Transforming Biodiversity Governance through Diversifying Values of Nature in Scenarios and Models

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Key messages:

- Improved use of scenarios and models that incorporate diverse values of nature can contribute to the achievement of the Global Biodiversity Framework through more systemic approaches (e.g., causality frameworks, detection and attribution) and evidence-based methods (e.g., integrated use of data, scenarios, and model-based indicators in designing and evaluating pathways towards achievement of the GBF).
- Scenarios play critical roles in both global and national biodiversity governance and assessment processes. Qualitative narrative development can facilitate inclusive governance, while quantitative assessment can strengthen evidence-based decisions.
- Models can support detection and attribution of biodiversity changes, especially in combination with fine-scale monitoring data of biodiversity and drivers of change. Where feasible and appropriate, biodiversity-centric modelling frameworks should be developed that incorporate key drivers and interventions with cross-sectoral policy to improve outcomes for nature and people.
- The Nature Futures Framework supports building positive futures for nature through a diverse set of perspectives on its nature and with causality-informed monitoring, assessment, and forecasting for scalable indicators, policy and spatial planning, and evidence generation.
- At the global level, collaborative capacity-building approaches (e.g., modellers networks) are needed to respond to evolving societal needs, including the financial sector that demands climate- and nature-related risk assessment and proactive mitigation/prevention.
- At the national level, governments need to coordinate and improve coherence across monitoring, modelling, indicator, and scenario programs, convening stakeholders to co-identify key questions, co-develop scenarios, and employ causality framework-based models that link to indicators used in key policy processes.
- Whole-of-society transformation requires engaging diverse agencies of change across scales and sectors. Improved coordination of science, policy and practice enhances resource and conservation efficacy.

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

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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 (UN 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. 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** (e.g., where to prioritise protection, restoration, and sustainable use based on the assessment of biodiversity and ecosystem services values, ecosystem degradations, and human needs, and for instance, considering accelerating climate change). Furthermore, there is a formal assessment within the CBD that evaluates whether the actions implemented by the Parties (i.e. nations) are 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 (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 as well as limitations**, including incomplete representation of biodiversity drivers, limited treatment of ecological interactions, substantial uncertainties in models and scenarios, and the scarcity of scenarios exploring alternative policy and management options (Rosa et al., 2017; Weiskopf et al., 2022, Rounsvelle et al. 2021).

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 dimensions of the global system and quantify future scenarios (Rotmans, 1990). In the terrestrial realm, the IMAGE modelling framework (Stehfest, 2014) provided one of the earliest platforms linking socioeconomic drivers to ecosystem outcomes globally. In the marine realm, Ecopath (Polovina 1984) offered a computationally efficient template for representing marine foodweb, later extended through EcoSim (Christensen and Paula 1992) with temporal and spatial dynamics. The global EwE/Ecopath-based ocean model (Alder et al. 2007) was developed as global marine IAM-equivalent projecting biomass and profits under different fishing efforts and socioeconomic drivers with EcoOcean (Coll et al 2022) integrating spatial-temporal foodweb dynamics.

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 development with quantitative modelling of land use, freshwater, fisheries, and biodiversity indicators (MA, 2005).

Since the MA, biodiversity research relied on the scenarios from the climate research – namely the **Representative Concentration Pathways (RCPs**, radiative forcing trajectories) and the **Shared Socioeconomic Pathways (SSP**, alternative socioeconomic futures defined by differing challenges to climate mitigation and adaptation with no further climate policies from the present day) – which informs the **Intergovernmental Panel on Climate Change (IPCC)** (Van Vuuren et al., 2011). The SSP-RCP scenario framework was supported by narratives and quantitative projections of population, GDP, energy, and land use (O'Neill et al., 2017; Riahi et al., 2017), which became the dominant framework for global environmental modelling, including biodiversity impact assessments (O'Neill et al. 2020).

Despite their widespread adoption, **SSP-RCP scenarios did not consider biodiversity policy objectives but only a limited set of socioeconomic futures**, mainly driven by differing trends in population and per capita income. Biodiversity was largely treated as a recipient of changes in climate and land and sea uses (Rosa et al. 2017, Kim et al. 2023). 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 (Alexander et al., 2023; Pereira et al., 2026). Similarly, although the **latest ScenarioMIP framework for 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).

