community levels including generalized dissimilarity model (GDM, [Ferrier et al., 2007](#)) and local-scale biodiversity databases ([Hudson et al., 2014](#)). Process-based models also advanced, including the LPJ dynamic global vegetation models ([Sitch et al., 2003](#)) that simulates vegetation and carbon cycle response to climate and the Madingley model ([Harfoot et al., 2014](#)) that represent whole ecosystem dynamics from the functional trait and metabolic processes of organisms. In the marine realm, Ecopath ([Polovina, 1984](#)) offered a computationally efficient template for representing marine foodweb, later extended through EcoSim and Ecospace ([Christensen and Pauly, 1992](#)) with temporal and spatial dynamics, respectively. The global EwE/Ecopath-based ocean model ([Alder et al., 2007](#)) was then developed as global marine IAM-equivalent projecting biomass and profits under different fishing efforts and socioeconomic drivers with EcoOcean ([Coll et al., 2020](#)) integrating spatial-temporal foodweb dynamics. Today, a wide variety of terrestrial, freshwater and marine biodiversity and ecosystem models exist.

In 2005, the Millennium Ecosystem Assessment (MA, 2001–2005) provided the first systematic global effort to explore future biodiversity and ecosystem services under alternative scenarios linked explicitly to land use and socioeconomic changes. Its four scenarios combined participatory storyline with quantitative modelling of land use, freshwater, fisheries, and biodiversity indicators (MA, 2005).

Since the MA, biodiversity science has relied primarily on scenarios developed by the climate research community, which informs the Intergovernmental Panel on Climate Change (IPCC) ([van Vuuren et al., 2014](#)). The Representative Concentration Pathways (RCPs, radiative forcing trajectories) and the Shared Socioeconomic Pathways (SSPs, socioeconomic futures defined by differing challenges to climate mitigation and adaptation with no further climate policies from the present day) were introduced. The SSP-RCP scenario framework was supported by qualitative storylines and quantitative projections of population, GDP, energy, land use, among others ([O'Neill et al., 2017](#); [Riahi et al., 2017](#)), and became the dominant framework for global environmental modelling in the past two decades, including the biodiversity impact assessments ([O'Neill et al., 2020](#)).

Despite their widespread adoption, SSP-RCP scenarios do not consider biodiversity policy objectives and only a limited set of socioeconomic futures, mainly driven by differing trends in population, per-capita income and the extension of business-as-usual (e.g., regional rivalry, inequality, fossil-fuelled development). Biodiversity was largely treated as a recipient of changes in climate and land and sea uses ([Popp et al., 2017](#); [Rosa et al., 2017](#)). As a result, biodiversity assessments using the SSP-RCP scenarios only provided limited opportunities to explore options for reversing the trend of loss and towards transformative futures ([Pereira et al., 2024, 2026](#)). This issue persists, and in the latest ScenarioMIP framework that informs the 7th Assessment Report (AR7) of the IPCC aimed to replace the SSP-RCP scenarios to explore more diverse mitigation and sustainability pathways, only a limited set of land conservation policies is considered in the Very Low (VL) emission scenario ([Van Vuuren et al., 2026](#)).

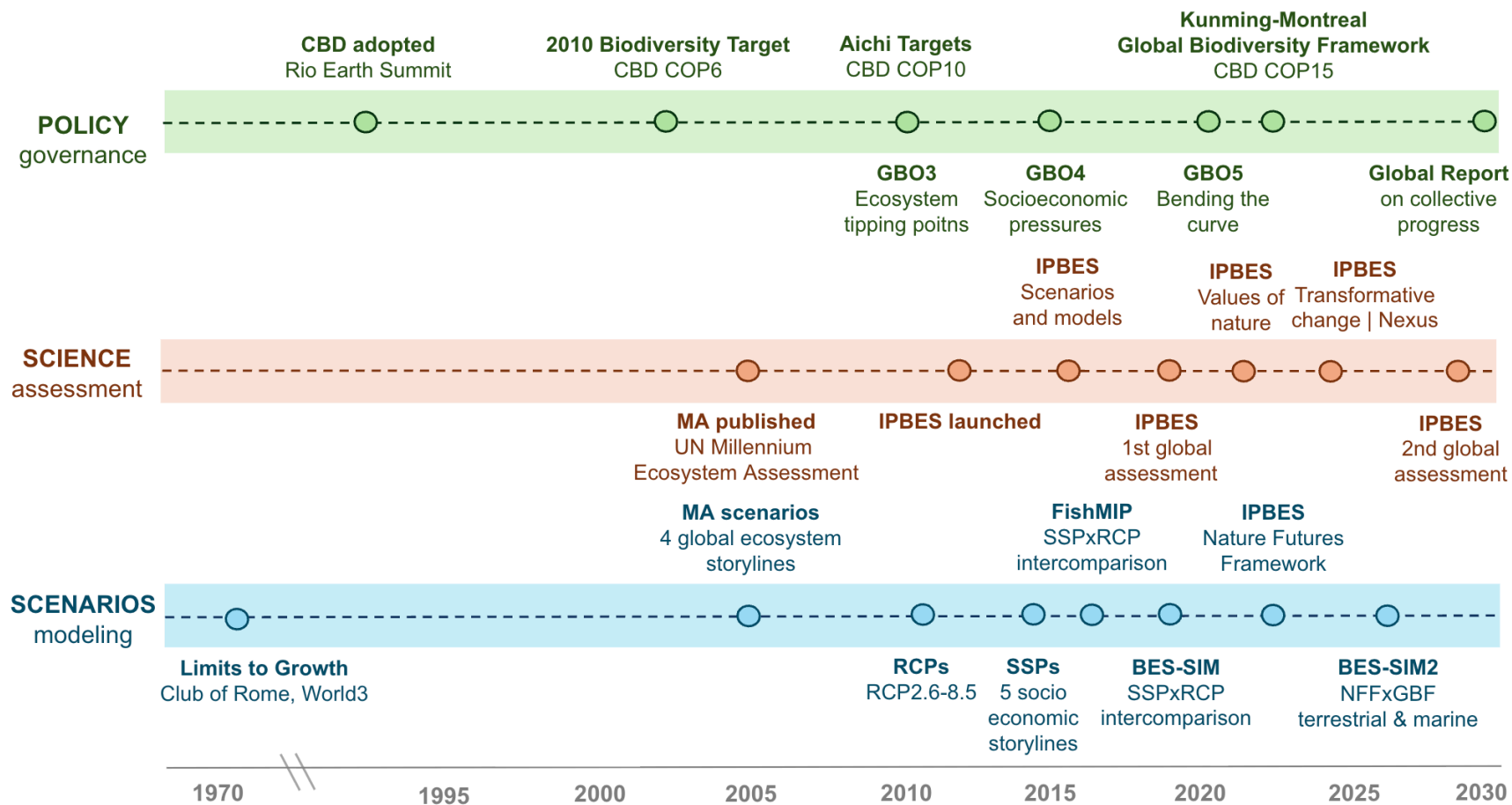


Figure 1. Chronogram of global policy (green), science (orange), and scenario (blue) initiatives focusing partly or in full on biodiversity and ecosystem services. Abbreviations are as follows: CBD = Convention on Biological Diversity; COP = Conference of the Parties; GBF = Global Biodiversity Framework; GBO = Global Biodiversity Outlook; MA = Millennium Ecosystem Assessment; MIP = Model Intercomparison Project; UN = United Nations; IPBES = Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services; IPCC = Intergovernmental Panel on Climate Change; RCP = Representative Concentration Pathways; SSP = Shared Socio-economic Pathways; BES-SIM = Biodiversity and Ecosystem Services Scenario-based Inter-Model comparison; NFF = Nature Futures Framework.

In the scientific collaboration between the IPBES and the IPCC, model intercomparison projects were initiated either as part of the Climate Model Intercomparison Project (CMIP) or independently to inform global assessments and reports. In the marine realm, model intercomparison was developed, in parallel to the initial development of IPBES, with the Fisheries and Marine Ecosystem Model Intercomparison Project (FishMIP) launching in 2013 (Novaglio et al., 2024) and providing the first global intercomparisons by 2019 (Lotze et al., 2019; Tittensor et al., 2017). The FishMIP ensemble suggested substantial trophic impacts from climate change, although, as indicated, the SSP-RCP scenarios do not explicitly provide trajectories of fishing dynamics, highlighting the need for novel scenarios integrating this key driver, which continue to be developed as complements to the SSP-RCP framework (Maury et al., 2025).

In the terrestrial realm, the gaps highlighted in the IPBES scenarios and models assessment (IPBES, 2016) led to the Biodiversity and Ecosystem Services Scenario-based Intercomparison of Models (BES-SIM), which informed the first global assessment of IPBES (IPBES, 2019). The BES-SIM harmonised land-use and climate inputs with three SSP-RCP combinations ranging from low to high climate change and from sustainable to fossil-fuel-based socioeconomic development to facilitate model intercomparisons across ten biodiversity and six ecosystem functioning and services models, with only a subset quantifying climate-change impacts (Kim et al., 2018). The exercise suggested continuing declines in terrestrial biodiversity with declining regulating ecosystem services at the cost of increasing provisioning services by 2050 across the three SSP-RCP pathways with varying magnitudes of change and geographic patterns (Pereira et al., 2024).

A fundamental critique emerging from these scenario and model intercomparison work was that all existing global scenario frameworks describe alternative pathways of human socioeconomic development, with biodiversity as a response variable in impact assessments (IPBES, 2016). In addition, these projects largely extrapolated historical trends and pressures without considering alternative sustainability policy and management options, making biodiversity declines a probable outcome. In addition, other major drivers of biodiversity loss, including resource exploitation, invasive alien species, and pollution, remained at best weakly represented (Andrijevic et al., 2023; Aschi et al., 2026; Kok, 2017; Maury et al., 2025).

One of the community-led initiatives responding to some of these outstanding gaps was Bending The Curve that combined four Integrated Assessment Models (IAMs) with eight terrestrial biodiversity models to explore whether biodiversity loss from habitat conversion could be reversed by 2050 (Leclère et al., 2020). On average, the models suggested that immediate coordinated actions to conserve and restore nature, reduce agricultural demand, and improve agricultural production, would lead to biodiversity trends becoming positive by 2050, however, in the absence of climate change (Leclère et al., 2020). These scenarios build on the SSPs, but complemented those with dedicated assumptions for more ambitious conservation action, including increased protection, restoration of agricultural land to natural ecosystems, and biodiversity-oriented spatial planning over all land (Kok et al., 2023).

In parallel, between 2016 and 2019, the IPBES Expert Group on Scenarios and Models started developing a new scenario framework placing biodiversity centrally through human-nature

relationships lens, explicitly recognising diverse worldviews and values (Lundquist et al., 2017; Pascual et al., 2017). The Nature Futures Framework (NFF) accommodates three complementary value perspectives on nature. 'Nature for Nature' prioritizes intrinsic values where biodiversity thrives independently of human utility, 'Nature for Society' optimizes instrumental values of ecosystem services sustaining human wellbeing, and 'Nature for Culture' centres relational values and diverse ontologies recognizing nature as kin, teacher, and identity (IPBES, 2025a; Pereira et al., 2020). These perspectives are not arranged hierarchically: the NFF acknowledges their mutually inclusive and reinforcing characteristics, and enables exploring how the consideration of plural value perspectives can help address root causes of biodiversity loss (IPBES, 2025b, 2022; Kim et al., 2023). Importantly, the multi-scale ambition of the NFF was initiating a paradigm shift to overcome the 'global bias' in environmental scenarios to offer a flexible framework that can facilitate and bridge applications from local to global scales to inform actions across agencies (Rosa et al., 2017). Formally adopted by IPBES in 2022, the NFF aligns closely with CBD's 2050 vision of 'Living in Harmony with Nature', and shifts biodiversity change from being a passive outcome to being co-determinants for nature positive futures (IPBES, 2025a).

Across this thirty-year development, these initiatives informed the CBD post-2020 GBF, strengthening the links between IPBES and IPCC, and helping to improve collaboration among modelling communities across disciplines and domains. Through them, several trends have emerged. The framing of scenarios is shifting from projection to co-production, with growing attention to values, diverse knowledge systems, justice, and agency (IPBES, 2025a, 2025b, 2022). The representation of biodiversity drivers has broadened beyond land-use and climate change, although major gaps remain in integrating other major drivers explicitly, including resource exploitation, pollution, and invasive alien species in global terrestrial systems (Aschi et al., 2026), dynamic scenarios of drivers beyond fishing for global marine biodiversity change (Maury et al., 2025), and underrepresentation of freshwater realm and cross-realm interactions (Kramer et al., 2023). Further key challenges include moving beyond the assumption of economic growth embedded in sustainability scenarios (Otero et al., 2020), improved representation of interlinkages and feedbacks between drivers (Harrison et al., 2015), the inclusion of biodiversity change as a fully interactive driver in scenarios (Lazurko et al., 2025b), the weaving of Indigenous and traditional knowledge into quantitative workflows (McElwee et al., 2020), and the development of policy- and context- relevant scenarios across scales (Rosa et al., 2017).

2. Modelling action targets and outcome goals of Global Biodiversity Frameworks

Since its establishment in 1992, the CBD has progressively developed global biodiversity targets, from the 2010 Biodiversity Target (Butchart et al., 2010; Mace and Baillie, 2007) to the Aichi Biodiversity targets adopted in 2010 (Tittensor et al., 2014). Parties adopted the Kunming-Montreal Global Biodiversity Framework (KM-GBF) in December 2022, through which the CBD's 2050 vision of 'Living in Harmony with Nature' is operationalised. There are four 2050 'outcome' goals – halting and reversing ecosystem loss and species extinction (Goal A), ensuring biodiversity's sustainable use so that nature's contributions to people are maintained (Goal B), promoting fair and equitable sharing of benefits from genetic resources

(Goal C), and securing sufficient financial, technical, and capacity-building means to implement the framework (Goal D). Twenty-three 2030 ‘action’ targets are grouped into three themes as the levers for change – reducing direct threats to biodiversity (T1-8), human-centred management (T9-13), and enabling conditions including finance, knowledge, and governance (T14-23) (see SI II for the full list).

Parties to the CBD utilize NBSAPs and National Target Templates to set their contribution to the GBF goals and targets, while a Monitoring Framework is used to track progress through a selection of mandatory ‘Headline’ indicators to capture overall trends, supported by voluntary ‘component’ and ‘complementary’ indicators that provide more detailed and context-specific insights into the goals and targets. Parties are to report on these indicators through regular ‘National Reports’, which are then analysed as part of a ‘Global Report’. In reality, parties tend to report primarily on national indicators and headline indicators but neglect others due to resource constraints, their complexity or absence of data or operational indicators (Affinito et al., 2025). To date, the latest CBD Global Report documents government actions related to targets with marginal inclusion of actions taken by non-state actors. When it comes to the goals on biodiversity and ecosystem services outcomes, the Global Report does not indicate whether the actions taken will lead to the achievement of the 2030 mission or 2050 goals (CBD Secretariat, 2026).

Critical science-policy challenges remain in the current landscape of parallel processes without joint mechanisms for evidence infrastructure (Leadley et al., 2022; McGowan et al., 2024; Perino et al., 2022). Achieving global goals requires a whole-of-society approach with national governments, academics, private sectors, civil society, and Indigenous and local communities as transformative agents to co-produce scale- and context-relevant evidence, integrating sources and interweaving knowledges across monitoring systems, environmental assessments, scenario programmes, and conservation practices, that can inform evidence-based actions and their anticipated outcomes on biodiversity to support biodiversity governance (Gonzalez et al., 2023b; IPBES, 2025c, 2025b; Kim et al., 2026a; Moersberger et al., 2024).

To understand the evidence landscape on the modelling resources and to assess their detection and attribution and scenario analyses capabilities in informing the achievement of global biodiversity goals and targets with nature’s value plurality, a semi-systematic, mixed-method review was conducted on a global scale. The database compiled and reviewed in this paper comprises 65 modelling resources that represent biodiversity, ecosystem services and socioeconomic processes relevant to the Goals A (Protect and Restore) and B (Prosper with Nature) of the KM-GBF with some representation of 23 KM-GBF targets, the value perspectives of the NFF, detection and attribution capabilities, with challenges and aspirations (Figure 2), and input requirements and output variables and indicators (Table 1) (see Supplement Information, SI I for the review protocol, II and III for overview of the model database, IV for model description, and Walkden et al. In review for detailed methodology). This review brought models into a living database and modellers into dialogue through workshops and interviews, building bridges and gaining understanding on how each model is used and how biodiversity can be represented or linked to other models (Kim et al., 2025).

Given the broad scope of the KM-GBF, this review prioritized the broad coverage of relevant domains and selective modelling resources based on their relevance to the KM-GBF and NFF, widespread use in science- and science-policy interfaces, and availability of modellers to participate in the study. The domains of models include biodiversity, ecosystems, ecosystem services, land, water, climate, energy, and economy and the methods include statistical/correlative, mechanistic/process-based, expert/knowledge-based, and in the majority of cases, a combination of these approaches. The resulting database is therefore a curated broad-coverage set rather than a comprehensive statistically representative set. It complements existing inventories of models assessed in the IPBES Scenarios and Models Methodological Assessment (IPBES, 2016), the SEEA biophysical modelling guidelines (United Nations Department of Economic and Social Affairs, 2023), and comparative reviews of the models across domains of relevance to KM-GBF (2020-2024) screened in the initial stage of database compilation (Walkden et al. In review). There are four types of modelling resources in the database: 1) models, 2) integrated frameworks with multiple models, 3) model-based indicators, and 4) model output databases. The review explicitly considers these as resources that are and can be used to monitor the KM-GBF through their output indicators (e.g., species richness, species abundance, Species Threat Abatement and Restoration, Living Planet Index), databases that can inform the GBF monitoring framework (e.g., ecosystem and natural capital data products in InVEST, Co\$tingNature, ARIES, and ENCORE databases), or integrative assessment tools that can inform on synergistic actions with minimized tradeoffs (e.g., systems models such as FeliX and DIVERSE).

At the Goal A species-level, extinction risk and abundance are informed by distributional models and pressure-reduction frameworks. At genetic diversity level, models such as SEED (Fournier De Lauriere et al., 2023) provides global genetic intactness mapping, representing a critical frontier. Biodiversity models span multiple realms, taxonomic groups, and drivers: for instance, species distribution models (Guisan and Thuiller, 2005) projecting environmental suitable areas for species, HexSim (Schumaker and Brookes, 2018) simulating spatial population dynamics, LPI (McRae et al., 2017) tracking population trends, GLOBIO (Schipper et al., 2020) providing mean species abundance, PREDICTS (De Palma et al., 2021) predicting biodiversity intactness, and STAR (Mair et al., 2021) assessing threatened species and restoration potential.

At the Goal A ecosystems level, dynamic global vegetation models such as LPJ-GUESS (Smith et al., 2014) predicts ecosystem responses to climate and land-use change while a foodweb models Madingley (Harfoot et al., 2014), Atlantis (Audzijonyte et al., 2019), and EcoOcean (Coll et al., 2020) integrate mechanistic processes across ecosystem functions. Ecosystem resilience to bioclimatic changes can be informed by BILBI's Bioclimate Ecosystem Resilience Index (Hoskins et al., 2020) while changes in the extent of natural ecosystems in vegetation models LPJ-GUESS and FATE-HD (Boulangeat et al., 2014) informing broader land system frameworks such as JULES (Best et al., 2011), LandSHIFT (Schüngel et al., 2022), and LandSymm (Arneth et al., 2023). In turn, the outputs from vegetation and land system models can serve as input to species, ecosystem, and ecosystem services models.

For the Goal B ecosystem services (or nature's contributions to people), InVEST (Sharp et al., 2016) maps impacts on nature's contributions to people to support natural capital investment strategies while model-based data platform ARIES (Villa et al., 2014) uses

Artificial Intelligence (AI) to support stakeholder-informed decision-making, including products from models such as InVEST. Co\$tingNature (Mulligan et al., 2020) is a globally pre-parameterised web-based spatial model for ecosystem-service baselines and scenario and intervention testing which can be applied at national scales and below with no GIS data and low local capacity requirements. Economic models such as EXIOMOD (Bulavskaya et al., 2016) can assess environmental impacts of economic activities, while ENCORE (Kiss-Dobronyi et al., 2021) supports analyzing cross-sectoral nature-related economic risks.

For Targets 1-23 on actions that reduce threats to biodiversity, maintain ecosystem services, and enabling conditions and tools, specialized models provide essential depth for targeted KM-GBF implementation challenges, offering precision and mechanistic understanding within domains that integrated models do not capture fully. For example, TreeMig (Lischke et al., 2026) focuses on forest landscape dynamics under climate change, providing the fine-scale spatial and temporal resolution needed to support Target 2 (ecosystem restoration) and Target 4 (species recovery) in forest systems. It enables forest managers to evaluate species-specific migration corridors and restoration site suitability with a level of taxonomic and ecological detail that broader frameworks cannot provide. Similarly, PLAIA's focus on the impacts of agrochemical production in the ocean provides the sector-specific pollution detail needed to inform Target 7 (pollution reduction), tracing nitrogen and pesticide pathways from manufacturing through to ecosystem contamination. WaterGAP's (Müller Schmied et al., 2021) focus on water resources, flows, and storage supports assessments of freshwater targets (T3, T10, T11) through hydrological processes – including groundwater depletion, seasonal flow regimes, and dam operations – that influence aquatic biodiversity, which remain oversimplified in multi-realm models. These specialized tools are effective for screening policies within specific domains and generating actionable evidence for sectoral interventions that require precision.

For holistic assessments of the KM-GBF, systems and integrated models demonstrate a widely used approach, representing dynamic systems interactions among multiple 'action' targets and 'outcome' goals informing coherent policy analyses with co-benefits and risks. In this model database, 45 models (69%) can work jointly with others, enabling cross-domain integration. System dynamics frameworks such as World3 (Nebel et al., 2024) and JUNIPER (Ioannou et al., 2026) represent cross-sectoral feedbacks among socioeconomic, resource and environmental variables, providing integrated perspectives on their implications for biodiversity while necessarily simplifying biodiversity processes. In the terrestrial realm, integrated models focused on land based sectors can support integrated analysis: e.g., evaluating species diversity, extent of habitat and compositional intactness for climate, biodiversity and food system transformation scenarios (Von Jeetze et al., 2025 with MAgPIE, European Commission, Directorate General for Environment, et al., 2024 with GLOBIOM/iBIOM). These models can also be used for exploratory scenario analysis (e.g., location-specific estimates of economic incentives required to meet area-based conservation and biodiversity targets) and are making steps towards integration of land- and sea-based sectors (Spillias et al., 2026). Models such as SIMPLE-G makes explicit links with the economy, representing land, water and agricultural-input decisions within global markets, and computes the location-specific economic incentives required to meet area-based conservation and biodiversity targets with the implication for food prices (Haqiqi and Hertel, 2025). In the marine realm, DIVERSE-DBEM (Cheung and Oyinlola, 2019) integrates marine

biodiversity, ecosystem services, fisheries, climate change, and socioeconomic dynamics to assess marine biodiversity futures and evaluates the effectiveness and trade-offs of conservation and sustainable-use strategies across sectors and scale.

However, integration imposes critical limitations: computational constraints demand simplified representations of processes that specialized models simulate in greater process-based detail (e.g., forest succession dynamics in MAgPIE versus TreeMig, marine food web complexity in DIVERSE versus EcoOcean). Moreover, the relatively coarse land-use classification and spatial resolution ($\sim 0.5^\circ$ grids equivalent to 55.6km) of global integrated assessment models limit their usefulness for addressing conservation problems at local scales, or related shifts in land management rather than agricultural expansion. Recent developments advance downscaling of global products at fine resolutions (e.g., 300m, 1km); however, their accuracy depends highly on the underlying data and assumptions that inform global models and most often do not reflect the local and national context or reality. Most critically, models focus largely on provisioning and regulating ecosystem services, with relational values or cultural services represented in only 25% of models given the local specificity, and a limited representation of the heterogeneity of human agency. As a result, equity dimensions that are central to Targets 13, 21, 22, and 23 are largely underrepresented in global models. Well-designed participatory modelling with a strong stakeholder-base can improve the engagement and presentation of Indigenous and local knowledge, diverse value perspectives, the whole-of-society and human rights-based approaches enshrined in Section C of the KM-GBF (Schaldach et al., 2026). Consequently, the current landscape of model integration remains strongest in representing biophysical-economic system dynamics, while socio-cultural dimensions essential for just and legitimate biodiversity governance received limited attention.

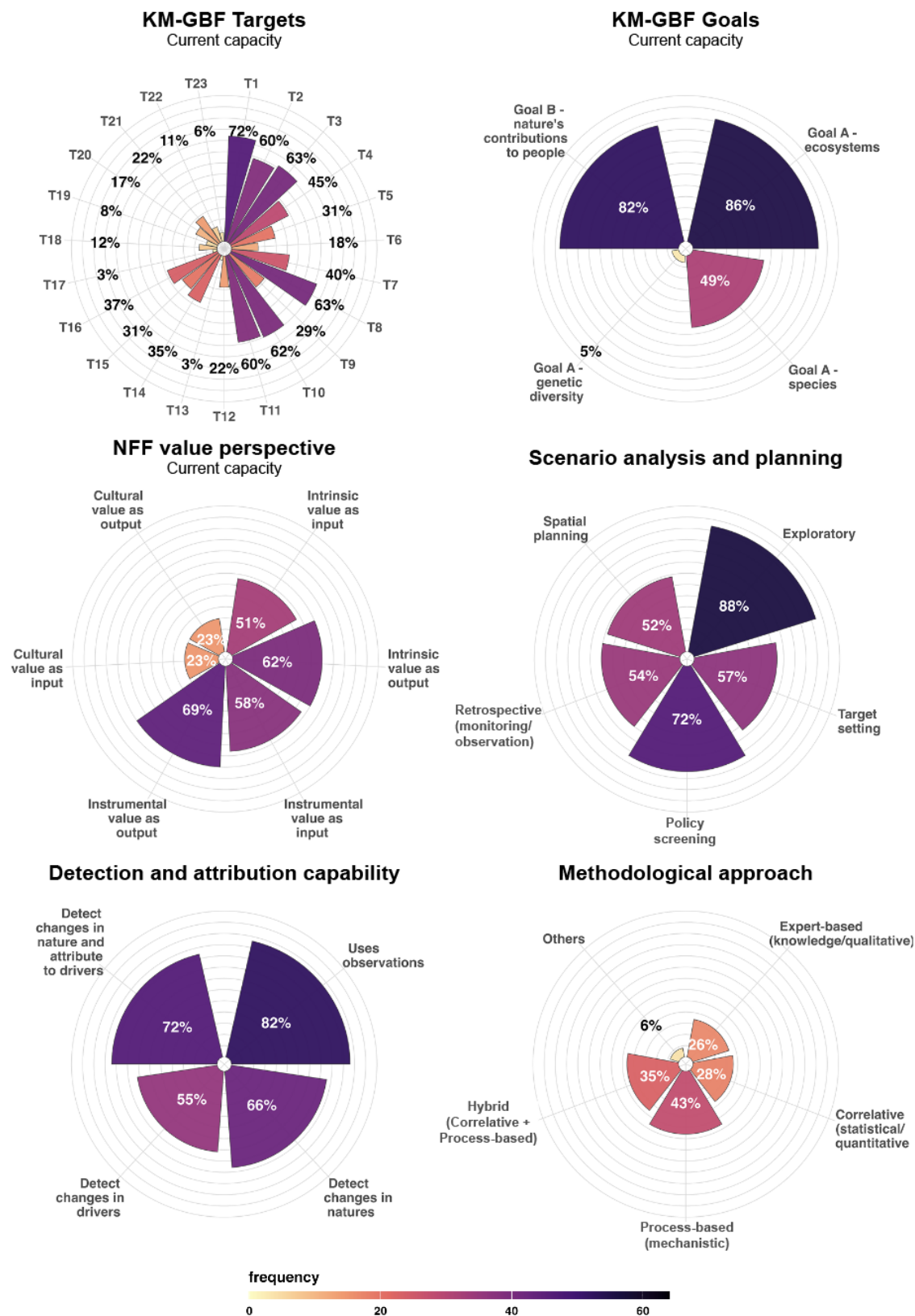


Figure 2. Descriptive statistics of 65 models in the database on main research questions.

Table 1. Key model input and outputs* relevant for KM-GBF across 65 model database in the form of variables, indicators and indices.

Model input requirements	Model outputs relevant for KM-GBF Targets	Model outputs relevant for KM-GBF Goals
Climate	Targets 1 Spatial planning & management	Goal A Genetic diversity
Meteorology / weather	Protected area, land use, conserved areas	Medicinal, biochemical, genetic resources
Temperature	Protected area representativeness and connectedness	Goal A Species
Precipitation	Bioenergy production	Extinction risk or rate
Cloud, radiation	Agricultural, urban, industrial land management	Biodiversity Vulnerability Index
Nature	Target 2 Ecosystem restoration	Area of habitat for species
Biotic factors	Ecological footprint per capita	Species richness
Abiotic factors / biogeography	Target 3 Protected / conserved areas	Keystoneness index
Soil properties	Area based protection measures to reduce emission	Species Threat Abatement and Restoration
Species demography / life history	River discharge surface runoff, nutrient in streams	Goal A Ecosystems
Species distribution	Changes in forest areas	Biomass (No. of trees, by functional group)
Species traits	Targets 4–5 Species recovery & Wildlife	Gross / Net primary productivity (GPP, NPP)
Ecosystem structure and conditions	Climate impact on species distribution	Mean species abundance
Baseline state / reference area	Potential climate and habitat suitability for species	Area of natural ecosystems
Biodiversity trend and response data	Species Threat Abatement and Restoration (STAR)	Mixed trophic level impact
Ecological footprint	Biodiversity vulnerability index	Biodiversity Habitat Index
People / Economy	Change in economically important species	Habitat loss, fragmentation
Human population density	Change in culturally important species	Ecosystem connectivity
Agriculture traits	Target 6 Invasive Alien Species	Bioclimatic Ecosystem Resilience Index
Demands / supply	Spread of IAS	Intactness (biodiversity, ecosystem)
Trade/stocks and flows, prices	Target 7 Pollution	Goal B Nature's contributions to people
Gross domestic product (GDP)	Generic waste production	Human health
National accounting data	Fertilizer, pesticides	Water use
Perceived condition of human nature systems	Nitrogen deposition, leaching, runoff	Nitrogen runoff
Service proportional human welfare	Phosphorous erosion, leaching, runoff	Water regulation and quality
Spatial pressures	Soil carbon, removal, erosion control	Pollination
Water use	Soil formation, protection, decontamination	Crop and livestock productivity
Mariculture sites	Concentration of major pollutant	Pest and pathogens regulation
Protected areas	Change in carbon pools	Carbon pools
Land use	Damage to ecosystems	Heat fluxes
Agricultural yields	Target 8 Climate	Climate regulation
Food per capita	Temperature	
Pollution and emission	Precipitation	
Methodological requirements	Climate regulation, carbon storage	
Baseline conditions	Solar radiation, humidity, air pressure	
Statistical relationships	Heat fluxes	
Thresholds as boundary conditions	CO2 concentration, GHG emission	
Local context and knowledge	Bioclimatic Ecosystem Resilience Index	

*Some model outputs are input to other models in this database (e.g., temperature into biodiversity models, protected area into land models)

3. Improving biodiversity evidence linking monitoring to modelling futures

As of August 2026, 89 of 196 Parties have not submitted an NBSAP aligned with the KM-GBF and 24 Parties have not submitted National Targets at all, and 56 Parties have not submitted National Report to detail progress made against their targets. Even within those submitted, many lack clear evidence of the effectiveness of intended interventions and do not cover all elements of the targets they contribute to (CBD Secretariat, 2026; Immerzeel et al., 2026). This suggests that with only four years left to achieve the 2030 targets, a sizable proportion of countries still lack a comprehensive and credible plan towards achieving KM-GBF. Parties have cited *data gaps, lack of technical capacity, complexity of the Framework, fragmented data and information, and challenges with cross-sectoral coordination* as key challenges in the preparation of NBSAPs and National Reports for nearly all of the targets in the monitoring framework (CBD Secretariat, 2026).

A key limitation of the current monitoring architecture of the KM-GBF and its reporting tools (NBSAPs, NRs) is temporal incoherence and disconnect. The KM-GBF sets global targets and goals to achieve towards 2030 and 2050 respectively within a given decade. It is forward-looking. However, the NBSAPs rarely adopt a scenario-based approach to connect near-term action targets to the likelihood of achieving the long-term 2050 biodiversity goals. Similarly, countries report through the National Reports on progress within a given decade but do not evaluate if past actions (e.g., 2000-2010) have contributed to biodiversity progression (e.g., 2020-2030), considering the time lag between implementing policy and observing its ecological impact. As a result, neither the NBSAPs nor National Reports operate with evidence to measure conservation effectiveness or set future targets based on evidence-based projections. Both function as simple ‘monitoring’ tools rather than as mechanisms for coordinated and effective conservation action.

Detection and attribution science forms the foundation of biodiversity evidence base by establishing causal links between environmental drivers and observed biodiversity changes, enabling a rigorous evaluation of policy and management essential for KM-GBF implementation (Dudney et al., 2025; Gonzalez et al., 2023b; Schrodtt et al., 2025; Tekwa et al., 2023). Detection involves identifying biodiversity changes relative to baselines or null models, while attribution establishes the causal contribution of one or more drivers to detect changes using quantitative statistical methods, process-based analyses, experiments, or qualitative inference based on ecological theory and multiple lines of evidence. Thus, detection and attribution serves a dual capacity critical in tracking the progress toward global biodiversity outcomes and designing interventions that can be effective based on best available evidence (Figure 3). Progress monitoring through National Reports and future planning through NBSAPs fundamentally depends on this capacity.

Retrospective analyses combining observations and models can assess whether observed changes are attributable to exogenous drivers independent of interventions – distinguishing policy success from unusual external pressures with empirical evidence. This attribution is essential for adaptive management for adjusting strategies based on evidence of what worked, what failed, and why. Ex-post studies leveraging methods for causal inference and policy evaluation (such as Grupp et al., 2026) can serve a double purpose: they can generate

evidence on the actual impacts of conservation interventions, thereby helping to identify effective policy levers, while strengthening the empirical grounding of (behavioural responses in) forward-looking models and scenarios. Detection and attribution frameworks are being woven into national monitoring and research programmes (Seaton et al., 2023) and global model intercomparison projects (Blanchard et al., 2024) with advanced development in climate science that can inform biodiversity science (Dudney et al., 2025).

This review distinguishes two modes of model application: explanatory and predictive. Explanatory models detect and attribute biodiversity changes to drivers and build and calibrate predictive models (Ferrier et al., 2017). Predictive models project the estimated plausible changes in biodiversity expected to result either from implemented actions (thereby informing monitoring) or from alternative policies and actions yet to be implemented (thereby informing monitoring). Models can be used in both ways. Explanatory models ideally underpin predictive models, with tested and attributed driver relationships that give projections a rigorous, evidence-based foundation beyond correlation alone. Detection establishes that a measured change in biodiversity has occurred relative to a baseline or counterfactual while attribution assigns statistical confidence to the causal drivers of that change (Gonzalez et al., 2023b; Schrodtt et al., 2025). This dual role of modelling – as a basis for both explanation and prediction – underlies the whole-landscape framework of KM-GBF across monitoring and planning.

Across the 65-model KM-GBF database, detection and attribution capacity exist but is incomplete and limited: 51 models (78%) reported to detect changes in nature (e.g., species abundance, ecosystem condition) and 47 models (72%) detect changes in drivers (e.g., land use, climate, pollution) partially or fully while 36 models (55%) claim detection and attribution linking nature's changes to specific drivers. Forty-one models (63%) use observation data 28 models (43%) regularly update the model with observation data. Attribution requires a combination of capabilities in models: causal inference through observation data, process-based causality built in the model structure, informed by counterfactual analyses for effect measures. However, most models in this review database do not fully demonstrate this capacity.

The dominant limitation is not essentially in modelling methods but in data infrastructure: PREDICTS, LPI, and GLOBIO each identify the absence of simultaneous, co-located driver-and-response monitoring as the binding constraint – biodiversity state and pressure data are typically collected separately, in different places or at different times, making causal attribution difficult even with the analytical capacity. This is compounded by coarse spatial resolution data (cited by 8 models including BILBI, MAgPIE, SIMPLE-G) and a lack of independent validation data for confirming accuracy outside the calibration set (5 models including PREDICTS, EcoOcean, TreeMig). These challenges are particularly great at the site level where remote sensing proxies are weakest. Collectively, these findings suggest that closing the detection-attribution gap depends on coordinated investment in co-designed monitoring systems between science and policy communities (or data producers, custodians and funders) that capture drivers and biodiversity responses together, at matching resolution and frequency (Table 2).

Progressing detection and attribution capabilities in biodiversity science ultimately requires partnership between monitoring, modelling, and policy communities developing sampling

protocols that are achievable, funded, and deliver primary purposes alongside scenario and policy needs. Harmonizing semantics in data, models, and their management systems across domains with the assistance of AI can be a pursuable avenue to ensure that models and data are Findable, Accessible, Interoperable and Reusable (FAIR) to support knowledge integration and evidence synthesis for science and policy including the IPBES and IPCC reports, System of Environmental-Economic Accounting (SEEA) national accounting systems, and other nature positive initiatives across public and private sectors (Gil et al., 2026; Immerzeel et al., 2026; United Nations, 2021). Modelling can reciprocally address data gaps by providing insights into complex causal pathways linking drivers to observed change and directly supporting targeted setting and monitoring, informing the design of decadal KM-GBF and its implementation through interoperable and adaptable NBSAPs and NRs.

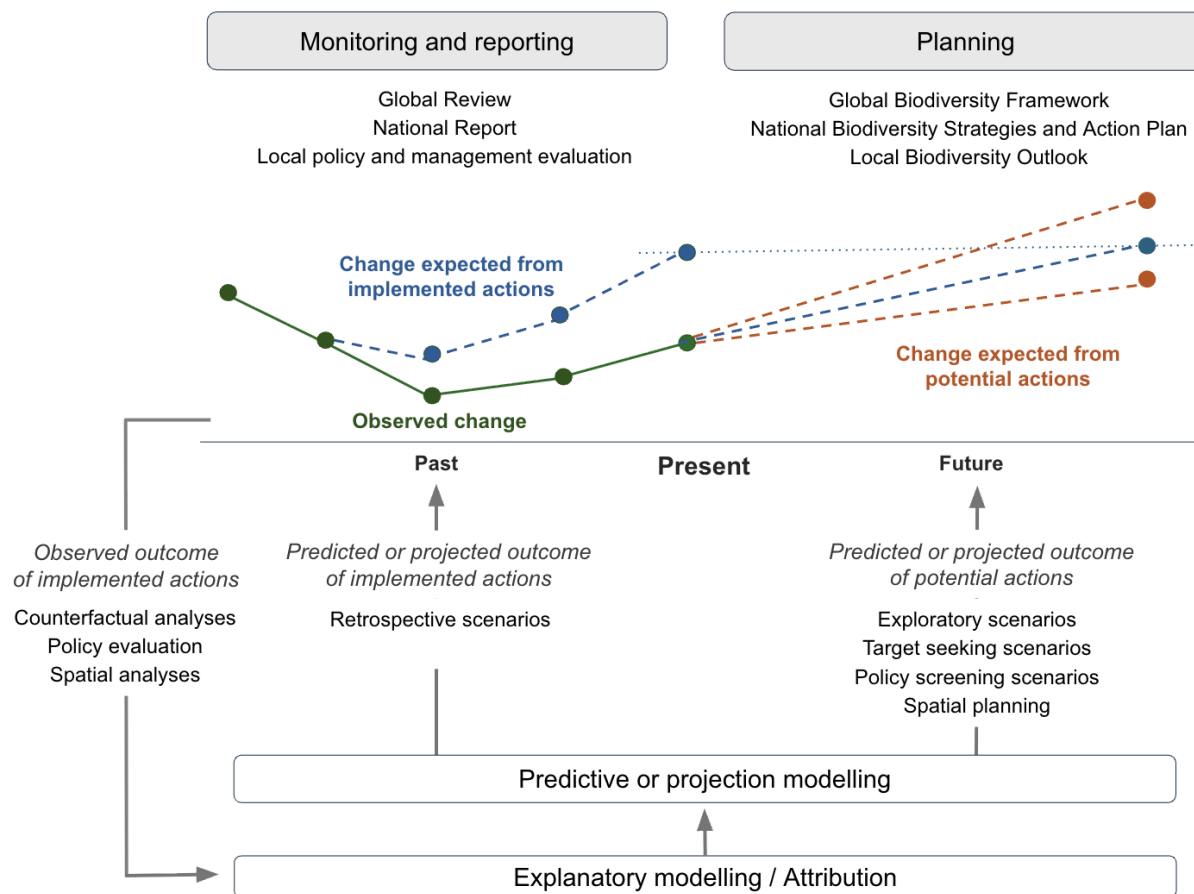


Figure 3. Throughout the policy cycle, reporting is conducted from local to national scales, aggregated globally to improve data interoperability and rigour and to enable scale and context specific use. For retrospective reporting, Global Reviews, National Reports and Policy Evaluations track progress and evaluate interventions. For prospective planning, the Global Biodiversity Framework, NBSAPs and National / Local Biodiversity Outlooks provide context on how the targets will be implemented and tracked. Along this entire process, models are used to support retrospective and prospective analyses with evidence generated from multiple knowledge systems (adapted from Ferrier, 2026).

Table 2. Key data and methodological gaps in models and potential solutions

Data and methodological gap	Description of challenges	Solutions
Time series biodiversity and ecosystem services data (<i>KM-GBF Target 20-21 biodiversity monitoring and technical cooperation</i>)	51 models flag improved data availability as primary development constraint	Long term ecological monitoring, standardization of monitoring systems, global data governance
Spatial resolution mismatch and groundtruthing models (<i>KM-GBF Target 1-3 spatial planning and prioritization</i>)	Coarse resolution (e.g., 0.5°) of global models vs. fine-scale data needs for local implementation	Scale-relevant model use, joint modelling of systems and specialized models, access to data, data interoperability across scales, cross-scale modelling via nesting or shared input
Uncertainty in model parameterization with coarse generalized extrapolations (<i>KM-GBF Targets 1-8 spatial planning and reducing threats, 20-21 monitoring capacity</i>)	Statistical relationships need expanded empirical studies across taxa, realms, and biogeographic regions to reduce bias/uncertainty	Meta-analyses and evidence synthesis of empirical studies, standard review protocol (e.g., ROSE, PRISMA)
Data and infrastructural gap in behavior, institutional, social and cultural dimensions of models (<i>KM-GBF Target 14-23 enabling conditions and instruments</i>)	Data and parameters rely on fragmented survey, correlational data, or assumptions rather than comprehensive data	Systematic monitoring of socio-cultural and institutional governance data (e.g., FAO, national administrative data)
Integration of Indigenous & local knowledge following the CARE principles (<i>KM-GBF Target 22 on IPLC, Goal C on equitable benefit sharing</i>)	Requires engagement and translation capacity (e.g., participatory modelling), respecting knowledge and data sovereignty	Engagement of IPLC through the entire process of monitoring, scenario design, modelling, and policy development and implementation

4. Scenario analyses with nature's value plurality in anticipatory governance

A central challenge for multilateral biodiversity action is translating global targets into nationally-relevant actions which are collectively achievable, sufficient to deliver desired global outcomes, and capable of being monitored and reported against. The KM-GBF employs a theory of change by which achieving the 2030 targets is assumed to result in the achievement of the 2030 Mission, as a necessary prerequisite to achieving the 2050 goals and Vision (CBD Secretariat, 2022). However, no comprehensive analysis exists demonstrating what is achievable, necessary or sufficient for achieving the targets, mission or goals at either the global or national levels, including whether this theory of change holds true. This risks delaying implementation while such an understanding is developed, and risks implementation failing to achieve the intended outcomes. Most fundamentally, we end up reporting and monitoring individualized actions without the understanding of whether as a nation or globally are on progressive pathways.

Scenarios and models can help to address some of these challenges by supporting planning and decision-making by exploring alternative pathways, assessing policy options and

evaluating potential outcomes. In accordance with the scenario types defined in the IPBES Scenarios and Models Methodological Assessment (IPBES, 2016), we evaluated model capabilities across five scenario types aligned with different stages of the policy cycle (Kim et al., 2023): 1) exploratory scenarios, which examine plausible futures based on alternative driver trajectories and support agenda-setting (Lazurko et al., 2025a); 2) target-seeking scenarios, which identify intervention pathways towards agreed goals and inform policy design (Van De Ven et al., 2026); 3) policy-screening scenarios, which compare the outcomes of alternative interventions and support implementation (Leclère et al., 2020); 4) retrospective evaluation scenarios, which evaluate past policies to identify gaps between objectives and outcomes (Tittensor et al., 2014); and 5) spatial planning as a cross-cutting application that can draw on other scenario types to support across policy stages given importance to place-based biodiversity conservation (GEO BON, 2026; United Nations, 2026).

Diverse societal actors, including government, scientific communities, civil society organizations, and private sector, can contribute to participatory scenario development through co-design of visions, pathways, and evidence infrastructure that enhance the incorporation of diverse worldviews, plural values, and knowledge systems. This multi-actor and multi-evidence based approach is essential considering that the current modelling capacity underrepresents cultural and relational perspectives, particularly of Indigenous People and local communities that are essential for context-relevant and implementable actions and inclusive and equitable outcomes central to the KM-GBF. Further, integrating diverse values of nature in the NFF – intrinsic, instrumental, and relational values – allows different societal priorities to be considered for more fair and just future pathways. This includes government concerns regarding agricultural productivity and food security (instrumental), Indigenous Peoples’ traditional management practices (relational), and conservation priorities of biodiversity protection and ecosystem resilience (intrinsic), which can compete but also synergize.

The NFF demonstrates how qualitative storylines and quantitative modelling can be iteratively developed and used (IPBES, 2025a; Okayasu et al., 2025). Vision and pathway storylines articulate diverse societal aspirations: ‘Nature for Nature’ scenarios can prioritize protected area expansion with reduced demand for products associated with habitat conversion. Models operationalize these ambitions through conservation targets such as 30% protection under (KM-GBF T3) and dietary shifts that reduce agricultural land pressure (Von Jeetze et al., 2025). ‘Nature for Society’ scenarios can modify demands for food, fibre and housing while maintaining provisioning services. Models translate these objectives through ecological intensification and constrained service flows (Godfray et al., 2010). ‘Nature for Culture’ scenarios can employ spatial layers identifying culturally valued landscapes developed through stakeholder consultations (Dou et al., 2023). Models integrate these by preventing conversion of sacred sites, traditional use areas, or ceremonial landscapes into used land. These scenarios establish normative targets and intervention logics that models can operationalize through parameter settings and constraints (Sieber et al., 2026).

Models in the database show varying capacities to represent these value perspectives at input and output levels. Across the database, 33 (51%) and 39 (60%) models can represent

intrinsic values (e.g., species persistence, extinction risk, ecosystem intactness), 38 (58%) and 45 (69%) models represent instrumental values (e.g., provisioning, regulating, and material ecosystem services), but only 15 (23%) and 16 (25%) models represent relational values (e.g., spiritual, aesthetic, identity-based connections to nature) at the input and output level respectively (Table 3). Aspirationally, models identify incorporating cultural services, traditional/Indigenous knowledge, and non-material values as a development priority. Closing this gap will require new data infrastructure, including culturally significant species, participatory or co-produced knowledge datasets compliant with CARE principles, and scenario co-development that embeds relational values throughout the entire quantitative to qualitative translation process.

Models are being used jointly in simulating NFF scenarios. At the global level, agenda setting scenarios can inform the development of GBF with achievable targets identified (Strassburg et al., 2020). For example, the BioFutures project used the LandSyMM joint modelling framework to simulate global land use futures under the NFF scenarios (UNEP-WCMC, 2026). Each of the scenarios achieved the 2030 targets but differed in their configurations of trade, governance, and societal values. Outputs from PREDICTS, Madingley and InVEST based on these projections suggest that we need increased ambition in the post-2030 targets to meet the 2050 goals in the KM-GBF.

At the national level, policy-screening or target-seeking scenarios can be used in NBSAP development to identify intervention portfolios using nationally calibrated models, data and local knowledge. The RESTORE+ project used a nationally adapted GLOBIOM/iBIOM model to assess the biodiversity and wider environmental outcomes of alternative combinations of conservation, restoration, and agricultural interventions in Indonesia, with the stated aim of informing the development of the Indonesian NBSAP (Boere et al., 2023). The Japanese PANCES project combined exploratory and policy-screening approaches, assessing the implications of alternative socioeconomic development pathways for land use, natural capital and ecosystem services and linking these outcomes to potential policy interventions (PANCES, 2020; Saito et al., 2019). The latest follow-on of PANCES uses the NFF in scenario and model development. However, these national examples remain rare (in contrast to climate policy) and the adoption of global scenario framework and models at national scale is yet widespread in biodiversity.

At implementation scales, spatial planning models help identify conservation priorities and feed directly into national biodiversity monitoring indicators. As an example, South Korea's Nature Futures project links land-use, climate, biodiversity, and ecosystem service models (SEALS, WRF, SDM, InVEST) to compare a business-as-usual scenario against four stakeholder-developed Nature Futures scenarios for 2050 (Kim et al., 2026b). The outputs generate national indicators showing how each scenario supports global frameworks like the GBF, SDGs, NDCs, and LDN.

Several priorities emerge for future development. These include expanding the representation of cultural values through participatory scenario co-creation with Indigenous Peoples and local communities, integrating the traditional ecological knowledge and local context into modelling workflows, and developing equity-focused metrics that assess how benefits and burdens are distributed among different regions and groups. One example model that does this is Co\$tingNature, differentiating local, regional and global beneficiaries

and the tradeoffs between them with beneficiaries and impacts on the economically and materially poor. Further, the NFF needs to be used jointly with other frameworks (e.g., justice framework, biocultural diversity, theories of change) to systematically explore distributions of required commitment across countries in meeting global action targets that are perceived to be fair and achievable (Nowak et al., 2026). Achieving genuine value pluralism will require continued methodological development and stronger engagement with formal planning and policy processes, with time and resources and following the CARE principles.

Globally, collaborative scenario and model development – scientists collaborating with other scientists across disciplines to combine and further improve models, and/or scientists with stakeholders to enhance their policy and local relevance and uptake – can support the design of achievable targets and provide guidance for implementation (Figure 4). Nationally, governments can coordinate monitoring, modelling, indicator, and scenario programmes, bringing scientific and implementation agencies to co-develop scenarios that reflect national priorities and best evidence. Indicators in NBSAPs and National Reports can be linked to sustained monitoring and observations with forecasting and impact assessment to improve detection and attribution capabilities. Together, these approaches can help shift biodiversity governance from reactive monitoring towards more anticipatory, adaptive, and transformative decision-making, grounded in inclusive visions and robust pathways with actionable and realizable 2030 targets and 2050 goals (Kim et al., 2023; Visseren-Hamakers et al., 2021).

Table 3. Illustrative capabilities on how models integrate NFF's nature's value perspectives in scenario analyses and how they inform the achievement of KM-GBF goals and targets. This table shows only a small subset of model capabilities in the database (see full dataset for more details).

NFF nature values	Illustrative model capabilities of NFF scenario analyses
Intrinsic Input: 51% (33/65 models) Output: 60% (39/65)	Represented via biodiversity state variables e.g., species richness, population abundance, ecosystem extent; BILBI uses spatial species community composition to prioritize compositionally unique areas (beta diversity) regardless of human benefit; ATLANTIS uses species presence/absence and abundance in the ocean to estimate ecosystem integrity from scenarios (Goal A)
Instrumental Input: 58% (38/65) Output: 69% (45/65)	Represented via ecosystem service dependencies and economic production parameters; InVEST models pollination, crop production, and water purification supply, demands and benefits, Co\$tingNature models grazing and fodder, fuelwood, timber, water purification, fisheries, wildlife services and non-wood forest products supply, demands and benefits (Goal B, Targets 10, 11); GLOBIOM/iBIOM models commodity demand, timber quotas, and bioenergy targets to explore biodiversity–production trade-offs (Goals A, B) and sustainable consumption (Target 16)
Relational/cultural Input: 23% (15/65) Output: 25% (16/65)	Least represented dimension with limited representation of Indigenous knowledge and relational/spiritual values; CLUMondo (van Asselen and Verburg, 2012) uses stakeholder/expert consultation on culturally significant landscapes; CRAFTY (Murray-Rust et al., 2014) models diverse land-manager values (profit, stewardship, tradition); ATLANTIS projects culturally important species under fishing regulations; Co\$tingNature quantifies recreation/aesthetic value changes but most as proxies, mapping sites of production and beneficiaries (Target 22, Goal C)

Multi-value integration	LandSyMM-PREDICTS-InVEST coupled models jointly assess global trade, food production and land-management behaviour, biodiversity integrity and water quality (Goal A, B, Targets 10, 14, 16, 18); Future-EI (Black et al., 2024) assesses biodiversity intactness, agricultural productivity, and landscape heterogeneity as an aesthetic-value proxy (Goals A, B, C, Targets 1,2,3,10,22); ARIES database holds intrinsic, instrumental, and relational values data from the SEEA framework (used in Philippines, Nigeria, Senegal natural capital accounting) (Goals B, D, Targets 14, 21).
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5. Model interoperability through intersectoral science-policy collaboration

Using scenarios and models in the KM-GBF implementation requires harmonising both input and output datasets across modelling domains to ensure interoperability to inform multilateral environmental agreements and reporting. The 65-model database reveals systematic patterns in data requirements, output variables, and integration opportunities that demand coordination (Table 1). The review identifies five broad classes of input data that cut across the modelling landscape: (1) *climate and environmental conditions* including meteorological data, oceanographic parameters, topography, water system characteristics, and geographic features; (2) *biodiversity and ecological data* encompassing species ranges and life histories, traits such as sizes and structures, food webs, environmental preferences, soil properties, trophic interactions, and ecosystem conditions; (3) *socioeconomic data* comprising demographic and economic projections, past, current and projected governance, enforcement and policy interventions, management strategies, sociocultural values, and human behavioural parameters; (4) *spatial pressures* on biodiversity arising from human activities, including land use/land cover maps, resource exploitation data, pollution and emission inventories, and infrastructure datasets; and (5) *methodological and model-specific data*, such as baseline conditions, statistical relationships, transfer functions, service demands, local expert knowledge, and information on systems interaction. Even for commonly used inputs, substantial variation exists in data sources, formats, and spatial and temporal resolutions, creating coordination challenges and opportunities for harmonization.

Model inputs demonstrate inherent interdependencies that require coordinated scenario design and parameterization. For example, agricultural yields and fertilizer/pesticide applications jointly determine nitrogen and phosphate runoff patterns (modelled in PLAIA (Stegmann et al., 2022), LM3-TAN, SWAT (Bieger et al., 2017), while trade flows, commodity prices, production and consumption patterns, and GDP growth trajectories interact within models such as MAgPIE, GLOBIOM/iBIOM, and EXIOBASE. These coupled dynamics require joint parameterization, as assumptions about interventions can propagate through linked model chains. For instance, dietary shifts towards plant-based consumption represented in models such as FABLE (Mosnier et al., 2023), FeliX (Ye et al., 2024), GLOBIO, JUNIPER, MAgPIE, and PLUM (Alexander et al., 2018) can simultaneously reduce livestock production demands, alter land use patterns, decrease nitrogen loading, and modify drivers of biodiversity change across terrestrial and freshwater systems (Rockström et al., 2025). Shifts in seafood consumption patterns can also alter demand for fisheries and aquaculture production that affects pressure for direct exploitation of marine resources and sea uses (Cheung et al., 2021).

Climate data provide another clear example of opportunities for harmonization: meteorological inputs such as temperature, precipitation, and radiation, required by vegetation models (e.g., LPJ-GUESS, FATE-HD, TreeMig), land systems models (e.g., LandSyMM, LandSHIFT, GLOBIOM/iBIOM), and ecosystem models (e.g., Madingley, NCAR-CLM (Lawrence et al., 2019), ED (Ma et al., 2022), EcoOcean), as well as the oceanographic inputs required by marine ecosystem models, are typically derived from large-scale earth-system model intercomparison programs such as CMIP. This reduces duplication and improves consistency across coupled modelling chains. Similarly, land use/land cover data – the most common input data category (used by 21 models) – could be harmonized through products such as ESA-CCI Land Cover or national land cover maps. This would enable models to operate from a common spatial baseline while producing more comparable biodiversity metrics. Biodiversity observation data (e.g., from GBIF, OBIS, eBird, and national monitoring programmes) can also support multiple modelling applications, including calibrating species distribution models (e.g., CLIMEX, HexSim (Schumaker and Brookes, 2018), RangeShifter (Bocedi et al., 2020), BIOMOD (Thuiller et al., 2009)), validating abundance projections (e.g., LPI, PREDICTS, GLOBIO), and parameterizing trophic interactions (e.g., EcoPath, EcoOcean, Madingley). These shared data sources can transform fragmented data collection efforts into a more coordinated and interoperable modelling infrastructure.

Many such resources are already used by biodiversity and ecosystem model intercomparison projects such as FishMIP (Lotze et al., 2019; Tittensor et al., 2017) and BES-SIM (Kim et al., 2018; Pereira et al., 2024), which prescribe or standardize both input data and output metrics and formats while still allowing sufficient flexibility for diverse range of ecological models that form the ensemble. This enables intercomparability among individual models with heterogeneous inputs producing heterogeneous outputs with varying definitions and resolutions, as well as providing estimates of inter-model variability, which provides a more robust basis for informing international Multilateral Environmental Agreements (MEAs). Such model intercomparisons have already informed outputs such as the IPBES Global Assessment Report (IPBES, 2019), the IPCC Special Report on the Ocean and Cryosphere in a Changing Climate (IPCC, 2022), and the IPCC AR6 report (Calvin et al., 2023). Agreement among models and observations can increase confidence in projections.

Model outputs indicate comparability despite heterogeneous data requirements and methodological approaches to modelling. For instance, biomass is produced by 13 models, including ED (Ma et al., 2022), FATE-HD, LPJ-GUESS, Madingley, and NCAR-CLM that can be cross-validated against satellite observations such as GEDI and ICESat-2, as well as flux tower measurements. On another example, species abundance, the projections from GMBI (Savage and Renton, 2014), PREDICTS, GLOBIO, LPI, and Madingley, employ different methodological approaches, including statistical response functions, mechanistic population dynamics, pressure-response relationships, yet address conceptually similar biodiversity metrics (Purvis, 2025). Semantic synchronization could support ensemble approaches where multiple models producing common indicators contribute to assessments of the same KM-GBF goals, allowing inter-model means and associated uncertainties quantified. Essential Biodiversity Variables and Essential Ecosystem Service Variables that provide standardization frameworks that align monitoring protocols with model requirements, linked to a catalogue of tools and workflows for national biodiversity observation networks such as the GEOBON BON in a Box and the EBV data portal, will enable model outputs to

contribute more directly to KM-GBF indicators while reducing the need for semantic translation (GEO BON, 2026; Griffith et al., 2026; Kim et al., 2026a). Improvement in model interoperability – including harmonized input-output specifications, open licence and identifiers for data and models, standardized data formats and workflow management systems, well-documented APIs, low-barrier access with simple interfaces and training manuals for capacity-limited users – can transform current multilateral collaborations into more systematic model ecosystems (Figure 4).

There is a role for individual model outputs to inform sustainable transitions through scale-specific and policy-relevant applications (Table 4). At the global scale, for instance, models such as MAgPIE, LandSyMM, and GLOBIOM/iBIOM are used to provide an integrated perspective of how dietary transitions could drive changes across conservation values, GHG emissions and socioeconomic outcomes. Regionally, models such as EcoOcean, EcoPath, Atlantis, DBEM and many others can project the effects of fishing effort management and the expansion of marine protected areas across shared ecosystems such as the Mediterranean and Coral Triangle and the tropical eastern Pacific region (Palacios-Abrantes et al. 2026). Freshwater models including WaterGAP, SWAT, and LM3-TAN operate at basin scales that span national boundaries, projecting nitrogen and pesticide pollution under agricultural intensification scenarios and evaluating trade-offs and equity considerations associated with water quality degradation, which are critical for international river basin agreements. Large scale models like GLOBIOM/iBIOM have also been refined to national scale for policy analysis in the European Union (European Commission. Directorate General for Environment. et al., 2024).

At the national scale, NBSAPs, Nationally Determined Contributions (NDCs), and Land Degradation Neutrality (LDN) targets that balance food security, biodiversity conservation, and climate mitigation were addressed by FABLE pathways developed by 29 country teams using harmonized methods and co-created with governments using standardized modelling. An application of LandSHIFT in Brazil used exploratory scenario analysis to assess sustainable pathways and biodiversity impacts in the states of Mato Grosso and Para (Göpel et al., 2020) while another application in India coupled LandSHIFT with impact models to assess the implication of food security and agricultural intensification on climate mitigation and biodiversity through trade-offs and synergies across the SDGs (Hinz et al., 2020). At the local scale, BILBI identifies optimal allocations of protection and restoration areas that maximize biodiversity representation by implementing targets 2 and 3 using fine-resolution habitat condition data and has been applied in countries such as Australia and Korea to support conservation prioritization, while CRAFTY's agent-based framework simulated heterogeneous land manager decision-making across a range of land users in the UK (Brown et al., 2022). Such models can assess how policy interventions influence land use outcomes under different societal and governance contexts and support context-specific NBSAP design.

Combining projections across scales can help to support coherent implementation across Multilateral Environmental Agreements by linking national and regional priorities with global sustainability objectives and can directly inform the KM-GBF targets. Achieving synergy across the many scales of multilateral environmental agreements – linking biodiversity commitments under the KM-GBF, climate action through NDCs, land-based

targets under Land Degradation Neutrality, and the wellbeing agenda of the SDGs – requires aligned policy alongside interoperable data and models across domains (Balbi et al., 2022) (Figure 4). Critically, models should capture interactions between drivers, since outcome projections depend on representing how such pressures compound and feed back on one another. By doing so, it is possible to simulate futures where multiple goals are jointly achieved, helping to identify leverage points where action in one domain generates benefits across others.

Several national experiences illustrate this multi-scale integration in practice within different domains. Germany's biodiversity monitoring initiative ([monitoringzentrum.de](https://www.monitoringzentrum.de)) has drawn sectoral ministers into a long-term convening space, embedding biodiversity considerations into cross-government dialogue (BfN, 2026). South Africa has gone further, establishing a legal mandate requiring biodiversity impact assessment within sectoral development processes such as mining (SANBI, 2026). Japan's National Ecosystem Assessment, together with its Japan Biodiversity Outlook and Local Biodiversity Outlook projects, has explicitly adopted GBF, SDG, and IPBES frameworks (Saito et al., 2019). The UK has developed and operationalized cross-sectoral scenarios and modelling frameworks that inform government planning nationally (UKCEH, 2026). Together, these examples underscore the critical importance of national coordination efforts joining existing capacities and programmes to tackle intertwined challenges coherently rather than piecemeal, as well as the need for models operating at all scales from local to global with improved interoperability across scale.

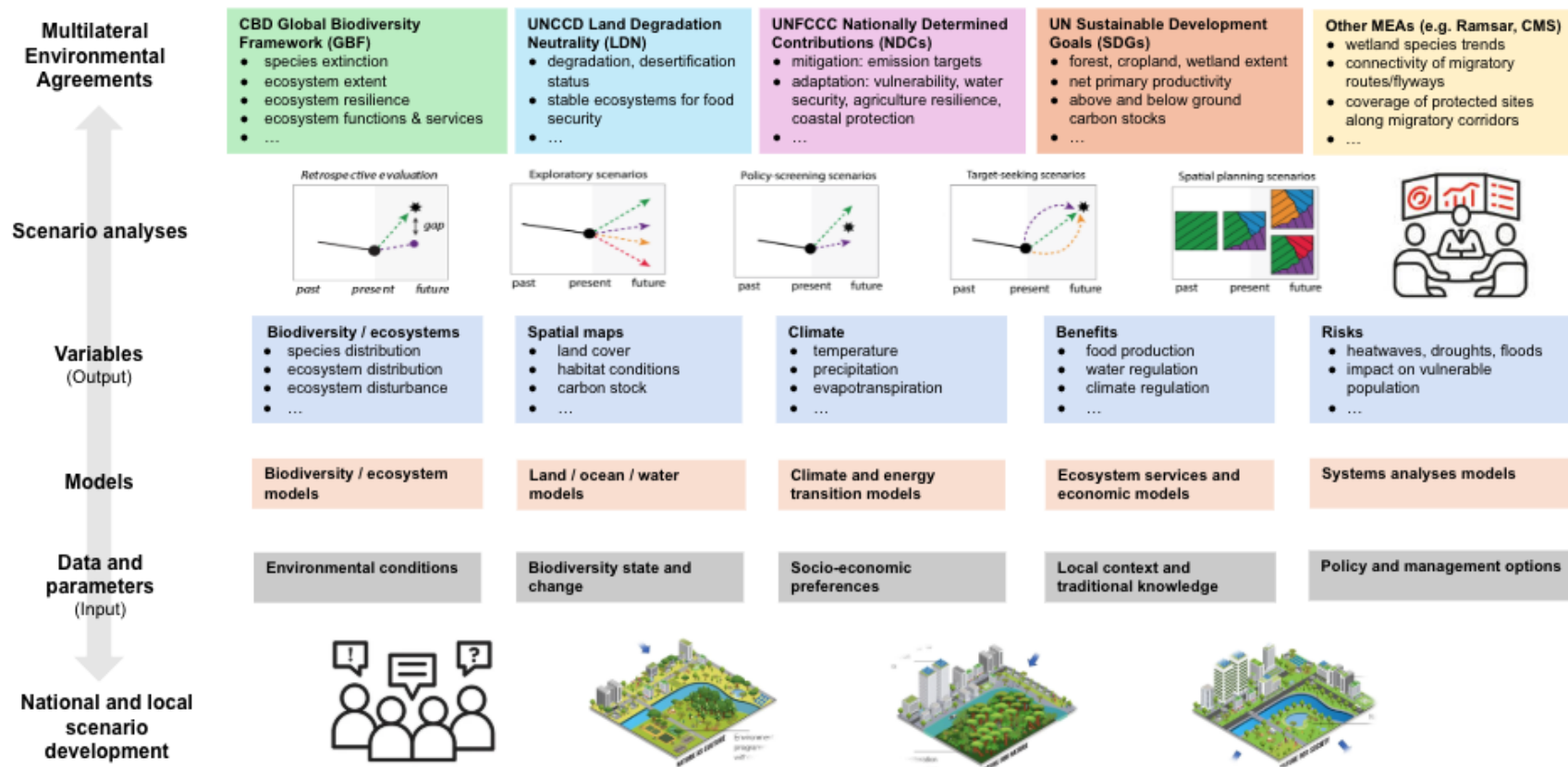


Figure 4. NFF scenarios reflecting diverse values of nature to informing MEAs (GBF, SDG, NDC, LDN goals and targets) via models harmonizing datasets and projecting indicators, i.e., starting from NFF scenarios and nature values, models require essential layers e.g., land cover, climate, socioeconomic projections/aspirations as input (see also Table 1), then the models output to inform MEAs via indicators (e.g., status of threatened species, restoration of degraded ecosystems, frequency of droughts and heatwaves, food security, etc.). Image credit to Mansur et al. 2022 for three urban Nature Futures maps.

Table 4. Key biodiversity-relevant interventions and sub-approaches across sectors simulatable with models in the database

Intervention	Sub-approaches	Models
Energy (KM-GBF Targets 7,8 indirectly)	Green energy transitions	FeliX, GLOBIOM/iBIOM, MAgPIE, MEDEAS (Solé et al., 2020), LandSyMM, IMAGE-MAGNET, GCAM (Calvin et al., 2019)
	Energy-efficient production	ecoinvent, MEDEAS
Pollution (KM-GBF Target 7)	GHG/emission mitigation and reduction	DICE (Barrage and Nordhaus, 2024), GCAM, GAINS (Amann et al., 2011), FeliX, GLOBIOM/iBIOM, MAgPIE, MEDEAS, ENV-Linkages (Chateau et al., 2014), MAGNET (Woltjer and Kuiper, 2014), JULES
	Eutrophication/acidification risk	GAINS, ReCiPe (Huijbregts et al., 2017), SWAT, GLOBIOM/iBIOM, GLOBIO
	Plastic/solid waste management	PLAIA
Resource extraction (KM-GBF Targets 5,9,10)	Forest management	ED, FATE-HD, FeliX, GLOBIO, GLOBIOM/iBIOM, IAP, LandSHIFT, LANDIS-II (Scheller et al., 2007), TreeMig, LandSyMM, GCAM
	Fisheries management	ATLANTIS, DIVERSE, EcoOcean, EcoPath
Consumption, trade (KM-GBF Targets 5,16)	Consumption changes	FABLE, FeliX, GLOBIOM/iBIOM, MAgPIE, PLUM, SIMPLE-G, LandSyMM, EXIOBASE, MAGNET, GCAM
	Shifts in trade	EXIOBASE, EXIOMOD, GLOBIOM/iBIOM, MAgPIE, MRIO-GTAP, PLUM, SIMPLE-G, CLUMondo, FABLE, MAGNET, GCAM
	Environmental impacts	BFM BFC, ecoinvent, GLOBIOM/iBIOM, EXIOBASE, EXIOMOD, FATE-HD, LandSHIFT, MRIO-GTAP, PLAIA, ReCiPe, World3, MAGNET, GCAM
Conservation, sustainable use (KM-GBF Targets 1,2,3,10)	Protected area	BILBI, CLUMondo, GLOBIOM/iBIOM, CRAFTY, FABLE, FATE-HD, Future-EI, IAP (Harrison et al., 2015), LandSHIFT, MAgPIE, SIMPLE-G, LandSyMM GLOBIO,, MAGNET, GCAM, Co\$tingNature
	Restoration	CLUMondo, CRAFTY, FABLE, FATE-HD, GLOBIOM/iBIOM, MAgPIE, SIMPLE-G, WRF (Skamarock et al., 2008), LandSyMM, Co\$tingNature
	Sustainable agriculture/fishery	GAINS, GLOBIOM/iBIOM, MAgPIE, PREDICTS, SIMPLE-G, LandSHIFT, LandSyMM, EcoOcean, EcoPath, SWAT, GLOBIO, GCAM
Nature- and ecosystem-based solution (KM-GBF Targets 1,8,11)	Urban systems planning	Future-EI, InVEST
	Hazard mitigation and adaptation	ATLANTIS, IAP, LandSyMM, CRAFTY, GLOBIOM/iBIOM, WRF, SWAT, FeliX, HexSim, MAGNET, WaterGAP
Behavioural change (KM-GBF Targets 10,16,20,21,22,23)	Diet change, food waste reduction	FABLE, FeliX, GLOBIO, GLOBIOM/iBIOM, JUNIPER, MAgPIE, PLUM, SIMPLE-G, GCAM, LandSyMM, MAGNET
	Education, knowledge exchange	IFs (Hughes et al., 2012), FABLE, LandSyMM
	Social norms, value shifts	AgentEx (Wijermans et al., 2016), CRAFTY, FeliX, LandSyMM

6. Developing joined evidence infrastructures to achieve global goals across scale

The Kunming-Montreal GBF envisions transformative change by 2030, yet achieving these ambitions requires more than political commitment – it demands systematic change across how we track and model biodiversity change and recovery, to semantic, technical and methodological standardization supporting causal understanding of ecological processes and biodiversity mainstreaming to leverage community resources and expertise. All grounded within a larger evidence infrastructure that connects observations to projections, projections to policy design, and policy implementation back to adaptive monitoring (Figure 5). Transforming currently largely isolated programmes and exercises into a coherent evidence infrastructure requires addressing three fundamental challenges: (i) integrating model-based scenario analysis into global biodiversity policy assessment to inform the full policy cycle from aspiration to implementation, (ii) move beyond fragmented data towards a standardized assessment of biodiversity change and improved causal understanding of ecological processes across scales, and (iii) an improved coordination across diverse agencies for change and enhance the understanding of the underpinning role of biodiversity across sectors and aspects of society to bridge biodiversity science with decision-making and implementation.

From aspiration to implementation

The KM-GBF mission has been formulated until 2030, this leaves only little time to move towards the achievement of the 23 targets. In light of this condensed timeframe, actions need to be prioritized to bundle resources and focus on actions with largest synergistic effects towards halting and reversing biodiversity loss. Scenarios and models are crucial tools to understand the option space and develop such prioritizations. However, the current progress report towards the 2030 mission and 2050 vision falls short on highlighting the important role of scenarios and integrated modelling to assess if the national commitments, together with contributions of non-state actors, will progress the world onto the trajectory of 'Living in Harmony with Nature' (CBD Secretariat, 2026).

Our review shows that the tools, frameworks and methods are in place to use predictive scenario modelling to explore KM-GBF target compliant strategies towards nature and people positive futures. Particularly promising is their broad capacity to integrate multiple value dimensions as conceptualized under the NFF. The active development of model-based scenarios can support the evaluation of contrasting intervention portfolios sketching out pathways towards protection-focused, ecological intensification and traditional management system scenarios. Prioritizing individual targets or sets of targets, model-based scenarios can reveal which combinations of interventions (e.g., dietary shifts, technological innovations, financial incentives) are sufficient to achieve anticipated biodiversity goals. The retrospective scenarios facilitate policy review by attributing observed changes to implemented actions rather than external drivers, helping distinguish policy success from failure and thus could provide vital support in NBSAP and NR revision and adaptation on the road towards the KM-GBF mission. A stronger integration of model-based scenario analysis will likely provide crucial evidence for the successful implementation of the KM-GBF. Existing infrastructure can deliver on parts of these needs, however, concerted coordination and purposeful developments along the data to decision pipeline are needed.

From fragmented data to causal understanding

Evidence-based policy fundamentally depends on causal understanding: which interventions lead to which outcomes, through which mechanisms, over which timescales (Ferraro et al., 2019). Detection and attribution science, complemented by ex-post statistical approaches from social sciences, provides this foundation (Tekwa et al., 2023). Yet effective application requires reconciling temporal and spatial scale mismatches between (1) ecological processes, (2) policy cycles, and (3) monitoring programs (Cumming et al., 2006; Essl et al., 2015).

Ecological processes differ across spatial and temporal scales imposing distinct challenges for biodiversity modelling and prediction. Where global models capture planetary patterns and inform international contexts, their coarse spatial resolution masks local heterogeneity relevant for conservation implementation. Similarly, national or local models capture context specific dynamics supporting local, regional or national conservation planning at the cost of low transferability. Moving model-based decision making forward, nested modelling architectures with cross-scale scenario analyses and related simulation experiments are crucial, where global boundary conditions constrain national projections, and bottom-up aggregation of national results helps assess whether collective commitments are sufficient to achieve planetary targets. Such a structure will also facilitate cross-scale feedback modelling, for example of local land use decisions that can get aggregated into national patterns that influence regional climate, which in turn affect local agricultural suitability and stakeholder decisions. Multiscale model development will be crucial to establish predictive modelling and scenario capacities to inform on policy implementation and progress.

Monitoring typically operates on annual to decadal timescales while policy cycles can operate over periods as short as 5-years (e.g., National Reports and NBSAP revisions). Meanwhile, ecological responses may unfold over decades to centuries with lag-times depending on the ecological system and scale of disturbance. Such legacy effects need to be accounted for in biodiversity models. However, currently integration and comprehensive assessment of temporal trends in biodiversity change is severely hampered by the absence of long-term time series across taxa, regions and ecosystems. Essential prerequisites for systematic long-term data are continuity in monitoring and reporting through semantic and methodological synchronization of variables and indicators, e.g., through established standards like EBVs and EESVs (Kim et al., 2026a). The lack of such semantic synchronization currently also hampers the technical synchronization across different models where only comparison across a small set of models is possible given the large heterogeneity of input and output variables.

Consequently, monitoring programs need to be stable across time with continued funding and methodological consistency so that developed indicators can be maintained across policy cycles and frameworks where national indicators and invested resources can be used most appropriately for informing national to global biodiversity policy targets. Continuous governance cycles can provide a relevant entry point for scientific assessments, cfr. climate policy analysis (Weitzel et al., 2019). The National Restoration Plans currently under development in the context of the EU Nature Restoration Law provide an example where science-based evidence can support policy design and implementation. The importance of

this continuity is also evident in the current KM-GBF reporting where parties strongly rely on national indicators which have readily available and reliable data. Beyond these challenges, model development also needs to better account for the implementation of behavioural, sociocultural, and Indigenous and local knowledge evidence, which currently remains structurally underrepresented in the scenario modelling landscape.

From siloed development to collaborative governance

Coordination challenges often arise not from technical limitations but from the absence of integrative, systems-based approaches to governance and financing across agencies. Governments designing NBSAPs and preparing National Reports require operational decision support, yet many lack in-house scenario modelling capacity and therefore rely on external consultancies that produce one-off or disconnected assessments rather than sustained evidence systems (Lindenmayer and Likens, 2010). One potential solution is the establishment of joint national ecological monitoring and modelling centers – analogous to meteorological services that maintain operational weather forecasting systems – to embed sustainable evidence-based support within government planning processes. Intermediate bridge-solutions towards such joint centres are the establishment of pre-parameterized policy options and pipelines that support target progress tracking and modelling via existing interfaces such as BON in a BOX (national) and the CBD Clearinghouse (global), informed by NBSAPs and National Reports, similarly to how it is being initiated in climate policy scenario simulation at global scale (Dafnomilis et al., 2026).

Multilateral institutions such as the CBD and IPBES synthesize model-based evidence into policy-relevant assessments, but integrated monitoring and modelling frameworks remain limited (Gonzalez et al., 2023b; Zurell et al., 2026). CMIP provides a useful example: standardized experiments enable ensemble projections that quantify structural uncertainty across modelling approaches, transforming the question "which model is correct?" to "what do models collectively tell us?", accompanied by explicit confidence estimates (Touzé-Peiffer et al., 2020). However, the existing MIP practices (CMIP, ISIMIP, ScenarioMIP) that inform the IPCC with global infrastructure do not treat biodiversity as a central topic in scenarios, modelling framework or the assessment, but rather as an end point in the impact assessment. The MIPs already exist in the marine ecosystem modelling space (e.g., FishMIP) with terrestrial initiatives being developed (e.g., BES-SIM2, Bending the Curve) that are designed to inform global governance and assessments. This review suggests that biodiversity science already possesses many of the necessary capacity for comparable coordination – including shared data sources, opportunities for model interoperability, and broadly comparable output variables – but lacks the institutional mechanisms needed to connect modelling communities, support collaboration and co-production, and sustain coordinated model development.

However, to enhance the global and regional model relevance to national and local use and application where implementation and impact occurs in biodiversity conservation, we advocate for continued development of models and new integrated frameworks to foster innovation and maintain the capacity to adapt biodiversity model infrastructure to evolving societal needs, aligning with and contributing to community standards as outlined above. Having both modelling approaches – standardizing model intercomparison and open model

innovation – in place will help prevent unnecessary model lock-ins and account for complexity-interpretability trade-offs, where predictive multi-driver models' causal transparency and domain-specific attribution models are complemented. This will be possible through simultaneous development of new sectoral and context-specific models capturing the specificities of systems and targets as well as integrated modelling projects that support integration of multi-model approaches into a coherent platform and language.

7. Conclusion

The lack of joint evidence infrastructure perpetuates a cycle in which insufficient data constrain model reliability, undermining the comprehensiveness and relevance of evidence, reducing policy uptake, and ultimately reinforcing the separation between monitoring and modelling and science and policy. This review shows that what remains largely absent is coordination and mechanisms: across scales linking local implementation to global targets; across knowledge systems incorporating diverse values of nature into formal projections; across domains connecting biodiversity science to climate, energy, health, food and water systems and to economic and financial decision-making; and across agencies aligning funding and incentives around shared evidence. Establishing these connections could help transform the KM-GBF from an aspirational declaration into an evidence-based framework for action, supporting the rigorous, inclusive, equitable and nature-positive futures that it envisions. The technical foundations are already present based on the database reviewed here. The imperative now is initiating and sustaining the collaboration and institutional commitment to operationalize this collective capacity for transformative change in global biodiversity governance.

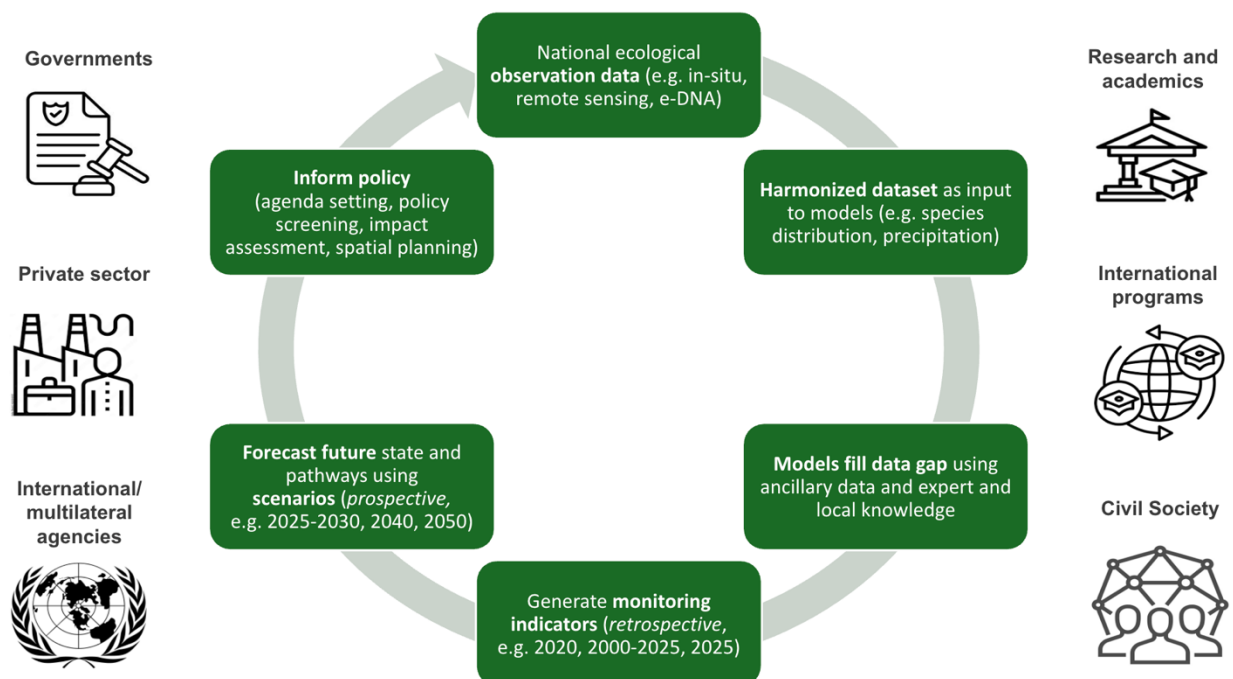


Figure 5. Data to decision flow from monitoring to data harmonization, modelling, indicator development, scenario design and modelling, and policy processes with agency of change across society.

Model Acronyms

ARIES: Artificial Intelligence for Environment & Sustainability
BA-BK-FW: Bioavailability-Biokinetic-Food Web
BFM BFC: Biodiversity Footprint Model and Biodiversity Footprint Calculator
BILBI: Biogeographic modelling Infrastructure for Large-scale Biodiversity Indicators
CRAFTY: Competition for Resources between Agent Functional TYpes
DIVERSE: Dynamic Integrated Marine Climate, Biodiversity, Fisheries, Aquaculture and Seafood Market
ED: Ecosystem Demography
ENCORE: Exploring Natural Capital Opportunities, Risks and Exposure
EXIOMOD: EXtended Input-Output MOdel
FABLE: Food, Agriculture, Biodiversity, Land-Use and Energy
FATE-HD: A spatially and temporally explicit vegetation model
FCM: Fuzzy Cognitive Maps
FeliX: Full of Economic-Environment Linkages and Integration dx/dt
GAINS: Greenhouse Gas - Air Pollution Interactions and Synergies
GCAM: Global Change Analysis Model
GLOBIO: GLOBal Biodiversity model for policy support
GLOBIOM/iBIOM: Global Biosphere Management Model
GMBI: General Model of Biological Invasions
IAP: Integrated Assessment Platform
IBAT/STAR: Integrated Biodiversity Assessment Tool / Species Threat Abatement and Restoration
IFs: International Futures
IMAGE: Integrated model to assess the global environment
IMAGE-DGNM: IMAGE-Dynamic Global Nutrient Model
InVEST: Integrated Valuation of Ecosystem Services and Tradeoffs
JULES: Joint UK Land Environment Simulator
LandSHIFT: LAND Simulation to Harmonize and Integrate Freshwater availability and the Terrestrial environment
LANDIS-II: LANDscape DIsturbance and Succession, version II
LandSyMM: the Land System Modular Model
LM3-TAN: Land Model (LM3)-TAN (Terrestrial and Aquatic Nitrogen)
LPI: Living Planet Index
LPJ-GUESS: Lund-Potsdam-Jena General Ecosystem Simulator
MAGNET: Modular Applied GeNeral Equilibrium Tool
MAGPIE: Model of Agricultural Production and its Impact on the Environment
MEDEAS: Modelling the Energy Development under Environmental And Socioeconomic constraints
MRIO-GTAP: Multi Regional Input Output
NCAR- CLM: National Centre for Atmospheric Research - Community Land use Model
PLUM: Parsimonious Land Use Model
PREDICTS: Projecting Responses of Ecological Diversity In Changing Terrestrial Systems
SEALS: Spatial Economic Allocation Landscape Simulator
SEED: Sustainable Ecology and Economic Development
SIMPLE-G: A Simplified International Model of Prices Landuse and the Environment- Gridded
SWAT: Soil and Water Assessment Tool
WaterGAP: Water - Global Assessment and Prognosis
WRF: Weather Research and Forecasting

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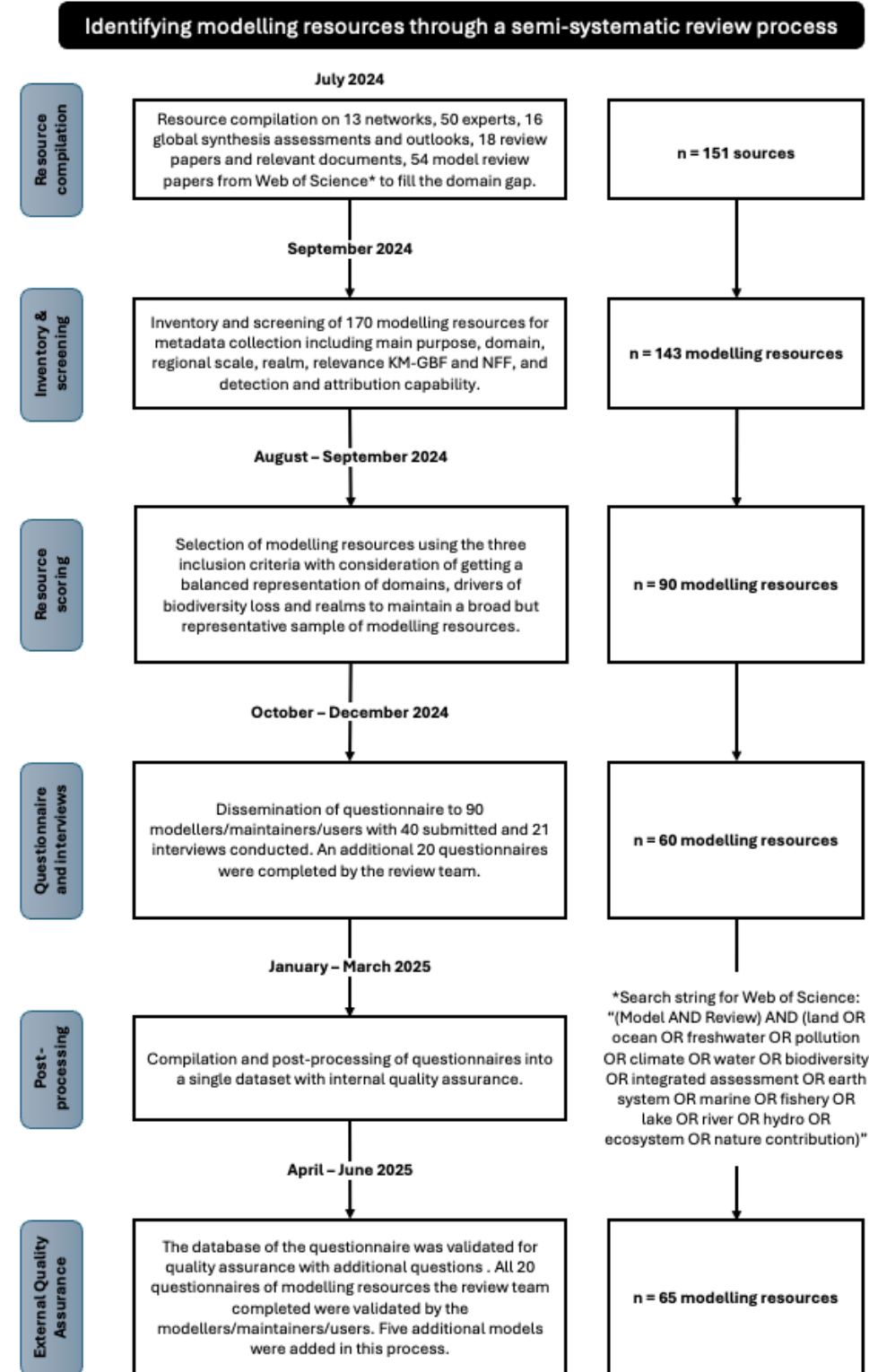
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Transforming biodiversity governance through improving evidence and diversifying values of nature in scenarios and models

Supplementary Information

I. Review protocol



II. Descriptive data of the model database

Table S1. The number of models in our dataset (n = 65) able to inform on components of Goals A and B of the KM-GBF and each of the 23 Targets.

KM-GBF Goal / Target	Number of Models
Goal A Species	32
Goal A Ecosystems	55
Goal A Genetic diversity	3
Goal B Nature's Contribution to people	53
Target 1 Spatial planning and effective management	46
Target 2 Restoration 30% degraded ecosystems	38
Target 3 Conservation 30% land, water, seas	40
Target 4 Halt species extinction, protect genetic diversity	29
Target 5 Sustainable use of wild species	20
Target 6 Minimize impact of invasive alien species	12
Target 7 Reducing pollution	26
Target 8 Minimizing climate change impact	41
Target 9 Managing wild species to benefit people	19
Target 10 Sustainable agri-, aqua-culture, fishery, forest	40
Target 11 Restore, maintain, enhance NCPs	39
Target 12 Enhance urban blue green spaces	14
Target 13 Genetic resource sharing, DSI	2
Target 14 Biodiversity in decision making	23
Target 15 Disclose and risk reduction from businesses	20
Target 16 Sustainable consumption choices	24
Target 17 Strengthen biosafety	2
Target 18 Reform incentives and subsidies	8
Target 19 Increased financial resources	5
Target 20 Capacity building, scientific and technological cooperation	11
Target 21 Accessible data, information and knowledge	14
Target 22 Inclusive, just participation in decision making	7
Target 23 Gender equality	4

III. Overview of model capabilities

[illegible]

[illegible]

IV. Key gaps in data, models, scenarios and indicators and development frontier

Gap 1. Bridging the invasive alien species modelling gap

[Biodiversity assessment will not be comprehensive or accurate without major drivers considered beyond land use and climate change – namely, pollution, IAS, and resource exploitation.]

Comprehensive biodiversity assessment requires consideration of major drivers beyond land use and climate change – namely invasive alien species (IAS), pollution, and resource exploitation (IPBES, 2024). Yet the review reveals critical underrepresentation: only 10 models address IAS despite their status as a leading cause of extinctions and ecosystem change globally. Bridging this gap necessitates scale-appropriate approaches, new data infrastructure, and methodological innovations translating invasion processes into policy-relevant impact metrics (Vicente et al., 2022).

At species and local-to-regional scales, process-based models exist but require adaptation for IAS applications. GMBI (Savage and Renton, 2014) exemplifies mechanistic population dynamics explicitly accounting for reproduction, maturation, mortality, and dispersal-parameters previously estimated using expert knowledge but now amenable to data-driven estimation through collation of new IAS datasets enabling model calibration. HexSim (Schumaker and Brookes, 2018) demonstrates flexibility, already simulating invasion spread, while frameworks like RangeShifter (Bocedi et al., 2020), MAXENT (Jarnevich and Young, 2015), and BIOMOD (Thuiller et al., 2009) offer distribution modelling capabilities to understand potential future spread and impacts of invasive alien species. However, these approaches remain purely correlational, only informed by geographically and taxonomically biased occurrence data or data limited in the absence of comprehensive population-scale information for parameterization (Jarnevich and Young, 2015). Context-specific expert knowledge remains important for determining whether spreading species pose invasion risks including potential impacts, suggesting hybrid data-expert approach as pragmatic way forward (Essi et al., 2020). Nevertheless, data on impacts of invasive alien species are increasingly becoming available at global scale facilitating future quantitative impact assessments and projections (Bacher et al., 2025; Diagne et al., 2021).

At global scales, species distribution models attempt macroecological projections accounting for invasion processes – transport, introduction, establishment – yet provide limited species identity information, impeding impact assessment central to policy relevance (Sardain et al., 2019; Seebens et al., 2021). The critical frontier lies in impact modelling: recent developments including the first global impacts evidence database enabling spatially explicit impact projections, though context dependency and impact diversity present challenges (Bacher et al., 2025; Henriksen et al., 2024). Economic cost modelling demonstrates one approach, though transferability assumptions require scrutiny (Zenni et al., 2021). IUCN's Species Threat Abatement and Restoration (STAR) (Mair et al., 2021) metric promoted for KM-GBF implementation relies on Red List assessments containing diverse limitations (Asefa et al., 2025) but first assessments at continental scale for invasive alien species already exist (Jiménez et al., 2025).

Integrating IAS into global biodiversity models such as GLOBIO (Schipper et al., 2020) or PREDICTS (De Palma et al., 2021) demands spatially explicit impact layers – the key currency for IAS as biodiversity change drivers, not richness or abundance. Once spatial impact layers exist under multiple scenarios analogous to land use and climate projections, IAS can join established driver frameworks. This integration requires resolving fundamental measurement challenges: How do we quantify impact reduction progress toward KM-GBF targets? The framework mandates impact minimization by 2030, yet lacks a quantifiable target. Further, introduction rates should be reduced by 50% until 2030, however, standardized baselines for introduction and establishment rates are lacking (McGeoch et al., 2023). Historic data gaps across taxonomic groups compound these challenges.

Development priorities emerge across scales. Species-level modelling requires expanded trait databases, dispersal observations, and demographic parameters, enabling mechanistic projections beyond expert opinion, while maintaining expert knowledge integration for risk assessment. Global modelling demands spatially explicit impact maps derived from systematic evidence synthesis, standardized impact metrics enabling cross-species comparison and aggregation, and scenario frameworks projecting invasion pathways under alternative futures – trade patterns, biosecurity policies, climate trajectories. Critically, impact metrics must align with policy targets: reduction rate requires baseline establishment, threat attribution to Red List species demands taxonomic expansion beyond well-documented vertebrates, and quantification of ecosystem service degradation enables economic valuation comparable to other drivers.

The database demonstrates capacity – population models, distribution frameworks, impact assessment tools exist – yet systematic integration transforming fragmented approaches into coordinated IAS modelling infrastructure remains unrealized. Achieving Target 6's mandate to eliminate or reduce IAS introductions and establishment by 50% demands this coordination, ensuring invasion biology's rich empirical foundations translate into operational decision support comparable to the maturity of climate and land use change modelling.

Gap 2. Linking economy models with biodiversity models for transformative economy scenarios

[Nature positive future scenarios require economic transformation and an improved consideration and representation of nature and nature's benefits to people in decision spaces.]

Nature-positive futures require fundamental economic transformation and comprehensive integration of nature's contributions into economic decision-making. Yet current modelling practices treat biodiversity and economic systems largely in isolation, limiting capacity to evaluate transformative pathways beyond conventional growth paradigms (Otero et al., 2020). Bridging this gap necessitates systematic coupling of biodiversity models with economic frameworks, enabling the evaluation of economic transformation scenarios essential for achieving KM-GBF targets.

The modelling database reveals emerging capacity for biodiversity-economy integration but highlights critical development needs. SIMPLE-G (Haqiqi and Hertel, 2025; Wang, 2024) exemplifies required linkages: the model demands high-resolution biodiversity metrics over

past decades, coefficients linking habitat area to biodiversity outcomes, and coefficients connecting biodiversity metrics to agricultural benefits – enabling feedback loops where biodiversity loss constrains agricultural productivity, recursively influencing land use decisions and economic returns. This bidirectionality remains absent in most frameworks, where biodiversity models receive economic drivers as exogenous inputs without reciprocal effects on production functions (Johnson et al., 2023). Developers explicitly request new simulations generating biodiversity metrics over time and express willingness to collaborate with multidisciplinary teams creating potentially emulators and modules – underscoring the collaborative infrastructure required for model coupling and integration (Walkden et al. In review.).

Fundamental to this integration is a multiscale analytical framework understanding how local to global economic forces – commodity demand, trade flows, financial markets – drive environmental stresses, while local or national responses spill over to other localities through teleconnections and supply chains (Green et al., 2019) (Green et al., 2019; Liu et al., 2013). The model database demonstrates this multi-scale architecture through models like FABLE (Mosnier et al., 2023) linking global boundaries to 24 national contexts, MAGPIE (Dietrich et al., 2019) coupling global agricultural markets with 0.5° land allocation, EXIOBASE (Stadler et al., 2018) tracking 163 industries across 49 regions, as well as SIMPLE-G, which connects grid-cell land-use decisions at 5-arcmin (0.083°) with global trade and food-security outcomes. However, realizing the full potential requires incorporating governance heterogeneity at finer scale where decisions are made: differing objective functions of private managers maximizing profit versus communal lands prioritizing subsistence, cultural values, and sustainability fundamentally shape landscape outcomes.

Biodiversity models can improve the integration of policy levers while linking to economic and market consequences through explicit market functions. Current models like MAGPIE, GLOBIOM (Havlík et al., 2011), SIMPLE-G, and ENV-Linkages (Chateau et al., 2014) demonstrate this through carbon pricing, subsidies and taxes, trade regulations, and protected area designations. Yet broader policy options – food system transformation, behavioural change incl. diets, an overhaul of agricultural subsidies, an ambitious revision of land use measures and an energy transition towards broad sustainability in the long-run – remain largely unexplored. Evaluating transformative pathways requires models projecting outcomes under fundamentally different economic policies, incentives and behaviour rather than incremental modifications of business-as-usual growth (Otero et al., 2024).

Private sector engagement introduces new coordination opportunities and challenges. Natural capital accounting, biodiversity-related financial disclosures, and supply chain risk assessments require linking biodiversity outcomes to corporate balance sheets – a frontier where ecological models must be coupled with multi-regional input-output frameworks, life cycle assessments, and computable general equilibrium models ([TNFD] Taskforce on Nature-related Financial Disclosures, 2025). This integration can reveal the financial materiality of nature loss, translating ecological concepts into the fiduciary language understood by corporate boards, financial institutions and sovereign investors. A new class of Earth-Economy models is emerging with the goal of informing financial institutions about the risks associated with degradation of biodiversity and other nature-based ecosystem services (Johnson et al., 2025). Early results from the GTAP-AEZ-InVEST modelling system

reveals disproportionate risk to low income economies from degradation of natural capital (Johnson et al., 2023)

Further, the corporate sector requires biodiversity metrics integrated with scenarios and economic assessment tools for supply chain impact evaluation and nature-related financial risk disclosure. Coupling spatially explicit biodiversity models withecoinvent's lifecycle assessment process inventories or EXIOBASE's multi-regional input-output framework enables product-level biodiversity footprints reflecting location-specific ecosystem dependencies and vulnerabilities, supporting corporate disclosure frameworks and financial portfolio alignment with nature-positive outcomes (Boakes et al., 2024; Chaplin-Kramer et al., 2017; Stadler et al., 2018) (Boakes et al., 2024; Chaplin-Kramer et al., 2017; Stadler et al., 2018).

Advancing these linkages requires coordinated development. Biodiversity scientists need to engage with economic modelers identifying location- and risk-specific relevant biodiversity and ecosystem services metrics translatable to production functions. Economists need to incorporate ecological constraints rather than treating nature as an infinite resource base or assume simplistic equilibria in ecological systems as in economic systems. Both domains of modellers need to collaborate with corporate practitioners and financial regulators with national experts ensuring outputs serve decision-making relevant to national and regional context. The model database demonstrates that technical foundations exist, yet the integration coupling socio-economic scenarios, corporate assessment, and nature-economy feedback modelling remains a critical frontier.

Gap 3. Tracking and projecting indicators for spatial planning, target setting, and impact evaluation

[National indicators can monitor how interventions are progressing nature, ideally using local and national data with region or global boundary conditions as relevant.]

National biodiversity indicators can inform policy at multiple scales by tracking whether implemented or planned actions advance nature's state nationally while guiding subnational spatial planning, implementation and evaluation (Ly et al., 2023; McGeoch et al., 2023). Yet fundamental coordination gaps limit indicator-model integration that inhibits evidence-based and scenario-based design of NBSAPs and rigorous retrospective evaluation in National Reports (NR) for conservation and policy efficacy (Purvis, 2025). The model database (Walkden et al., In review) shows capacity of model-based indicators to inform the KM-GBF including: Living Planet Index (LPI) (McRae et al., 2017), Red List Index (RLI) (Cazalis et al., 2024, 2022), STAR, Mean Species Abundance (MSA) (Schipper et al., 2020) and the Biodiversity Intactness Index (BII) (De Palma et al., 2021). These complementary metrics offer distinct and synergistic roles across ecological context and scales. Therefore, developing a coordinated evidence infrastructure requires an understanding of the different functions of these indicators and data-model linkages; and embedding diverse knowledge systems beyond conventional model-based requirements, which both CBD and IPBES recognizes through value pluralism and diverse stakeholders and worldviews.

Complementary indicators represent different facets of biodiversity and ecological changes: LPI tracks abundance trends in monitored populations (representing estimated 6% of

vertebrates); RLI aggregates extinction risk changes across assessed species (representing estimated 10% of described species); STAR quantifies threat abatement and restoration potential at site-to-national scales to identify cost-effective threat reduction portfolios; MSA and BII estimate compositional intactness relative to pristine baselines. Models inform scenario analyses and spatial planning by projecting these metrics under alternative future scenarios and interventions. BILBI (Hoskins et al., 2020) optimizes protection-restoration allocations maximizing biodiversity conservation with governance constraints.

The primary challenge and limitation for these metrics is the lack of primary observational data constraining both retrospective trend analyses and prospective scenario analyses (Proença et al., 2017; Sutherland et al., 2026). This data scarcity and sparsity manifests in geographic and taxonomic biases – e.g., extensive monitoring in temperate vertebrates, severe gaps in tropical invertebrates and marine systems – limiting representativeness (Bowler et al., 2021; Hughes et al., 2021). However, ancillary data offers pathways forward in some cases: lists of functionally, culturally, or economically important species can subset to inspect trends in policy-relevant taxa, while world heritage site locations can facilitate locality-specific trend analyses informing protected area effectiveness (Target 3) and ecosystem restoration (Target 2).

Another limitation constraining scenario-based policy design is indicator-driver disconnection. LPI and RLI document past trends but lack systematic linkage to experienced pressures (e.g., pollution exposure, land use conversion, climate anomalies, exploitation intensity). Without explicitly linking observed trends to such drivers these indicators have limited capacity to project future trends under alternative scenarios. Simultaneous and consistent monitoring that records population states and drivers enable attribution of observed trends to specific pressures, unlocking predictive capacity. For instance, understanding how land use change impacts mammal populations and soil health enables evaluating Target 1 spatial planning. Knowing pollution drives amphibian declines in specific contexts allows projecting outcomes under Target 7 pollution reduction scenarios.

Scale transferability presents both opportunities and constraints. RLI exemplifies successful cross-scale application: standardized, scale-independent assessment criteria enable national Red Lists constructed from region-specific data translating to RLI at varying taxonomic and geographic resolutions, facilitating global-national-local consistency (Cazalis et al., 2022). This repeatability improves capacity by providing information across policy-relevant scales and enables countries to track national extinction risk projections comparable to global assessments while maintaining subnational specificity. However, Red List category assignment remains largely manual, limited to regions collecting species-relevant information meeting assessment criteria, with irregular updates constraining temporal resolution for adaptive management (Cazalis et al., 2024).

Advancing coordination requires step-change national commitments utilizing NBSAPs and NRs as tools for designing and implementing KM-GBF and other multilateral environment agreements (Kim et al., 2026). This demands integrating model-based projections with diverse knowledge systems – e.g., traditional ecological knowledge tracking key functional or culturally important species unrepresented in Western taxonomies, local community observations documenting ecological changes preceding formal monitoring, Indigenous land management effectiveness rivalling protected areas yet unmeasured by conventional

metrics. The NFF responds through flexible value integration: Nature for Nature emphasizing extinction risk or ecological integrity (LPI, RLI, MSA, BII), Nature for Society prioritizing ecosystem service provision (MSA-ecosystem function linkages), and Nature for Culture centring culturally significant species and landscapes requiring human-nature co-existence (Kim et al., 2023). Scalable workflows from data collection through indicator calculation for their use in policy processes enable more comprehensive integration of value pluralism with transparency, transforming fragmented monitoring data and analytical capacities into coordinated evidence infrastructure, supporting rigorous and inclusive KM-GBF implementation grounded in both scientific modelling and diverse ways of stewarding nature.

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IV. Metadata of models

Model	Model Full Name	Objective	Reference
AgentEx	AgentEx	The AgentEX model supports the understanding of human behaviour and decision-making regarding the management of a common resource pool. The aim of the model is to identify possible factors and aspects of human decision-making behaviour that can explain observed outcomes of experiments.	Wijermans, N., Schill, C., Lindahl, T., & Schlüter, M. (2016). "AgentEx". CoMSES.
ARIES	Artificial Intelligence for Environment & Sustainability	The ARIES is a platform for model integrations using semantic artificial intelligence (AI) to develop open, safe, and accurate methods for sharing and linking scientific models, and datasets, in the field of environmental sustainability. It is designed to empower stakeholders to make better-informed decisions and drive positive change.	Javier Martínez-López, Kenneth J. Bagstad, Stefano Balbi, Ainhoa Magrach, Brian Voigt, Ioannis Athanasiadis, Marta Pascual, Simon Willcock, Ferdinando Villa, Towards globally customizable ecosystem service models, Science of The Total Environment, Volume 650, Part 2, 2019, Pages 2325-2336, ISSN 0048-9697
ATLANTIS	ATLANTIS	The ATLANTIS model supports the prediction of the response of marine species (population, dynamics and distribution) of human impacts on the environment including fisheries, changes in land use, non-point source pollution, climate and the effect of wind and wave farms. It can incorporate biophysical economic and social aspects such as level of compliance to regulations. The model consists of a deterministic biogeochemical whole ecosystems model based around the management strategy evaluation approach (MSE).	Audzijonyte A, Pethybridge H, Porobic J, Gorton R, Kaplan I, Fulton EA. Atlantis: A spatially explicit end-to-end marine ecosystem model with dynamically integrated physics, ecology and socio-economic modules. Methods Ecol Evol. 2019; 10: 1814–1819.
BA-BK-FW	Bioavailability-Biokinetic-Food Web	The BA-BK-FW model supports the prediction and quantification of the effects of metals on marine food webs. It serves as a tool for Environmental Risk Assessment (ERA) in scenarios involving metal contamination from human activities like deep-sea mining.	Irene Martins, Alexandra Guerra, Ana Azevedo, Ombéline Harasse, Ana Colaço, Joana Xavier, Miguel Caetano, Marina Carreiro-Silva, Inês Martins, Teresa Neuparth, Joana Raimundo, Joana Soares, Miguel M. Santos, A modelling framework to assess multiple metals impacts on marine food webs: Relevance for assessing the ecological implications of deep-sea mining based on a systematic review, Marine Pollution Bulletin, Volume 191, 2023, 114902, ISSN 0025-326X
BFM BFC	Biodiversity Footprint Model and Biodiversity Footprint Calculator	The BFM model supports the assessment of impact on land use, GHG emission, water use and nitrogen and phosphorus emission to water of a company or product, combining these values to provide a calculation of a biodiversity footprint (terrestrial & freshwater).	Van Rooij, W. & Arets, E. 2016. Biodiversity Footprint Assessment of Leading Companies. Plansup & Alterra, Wageningen.

Model	Model Full Name	Objective	Reference
BILBI	Biogeographic modelling Infrastructure for Large-scale Biodiversity Indicators	The BILBI model supports the prediction of terrestrial biodiversity change (sp. abundance, persistence and range) due to climate and land use change. It works at a high spatial resolution for the entire land surface of the planet with data for over 400K species spanning plants, vertebrates and invertebrates.	Hoskins, A.J. et al (2020) BILBI: Supporting global biodiversity assessment through high-resolution macroecological modelling. <i>Environmental Modelling & Software</i> 132: 104806. Ware et al. (2026). Global indicator data tracking changes in species-level biodiversity persistence, ecosystem resilience under climate change, and protected-area representativeness and connectedness. https://doi.org/10.32942/X26Q2G
CLIMEX	CLIMEX	The CLIMEX model supports the prediction of the impact on species distribution (animal or plant) of climate change. It consists of a dynamic simulation model and has been used to model the potential spread of invasive species. It attempts to mimic the biological mechanisms that limit species geographical distribution and determine the seasonal phenology and relative abundance.	
CLUMondo	CLUMondo	The CLUMondo model provides spatially explicit prediction of terrestrial land use change due to predicted future societal demands (scenarios) for land derived goods and services. Land allocated to meet these demands based on prioritization of locations with the highest suitability for each land use with a capacity to incorporate both abiotic and societal factors (e.g., environmental policy).	van Asselen, S. and Verburg, P.H. (2012), A Land System representation for global assessments and land-use modeling. <i>Glob Change Biol</i> , 18: 3125-3148.
Co\$tingNature	Co\$tingNature	Co\$ting Nature (V3) is a web based policy-support tool which maps supply and realised delivery of 18 ecosystem services to local, national and global beneficiaries, with biodiversity, pressure and threat indices, and tests the impact of BAU land use change scenarios, conservation and restoration interventions. It provides datasets at 1 km–1 ha resolution globally and down to 10 m locally (Co\$tingNature/local) in a multi-resolution, pre-parameterised modelling framework. It is freely available and is widely used by >3500 organisations across >180 countries.	Mark Mulligan, Arnout van Soesbergen, David G. Hole, Thomas M. Brooks, Sophia Burke, Jon Hutton, Mapping nature's contribution to SDG 6 and implications for other SDGs at policy relevant scales, <i>Remote Sensing of Environment</i> , Volume 239, 2020, 111671, ISSN 0034-4257
CRAFTY	Competition for Resources between Agent Functional Types	The CRAFTY model simulates land use change as a result of climate, socio-economic and behavioural drivers. The model is agent-based, representing land managers that make decisions based on their provision of ecosystem services, the values of those services, and individual and social preferences. The model includes a range of forms and intensity of land use and management.	Murray-Rust, D., Brown, C., van Vliet, J., Alam, S. J., Robinson, D. T., Verburg, P. H., & Rounsevell, M. (2014). Combining agent functional types, capitals and services to model land use dynamics. <i>Environmental Modelling and Software</i> , 59, 187–201.

Model	Model Full Name	Objective	Reference
DICE-2023	DICE-2023	The DICE model (Dynamic Integrated model of Climate and the Economy) estimates the SCC and evaluates climate policies across the literature and policy realm. It is based on a standard neoclassical model of optimal economic growth known as the Ramsey model. The model augments the Ramsey model to include climate investments. In this augmented approach, society can give up consumption today to mitigate climate change and thus increase well-being in the future through avoided climate damages. The model contains all elements from economic activity and emissions through climate change to damages and policy in a manner that represents simplified best practice in each area.	L. Barrage, & W. Nordhaus, Policies, projections, and the social cost of carbon: Results from the DICE-2023 model, Proc. Natl. Acad. Sci. U.S.A. 121 (13) e2312030121, (2024).
DIVERSE	Dynamic Integrated Marine Climate, Biodiversity, Fisheries, Aquaculture and Seafood Market Model	The DIVERSE model supports the prediction of the impacts on marine invertebrates and fisheries of change in climate change and fishing scenarios. It is underpinned by a system of linked and harmonised infrastructure of environmental biodiversity fisheries and socio-economic data.	William W. L. Cheung et al., Marine high temperature extremes amplify the impacts of climate change on fish and fisheries.Sci. Adv.7,eabh0895(2021).
ecoinvent	ecoinvent	The ecoinvent is a database of life cycle inventory data, allowing users to assess the environmental impact of various products, processes, and services.	
EcoOcean	EcoOcean	The EcoOcean model is a spatially and temporally explicit mechanistic marine ecosystem modelling (MEM) complex of the global ocean, that unifies the consideration of spatial-temporal food-web dynamics ranging from primary producers to top predators with the impacts of environmental change (including an internal niche model) and worldwide fisheries (including a bioeconomic model).	Coll, M., Steenbeek, J., Pennino, M. G., Buszowski, J., Kaschner, K., Lotze, H. K., Rousseau, Y., Tittensor, D. P., Walters, C., Watson, R. A., & Christensen, V. (2020). Advancing Global Ecological Modeling Capabilities to Simulate Future Trajectories of Change in Marine Ecosystems. Frontiers in Marine Science, 7, 567877.
EcoPath	EcoPath	EwE is a tool for modeling and assessing marine ecosystems, particularly focusing on the interactions among different species and the impacts of various environmental and human factors. The model aims to simulate the flow of energy and biomass through food webs, accounting for species interactions (predation, competition, etc.), and the effects of human activities like fishing.	Christensen, V. and Walters, C.J., 2004. Ecopath with Ecosim: methods, capabilities and limitations. Ecological modelling, 172(2-4), pp.109-139.

Model	Model Full Name	Objective	Reference
ED	Ecosystem Demography	The ED model is an individual-based model of vegetation dynamics with integrated submodels of plant growth, mortality, phenology, biodiversity, disturbance, hydrology, and soil biogeochemistry. Individual plants of different functional types compete mechanistically in ED under local environmental conditions for light, water, and nutrients. ED differs from most other terrestrial models by formally scaling up physiological processes through individual-based vegetation dynamics to ecosystem scales, while simultaneously modeling natural disturbances, land use, and the dynamics of recovering lands.	Ma, L., Hurtt, G., Ott, L., Sahajpal, R., Fisk, J., Lamb, R., Tang, H., Flanagan, S., Chini, L., Chatterjee, A., and Sullivan, J.: Global evaluation of the Ecosystem Demography model (ED v3.0), <i>Geosci. Model Dev.</i> , 15, 1971–1994, 2022
ENCORE	Exploring Natural Capital Opportunities, Risks and Exposure	ENCORE (Exploring Natural Capital Opportunities, Risks and Exposure) is a free, online tool that helps organisations explore their exposure to nature-related risk and take the first steps to understand their dependencies and impacts on nature. The ENCORE natural capital module sets out how the economy – sectors, subsectors and activities – depends and impacts on nature. This covers 21 sectors, 25 ecosystem services, 13 pressures and 8 natural capital and biodiversity components. "Materiality" scores from "very low" to "very high" are used to qualify the potential pressure or dependency of an economic activity. Input-output models have been using this database to link nature with economy.	Bekker, S. et al. (2026). ENCORE: the global infrastructure for screening business risks, dependencies and impacts on nature. <i>EcoEvoRxiv</i> [Preprint]. https://ecoevorxiv.org/repository/view/14794/
ENV-Linkages	ENV-Linkages	The ENV-Linkages model is a tool for evaluating the economic, environmental, and social impacts of policy decisions, particularly related to sustainable development. It integrates both macroeconomic and environmental models to simulate the effects of various policies on the economy, society, and the environment.	Château, J., R. Dellink and E. Lanzi (2014), "An Overview of the OECD ENV-Linkages Model: Version 3", OECD Environment Working Papers, No. 65, OECD Publishing, Paris.
EXIOBASE(MRIO)	EXIOBASE 3	EXIOBASE 3 provides a time series of environmentally extended multi-regional input-output (EE MRIO) tables ranging from 1995 to a recent year. Of the available EE MRIO databases, EXIOBASE stands out as a database compatible with the System of Environmental-Economic Accounting (SEEA) with a high sectorial detail matched with multiple social and environmental satellite accounts. The overall objective of EXIOBASE is to provide a global EE MRIO database with high suitability for environmental analysis. Starting from the initial version, EXIOBASE aimed to be suitable for answering sustainability questions of the EU and its main trading partners as well as for major global economies.	Stadler et al. "EXIOBASE 3: Developing a Time Series of Detailed Environmentally Extended Multi-Regional Input-Output Tables." <i>Journal of Industrial Ecology</i> 22, no. 3 (2018): 502–15.

Model	Model Full Name	Objective	Reference
EXIOMOD	EXtended Input-Output MODEL	EXIOMOD is an "environmentally extended" economic model able to measure the environmental impact of economic activities. As a multisector model, it accounts for the economic dependency between sectors. It is also a global and multi-country model with a consistent trade linking between countries at the commodity level. Based on national account data, it can provide compressive scenarios regarding the evolution of key economic variables such as GDP, value-added, turn-over, (intermediary and final) consumption, investment, employment, trade (exports and imports), public spending or taxes. While its core model concerns intra-economy interactions, it has been extended (the "EX" in "EXIOMOD") to cover economy interactions with other domains. Thanks to its environmental extensions, it makes the link between the economic activities of various agents (sectors,consumers) and the use of a large number of resources (energy, mineral, biomass, land, water) and negative externalities (greenhouse gases, wastes). EXIMOD uses EXIOBASE database.	Bulavskaya, T. et al. (2016) 'EXIOMOD 2.0: EXtended Input-Output MODEL : A full description and applications'
FABLE	Food, Agriculture, Biodiversity, Land-Use and Energy	Quantifies impacts of future agricultural and land use policy scenarios on land use, food security, food consumption, water use, GHG emissions, and biodiversity conservation. The FABLE consortium consists of 29 country teams who co-create national scale pathways for sustainable land use and food systems with policy makers through "Scenathons" (scenario marathons),which are then aggregated at the global scale with rest of the world regions, taking account of trade, and compared against global targets.	Mosnier, A., et al.: A decentralized approach to model national and global food and land use systems, Environ. Res. Lett, 18, 045001, https://doi.org/10.1088/1748-9326/acc044 , 2023a. Mosnier, A., et al.: How can diverse national food and land-use priorities be reconciled with global sustainability targets? Lessons from the FABLE initiative, Sustain Sci, 18, 335–345, https://doi.org/10.1007/s11625-022-01227-7 , 2023b.
FATE-HD	FATE-HD	FATE-HD is a dynamic landscape vegetation model that simulates interactions between plant modelling entities (e.g., species or plant functional groups), their population dynamics and dispersal, whilst taking into account external drivers such as disturbance regimes, and environmental variations.	Isabelle B, Damien G, Wilfried T. FATE-HD: a spatially and temporally explicit integrated model for predicting vegetation structure and diversity at regional scale. Glob Chang Biol. 2014;20(7):2368-2378.
FCM	Fuzzy Cognitive Maps	The Fuzzy Cognitive Maps (FCM) supports stakeholder involvement the delivery of effective positive action to help preserve nature and/or tackle climate challenges. It provides a formal way to integrate and test expert knowledge mapping the relations between elements (e.g., concepts, events, project resources) of a "mental landscape" and the "strength of impact" of these elements. The focus is on understanding not predictions and the approach can incorporate multiple expert stakeholders form diverse	Sarmiento, I., Cockcroft, A., Dion, A. et al. Fuzzy cognitive mapping in participatory research and decision making: a practice review. Arch Public Health 82, 76 (2024).

Model	Model Full Name	Objective	Reference
		backgrounds. An FCM consists of biophysical models combined with qualitative data.	
FeliX	Full of Economic-Environment Linkages and Integration dX/dt	The FeliX model predicts on a global scale major stock changes (e.g., depletion of natural resources, accrual of carbon dioxide in the atmosphere) and the aggregate consequences of policies and technologies (e.g., afforestation, emissions reduction) over time. It explicitly incorporates human behaviors and their dynamic interactions among global systems. FeliX includes nine integrated modules, population, economy, energy, water, land, food, carbon cycle, climate, and biodiversity (sp extinction rate, mean sp. abundance and sp. regeneration rates).	Ye, Q., Liu, Q., Swamy, D., Gao, L., Moallemi, E. A., Rydzak, F., Eker, S., 2024. FeliX 2.0: An integrated model of climate, economy, environment, and society interactions. <i>Environmental Modelling & Software</i> 179, 106121.
Future-EI	Future-EI	The Future EI is a model pipeline coupling spatial explicit land use change model, process based models of Nature contribution to people, and Species Distribution Models. It provides prediction of spatially explicit land use change, species diversity and NCP (including provision of food, fiber and fuel) resulting from policy and/or demographic drivers.	Black, B., Adde, A., Farinotti, D., Guisan, A., Külling, N., Kurmann, M., Martin, C., Mayer, P., Rabe, S.-E., Streit, J., Zekollari, H., Grêt-Regamey, A., 2024. Broadening the horizon in land use change modelling: Normative scenarios for nature positive futures in Switzerland. <i>Reg Environ Change</i> 24, 115.
GAINS	Greenhouse Gas - Air Pollution Interactions and Synergies	The GAINS model is an analytical framework for assessing future potentials and costs for reducing air pollution impacts on human health and the environment while simultaneously mitigating climate change through reduced greenhouse gas emissions. It explores synergies and trade-offs in cost-effective emission control strategies so as to maximize benefits across multiple scales.	Amann, M., Bertok, I., Borken-Kleefeld, J., Cofala, J., Heyes, C., Höglund-Isaksson, L., Klimont, Z., Nguyen, B., Posch M, Rafaj P, Sandler R, Schoepp W, Wagner F, Winiwarter W. (2011). Cost-effective control of air quality and greenhouse gases in Europe: Modeling and policy applications. <i>Environmental Modelling & Software</i> 10.1016/j.envsoft.2011.07.012 and Höglund-Isaksson, L., Gomez-Sanabria, A., Klimont, Z. Rafaj, P., & Schöpp, W. (2020). Technical potentials and costs for reducing global anthropogenic methane emissions in the 2050 timeframe –results from the GAINS model. <i>Environmental Research Communications</i> 2 (2), e025004. 10.1088/2515-7620/ab7457
GCAM	Global Change AnalysisModel GCAM	GCAM supports the prediction of impacts on commodity prices, energy use, land-use, water use, emissions, climate of different future scenarios. Future scenarios can incorporate population labour technology and policy, and outputs are semi-spatially explicit. GCAM consists of a global energy-economic-agriculture-land use market equilibrium model linked with a simple climate model, with an optional demeter model to downscale land-use change prediction to user defined scales.	Calvin, Katherine, et al. "GCAM v5. 1: representing the linkages between energy, water, land, climate, and economic systems." <i>Geoscientific Model Development</i> 12.2 (2019): 677-698. Zhao, Xin, et al. "Trade-offs in land-based carbon removal measures under 1.5 C and 2 C futures." <i>Nature Communications</i> 15.1 (2024): 2297.

Model	Model Full Name	Objective	Reference
GLOBIO	GLObal Biodiversity model	The GLOBIO model assesses impacts of future policy pathways and scenarios on terrestrial biodiversity at regional and global level. It produces mean species abundance (MSA) indicator driven by six human pressures: land use, road disturbance, fragmentation, hunting, atmospheric nitrogen deposition and climate change.	Schipper AM, Hilbers JP, Meijer JR, et al. Projecting terrestrial biodiversity intactness with GLOBIO 4. <i>Glob Change Biol.</i> 2020; 26: 760–771.
GLOBIOM & iBIOM	Global Biosphere Management Model	GLOBIOM & iBIOM models allow exploration of implications of policy on land use, fresh water quality and quantity, biomass energy deployment, agriculture and forestry management and climate change. It is achieved in iBIOM modeling platform by coupling the spatial explicit economic equilibrium land use model GLOBIOM to models of species diversity, fresh water dynamics (quantity and quality), agriculture and forestry management, and responses to climate change.	IBF-IIASA (2023). Global Biosphere Management Model (GLOBIOM) Documentation 2023 - Version 1.0. International Institute for Applied Systems Analysis , Laxenburg, Austria. https://pure.iiasa.ac.at/18996 .
GMBI	General Model of Biological Invasions	GMBI is a population dynamics of alien species with discrete time steps and spatially explicit.	Savage & Renton (2014) Requirements, design and implementation of a general model of biological invasion. <i>Ecological Modelling</i> , 272, 394-409. .
HexSim	HexSim	The HexSim is a platform for simulating plant or wildlife population dynamics and interactions. IT is a spatially-explicit, individual-based model that allows forecasting and backdating of species dynamics in response to a range of stressors (e.g., land use or climate change) and interactions with other species. HexSim is also used in other disciplines such as epidemiology and landscape genetics.	Schumaker NH, Brookes A. 2018. HexSim: a modeling environment for ecology and conservation. <i>Landscape Ecology</i> 33:197-211.
IAP	Integrated Assessment Platform	The CLIMSAVE Integrated Assessment Platform (IAP2.1) is a user-friendly, interactive web-based tool that enables European stakeholders to explore the complex multi-sectoral issues surrounding impacts, vulnerability and adaptation to climate and socio-economic change across Europe within the agriculture, forestry, biodiversity, water, coastal and urban sectors. It integrates 10 meta-models (including Watergap and LPJGuess).	Harrison PA, et al. (2016). Climate change impact modelling needs to include cross-sectoral interactions. <i>Nature Climate Change</i> , 6(9): 885-890. DOI: 10.1038/NCLIMATE3039. Harrison PA, et al. (2015). Cross-sectoral impacts of climate change and socio-economic change for multiple European land- and water-based sectors. <i>Climatic Change</i> , 128: 279-292, DOI 10.1007/s10584-014-1239-4.
IBAT/STAR	Integrated Biodiversity Assessment Tool / Species Threat Abatement and Restoration	The IBAT is a planning tool primarily for business providing (paid for) assessment of likely biodiversity impact of proposed development (e.g., new infrastructure) helping organizations identify and act on biodiversity related risks and opportunities. It utilizes global spatially explicit biodiversity data sets to identify at risk species. It is paid for impact reports, includes STAR metric, and generates funding to support biodiversity datasets.	Mair, L., Bennun, L.A., Brooks, T.M. et al. A metric for spatially explicit contributions to science-based species targets. <i>Nat Ecol Evol</i> 5, 836–844 (2021).
IFs	International Futures	The IFs model to support the exploration of long-term global future for 188 countries. It links responses to user defined scenarios across economic, demographic, education, health, environment,	Hughes, Barry B. Exploring and Shaping International Futures. Fifth. World-Systems Evolution and Global

Model	Model Full Name	Objective	Reference
		technology, domestic governance, infrastructure, agriculture, energy and environment.	Futures. Springer, 2026. https://doi.org/10.1007/978-3-032-22084-4 .
IMAGE-DGNM	IMAGE-Dynamic Global Nutrient Model	IMAGE-DGNM is a spatially explicit, globally applicable framework that dynamically simulates in-stream biogeochemical processes. Simulated compounds, transformation and exchange processes, and their parameterization are user defined. IMAGE-DGNM can be used for hindcasting and projections, including on long-term pollution legacy effects in fresh waters, groundwater and soils. IMAGE-DGNM is coupled with the integrated assessment model IMAGE.	Vilmin, L., Mogollón, J. M., Beusen, A. H. W., van Hoek, W. J., Liu, X., Middelburg, J. J., & Bouwman, A. F. (2020). Modeling process-based biogeochemical dynamics in surface fresh waters of large watersheds with the IMAGE-DGNM framework. <i>Journal of Advances in Modeling Earth Systems</i> , 12, e2019MS001796.
InVEST	Integrated Valuation of Ecosystem Services and Tradeoffs	The InVEST model supports mapping the impact on goods and services from nature that sustain human life (food, water quantity and quality etc.) of alternative management choices. It enables decision makers to assess quantified tradeoffs associated with alternative management choices and to identify areas where investment in natural capital can enhance human development and conservation. The model consists of a suite of open source models.	J.W. Redhead, C. Stratford, K. Sharps, L. Jones, G. Ziv, D. Clarke, T.H. Oliver, J.M. Bullock, Empirical validation of the InVEST water yield ecosystem service model at a national scale, <i>Science of The Total Environment</i> , Volumes 569–570, 2016, Pages 1418-1426, ISSN 0048-9697
JULES	Joint UK Land Environment Simulator	The JULES is a land surface model, simulating land-atmosphere exchanges of water, energy, carbon and nitrogen, and stores and fluxes in soil and vegetation. It is capable of predicting response of atmospheric processes and feedbacks resulting from changes in land use/management and climate.	Best, M. J., Pryor, M., Clark, D. B., Rooney, G. G., Essery, R. L. H., Ménard, C. B., Edwards, J. M., Hendry, M. A., Porson, A., Gedney, N., Mercado, L. M., Sitch, S., Blyth, E., Boucher, O., Cox, P. M., Grimmond, C. S. B., and Harding, R. J.: The Joint UK Land Environment Simulator (JULES), model description – Part 1: Energy and water fluxes, <i>Geosci. Model Dev.</i> , 4, 677–699, , 2011.
JUNIPER	Joint Use of Nexus Indicators for Policy and Environmental Resilience	JUNIPER is a data-driven system dynamics model that operationalises the Water–Energy–Food–Transport–Health–Biodiversity (WEFTHB) nexus. Using harmonised annual data, it represents cross-sectoral interactions and produces indicators for water, energy, food, transport, health, greenhouse gas emissions and biodiversity (RLI and RLle) at national and European levels. It supports historical baseline assessment and scenario-based policy screening.	Ioannou, A., Kasiteropoulou, D., Ziliaskopoulos, K., & Laspidou, C. (2026). JUNIPER: Joint Use of Nexus Indicators for Policy and Environmental Resilience—Case Study of Greece. SSRN. https://doi.org/10.2139/ssrn.6863181 Ioannou, A., Kasiteropoulou, D., Ziliaskopoulos, K., & Laspidou, C. (2025). WEFTH Nexus Data 2000–2019 for Six European Countries (JUNIPER model) [Dataset]. Zenodo. https://doi.org/10.5281/zenodo.16947695
LANDIS-II	LANDscape Disturbance and Succession, version II	The LANDIS-II is a forest succession model capable of predicting how forest and scrub land will respond to different future scenarios based on response to abiotic factors (including future climate) and human interventions. It predicts tree species diversity, and via a set of extension, bird and mammal species abundance and diversity, and water flows .	Scheller, R. M., J. B. Domingo, B. R. Sturtevant, J. S. Williams, A. Rudy, E. J. Gustafson, and D. J. Mladenoff. 2007. Design, development, and application of LANDIS-II, a spatial landscape simulation model with flexible spatial and temporal resolution. <i>Ecological Modelling</i> 201 (3-4): 409-419.

Model	Model Full Name	Objective	Reference
LandSHIFT	LAND Simulation to Harmonize and Integrate Freshwater availability and the Terrestrial environment	LandSHIFT is a tool for medium-term scenario analysis (20–50 years) and the assessment of environmental impacts of land-use change. It is designed to carry out a wide range of tasks, including the identification of competition for land and future “hot spots” of land-use change as well as the comparison of future rates of change in different parts of the world. We classify LandSHIFT as an integrated land system model as it provides a link between the human dimensions of land-use change (including economic drivers) with simulations of climate, the water cycle, biodiversity risk, and other global change processes and issues. It couples national or regional projections of land use demands with downscaling of land use change patterns at roughly 9x9 km grid resolution in global and 1x1 km grid resolution in sub-national simulation experiments.	Jan Schüngel, Benjamin Stuch, Claudia Fohry, Rüdiger Schaldach, Effects of initialization of a global land-use model on simulated land change and loss of natural vegetation, Environmental Modelling & Software, Volume 148, 2022, 105287, ISSN 1364-8152, . Schaldach, R., Alcamo, J., Koch, J., Kölling, C., Lapola, D. M., Schüngel, J., & Priess, J. A. (2011). An integrated approach to modelling land-use change on continental and global scales. Environmental Modelling & Software, 26(8), 1041-1051.
LandSyMM	LandSyMM: the Land System Modular Model	LandSyMM is an integrated framework that provides predictions of future land use under alternative futures (scenarios) and the resulting impacts on food, fiber, biodiversity, ecosystem services and climate. It couples process based models to provide spatially explicit prediction, representing interactions between land use, climate, ecosystems and human decision-making, which include a socio-economic, land-use model (PLUM), a dynamic global vegetation model (LPJ-GUESS), a general ecosystem model of trophic levels (Madingley), a climate system emulator (IMOGEN), and a sub-national behavioral model of land user decision-making (CRAFTY).	Arneth A, Leadley, P., Claudet, J., Coll, M., Rondinini, C., Rounsevell, M.D.A., Shin, Y., Alexander, P., Fuchs, R. 2023. Making protected areas effective for biodiversity, climate and food. Global Change Biology 1–12; Burns, J. et al., Global land futures under values-based scenarios of the Kunming-Montreal Global Biodiversity Framework (January 16, 2026). https://ssrn.com/abstract=6770023
LM3-TAN	Land Model (LM3)-TAN (Terrestrial and Aquatic Nitrogen)	The LM3-TAN model predicts the combined terrestrial effects of anthropogenic N inputs, atmospheric CO ₂ , land use, and climate on water and air pollution.	Lee, M., Malyshev, S., Shevliakova, E., Milly, P. C. D., and Jaffé, P. R.: Capturing interactions between nitrogen and hydrological cycles under historical climate and land use: Susquehanna watershed analysis with the GFDL land model LM3-TAN, Biogeosciences, 11, 5809–5826, 2014.
LPI	Living Planet Index	The LPI is developed on a biodiversity model that uses population level information and environmental variables (land-use change and climate change) to predict vertebrate population trends spatially and temporally. The model is linked to a biodiversity indicator, aimed at tracking progress towards national and international policy targets; communication tool; global biodiversity change research.	Cornford, R. et al. (2023) ‘Ongoing over-exploitation and delayed responses to environmental change highlight the urgency for action to promote vertebrate recoveries by 2030’, Proceedings of the Royal Society B: Biological Sciences, 290(1997); McRae L, Deinet S, Freeman R (2017) The Diversity-Weighted Living Planet Index: Controlling for Taxonomic Bias in a Global Biodiversity Indicator. PLoS ONE 12(1): e0169156

Model	Model Full Name	Objective	Reference
LPJ-GUESS	Lund–Potsdam–Jena General Ecosystem Simulator	The LPJ-GUESS is a dynamic global vegetation model, which simulates carbon-water-nitrogen cycling in ecosystems in response to predictions of land-use change and climate change.	Smith B, Warlind D, Arneth A, Hickler T, Leadley P, Siltberg J, et al. Implications of incorporating N cycling and N limitations on primary production in an individual-based dynamic vegetation model. <i>Biogeosciences</i> . 2014;11(7):2027-54.
Madingley	Madingley	Madingley is an integrated processbased, mechanistic, general ecosystem model that uses a unified set of fundamental ecological concepts and processes to predict the structure and function of the ecosystems at various levels of organization for marine or terrestrial.	Harfoot, M. B. J. et al. 2014. Emergent global patterns of ecosystem structure and function from a mechanistic general ecosystem model. – <i>PLoS Biol</i> .
MAGNET	Module Applied General Equilibrium Tool	The MAGNET model supports the assessment of the impact of policy scenarios on land use, agriculture prices, bioenergy production, nutrition and household food security. The model projects impacts at the level of country or region and thus are not spatially explicit. It is a global macro-economic model with focus on bioeconomy and land use.	Woltjer & Kuiper (2014) 'The MAGNET Model: Module description'.
MAGPIE	Model of Agricultural Production and its Impact on the Environment	The MAGPIE model assesses global land-system dynamics in response to a wide range of scenario drivers.. It is spatially explicit and the objective function of the model is to minimise the cost of production for a given amount of regional food, feed and bioenergy demand under biophysical and socioeconomic constraints. Biophysical constraints include dynamic crop yields, water availability, or cropland availability. Socioeconomic constraints include production costs, technological change, trade patterns or a broad set of policy interventions. Crop, water and vegetation dynamics (e.g., forest growth and associated carbon uptake) are derived from the grid-based dynamic vegetation model LPJmL.	Bodirsky, B. L., Beier, F., Humpenöder, F., Leip, D., Crawford, M. S., Chen, D. M.-C., von Jeetze, P., Springmann, M., Soergel, B., Nicholls, Z., Streffer, J., Lewis, J., Heinke, J., Müller, C., Karstens, K., Weindl, I., Stevanović, M., Rein, P., Sauer, P., ... Popp, A. (2025). A food system transformation pathway reconciles 1.5 °C global warming with improved health, environment and social inclusion. <i>Nature Food</i> , 6(12), 1133–1152. https://doi.org/10.1038/s43016-025-01268-y
MEDEAS	pymedeas/MEDEAS	The MEDEAS model supports the energy transition towards a zero carbon economy taking into account physical as well as social constraints. It incorporates environmental and material limits, including limits and impact of land use for renewable energy production, energy scarcity, climate change impacts, materials scarcity and socioeconomic issues including the creation and quality of jobs.	Solé, J. et al. (2020) 'Modelling the renewable transition: Scenarios and pathways for a decarbonized future using pymedeas, a new open-source energy systems model', <i>Renewable and Sustainable Energy Reviews</i> , 132, p. 110105
MetaLandSim	MetaLandSim	The MetaLandSim is a model that simulates species persistence on dynamic landscapes, in a way which can be easily combined with land use and climate change scenarios. This enables the prediction of metapopulation dynamics and range expansion for a variety of taxa and ecological systems.	Frederico Mestre, Fernando Cánovas, Ricardo Pita, António Mira, Pedro Beja, An R package for simulating metapopulation dynamics and range expansion under environmental change, <i>Environmental Modelling & Software</i> , Volume 81, 2016, Pages 40-44, ISSN 1364-8152.

Model	Model Full Name	Objective	Reference
MRIO-GTAP	Multi Regional Input Output	The MRIO is an economic approach which track financial flows between countries' major economic sectors. MRIO approaches can be extended from financial flows to estimate resource flows by incorporating data from the National Footprint and Biocapacity Accounts. The MRIO-based Footprint data allows us to track detailed resource flows between countries' major economic sectors to further sub-categorize national Footprint data into more specific consumption and industry related components.	
NCAR- CLM	National Centre for Atmospheric Research - Community Land use Model	The NCAR-CLM model improves climate modelling by examining the physical chemical and biological processes by which terrestrial ecosystems affect and are affected by the climate. In addition to modelling impact of land use and management on atmospheric process and climate change, CLM provides predictions of food production, frequency of forest fire, air quality, terrestrial carbon storage, and water fluxes.	Lawrence, D. M., Fisher, R. A., Koven, C. D., Oleson, K. W., Swenson, S. C., Bonan, G., et al. (2019). The Community Land Model version 5: Description of new features, benchmarking, and impact of forcing uncertainty. <i>Journal of Advances in Modeling Earth Systems</i> , 11, 4245–4287.
PLAIA	PLAIA	PLAIA models the global plastics sector and its impacts up to 2100 for 26 world regions, providing a long-term, dynamic perspective of the sector and its interactions with other socioeconomic and natural systems. The model links the upstream chemical production with the downstream production of plastics, their use in different sectors, and their end of life. Therefore, PLAIA can assess material use and emission mitigation strategies throughout the whole life cycle in an IAM/IMAGE, including the impacts of the circular economy on mitigating climate change. PLAIA projects plastics demand, production pathways and specifies the annual plastic waste generation, collection, and the impact of waste management strategies. It also shows the fossil and bio-based energy and carbon flows in product stocks, landfills, and the emissions in production and at the end of life.	Paul Stegmann, Vassilis Daioglou, Marc Londo, Martin Junginger, The plastics integrated assessment model (PLAIA): Assessing emission mitigation pathways and circular economy strategies for the plastics sector, <i>MethodsX</i> , Volume 9, 2022, 101666, ISSN 2215-0161, .
PLUM	Parsimonious Land Use Model	PLUM simulates global land use and food-system dynamics in response to changes in food demand, crop yields, climate and other scenario drivers. It represents spatially explicit changes in land use and management intensity, including agricultural expansion and intensification, with crop yield responses derived from the LPJ-GUESS dynamic vegetation model. Food and timber demand are represented using the Modified An Implicit Directly Additive Demand System (MAIDADS), with commodity prices and international trade modelled endogenously. PLUM links demand and market conditions to land-use and production decisions, allowing feedbacks between demand, prices, trade, yields and land use to emerge.	Alexander, P., Rabin, S., Anthoni, P., Henry, R., Pugh, T. A. M., Rounsevell, M. D. A., & Arneth, A. (2018). Adaptation of global land use and management intensity to changes in climate and atmospheric carbon dioxide. <i>Global Change Biology</i> , 24, 2791–2809. https://doi.org/10.1111/gcb.14110 . Arendarczyk, B., Rabin, S., Bampoh, D., Arneth, A., Rounsevell, M. D. A., & Alexander, P. (2025). Response of global forest management to changes in wood demand. <i>Global Change Biology</i> , 31, e70573. https://doi.org/10.1111/gcb.70573 .

Model	Model Full Name	Objective	Reference
PREDICTS	Projecting Responses of Ecological Diversity In Changing Terrestrial Systems	PREDICTS models and predicts how land use, land management and related pressures affect terrestrial biodiversity (species abundance, richness and compositional similarity). It is the foundation of the Biodiversity Intactness Index (BII) and aims to support decision makers to choose scenarios or actions that are good for nature with a focus on local ecosystem health, which can be averaged meaningfully within any area of interest. The statistical models are fitted to data from a large and still-growing global database on the composition of species communities across a gradient of land use and land use intensities collected from published literature.	De Palma, A., Hoskins, A., Gonzalez, R.E. et al. Annual changes in the Biodiversity Intactness Index in tropical and subtropical forest biomes, 2001–2012. Sci Rep 11, 20249 (2021).
RangeShifter	RangeShifter	The RangeShifter is a spatially-explicit, individual-based simulation platform that allows modelling species' range dynamics, such as expansion and shifting, and patch connectivity by linking complex local population dynamics and dispersal behaviour, while also taking into account inter-individual variability and evolutionary processes. It is highly flexible in terms of the spatial resolution and extent, and regarding the complexity of the considered ecological processes. Due to its modular structure, the level of detail in demographic and dispersal processes can be easily adapted to different research questions and available data.	Bocedi G, Palmer SCF, Malchow AK, Zurell D, Watts K, Travis MJJ (2021) RangeShifter 2.0: An extended and enhanced platform for modelling spatial eco-evolutionary dynamics and species' responses to environmental changes. Ecography 44:1453-1462.
ReCiPe	ReCiPe	The ReCiPe is a method for the life cycle impact assessment (LCIA) with the primary objective to transform the long list of life cycle inventory results into a limited number of indicator scores at midpoint and endpoint of damage/impact pathways. Three areas of protection at the end point include human health, ecosystem quality, resource scarcity. Environmental mechanisms include climate change, ozone depletion, ionizing radiation, fine particulate matter, photochemical ozone formation, terrestrial acidification, freshwater eutrophication, marine eutrophication, toxicity, mineral resource scarcity, fossil resource scarcity.	Huijbregts, M.A.J., Steinmann, Z.J.N., Elshout, P.M.F. et al. ReCiPe2016: a harmonised life cycle impact assessment method at midpoint and endpoint level. Int J Life Cycle Assess 22, 138–147 (2017).
SEALS	Spatial Economic Allocation Landscape Simulator	The SEALS model predicts land-use change, integrating with IAMs or CGEs to convert regional estimates of change to high-resolution estimates.	von Jeetze, P.J., Weindl, I., Johnson, J.A. et al. Projected landscape-scale repercussions of global action for climate and biodiversity protection. Nat Commun 14, 2515 (2023).
SEED	Sustainable Ecology and Economic Development	The SEED model provides a standardized estimate (index value) of biodiversity intactness that is inclusive of all levels of ecological variation and taxonomic groups. It is produced by combining earth observation with global datasets to define an index value, and provided as a paid for service provided to companies and government (e.g., 30 x30 m resolution).	McElderry, R. M. et al. (2023) 'Assessing the multidimensional complexity of biodiversity using a globally standardized approach'.
SIMPLE-G	A Simplified International	The SIMPLE-G is a global gridded economic equilibrium model that represents spatially differentiated supply, demand and markets for	Haqiqi and Hertel (eds.), SIMPLE-G: A Gridded Economic Approach to Analysis of Sustainability of

Model	Model Full Name	Objective	Reference
	Model of Prices Landuse and the Environment-Gridded	land, water, fertilizer and other agricultural inputs. It links 750-m to 10-km grid-cell decisions with global food markets: changes in food demand affect local land use, while local production and land-use decisions feed back into prices, trade and food-security outcomes. Its land-use module distinguishes protected and natural land, cropland, pastureland and managed forest, with location-specific land-conversion suitability and profitability. Economic and environmental adjustments are linked across locations through crop, labor and other commodity markets, generating spatial spillovers between local decisions and wider market conditions. The multi-crop version connects changes in global demand for individual crops to local input use, land-use decisions and land-cover outcomes. SIMPLE-G has been used to assess biodiversity and conservation targets under location-specific market incentives and biophysical constraints.	the Earth's Land and Water Resources; Springer, 2025. doi: 10.1007/978-3-031-68054-0
SWAT	Soil and Water Assessment Tool	SWAT is a continuous watershed model developed by the USDA-ARS. Using a daily time-step, SWAT employs a digital elevation model (DEM), soils, land cover, and climate data (specifically, precipitation, temperature, wind speed, solar radiation, and relative humidity) to define HRUs that are nonspatially located in a sub-basin. In each HRU, SWAT reproduces water, plant, nutrient, and other land processes, the water and eroded sediments are transferred to the sub-basin outlet and routed from there throughout the basin using variations of the kinematic wave flood method. Water flow is then used to model the fate of sediments, nutrients, and other water quality properties. As previously mentioned, SWAT may be the most popular watershed model, likely due to its public domain license (cc-zero), detailed documentation, computational efficiency, parsimonious model structure for many subroutines, and user-friendly GUI.	Bieger, Katrin, Jeffrey G. Arnold, Hendrik Rathjens, Michael J. White, David D. Bosch, Peter M. Allen, Martin Volk, and Raghavan Srinivasan, 2017. Introduction to SWAT+, a Completely Restructured Version of the Soil and Water Assessment Tool. Journal of the American Water Resources Association (JAWRA) 53(1): 115-130.
TreeMig	TreeMig	The TreeMig forest landscape model predicts forest succession and tree species migration, capable of modelling both natural and plantation forest. It is ideally suited to predicting temporal and spatial change in forest species and structural diversity over extended time periods (100yrs) due to climate change at local to continental scale.	Lischke, H., Zimmermann, N.E., Bolliger, J., Rickebusch, S. & Löffler, T.J. (2006) TreeMig: A forest-landscape model for simulating spatio-temporal patterns from stand to landscape scale. Ecological Modelling, 199, 409-420. Lischke, H., Böhm, D., Schmatz, D. R., Psomas, A., Löffler, T., Joss, A. and Scherrer, D. 2026. TreeMig framework ver. 1.0: an R package with GUI to simulate spatio-temporal forest dynamics. - Ecography 11. doi: 10.1002/ecog.08172.

Model	Model Full Name	Objective	Reference
WaterGAP	Water - Global Assessment and Prognosis	The WaterGAP model computes water flows and storages as well as human water use on all continents of the Earth except Antarctica during 1901 to present or under future climate change.	Müller Schmied, H., Cáceres, D., Eisner, S., Flörke, M., Herbert, C., Niemann, C., Peiris, T. A., Popat, E., Portmann, F. T., Reinecke, R., Schumacher, M., Shadkam, S., Telteu, C.-E., Trautmann, T., Döll, P. (2021): The global water resources and use model WaterGAP v2.2d: Model description and evaluation. Geosci. Model Dev., 14, 1037–1079.
World3	World3	The World3 model is a coarse, non spatially explicit system dynamics model for computer simulation of interactions between population, industrial growth, food production and limits in the ecosystems of the earth. The main systems are: population, non renewable resources, pollution, industrial output, food, services, life expectancy, human welfare, ecological footprint. It was originally produced and used by a Club of Rome study that produced the model and the book The Limits to Growth (1972) and was recently updated for a new run (2020).	Nebel, A., Kling, A., Willamowski, R., & Schell, T. (2024). Recalibration of limits to growth: An update of the World3 model. Journal of Industrial Ecology, 28, 87–99.
WRF	Weather Research and Forecasting	The WRF model supports weather forecasting and the prediction of impact on weather of changes in land use, GHG emissions and climate. It provides accurate numerical weather predictions and atmospheric simulation tools for both research and operational forecasting.	Skamarock W C, Klemp J B, Dudhia J, Gill D O. Barker DM, Duda M G, Huang X Y, Wang W and Powers J G 2008: A Description of the Advanced Research WRF Version 3; Mesoscale and Microscale Meteorology Division, National Center for Atmospheric Research, Boulder, Colorado, USA, NCAR TECHNICAL NOTE. NCAR/TN-475+STR, June 2008, 113 pp.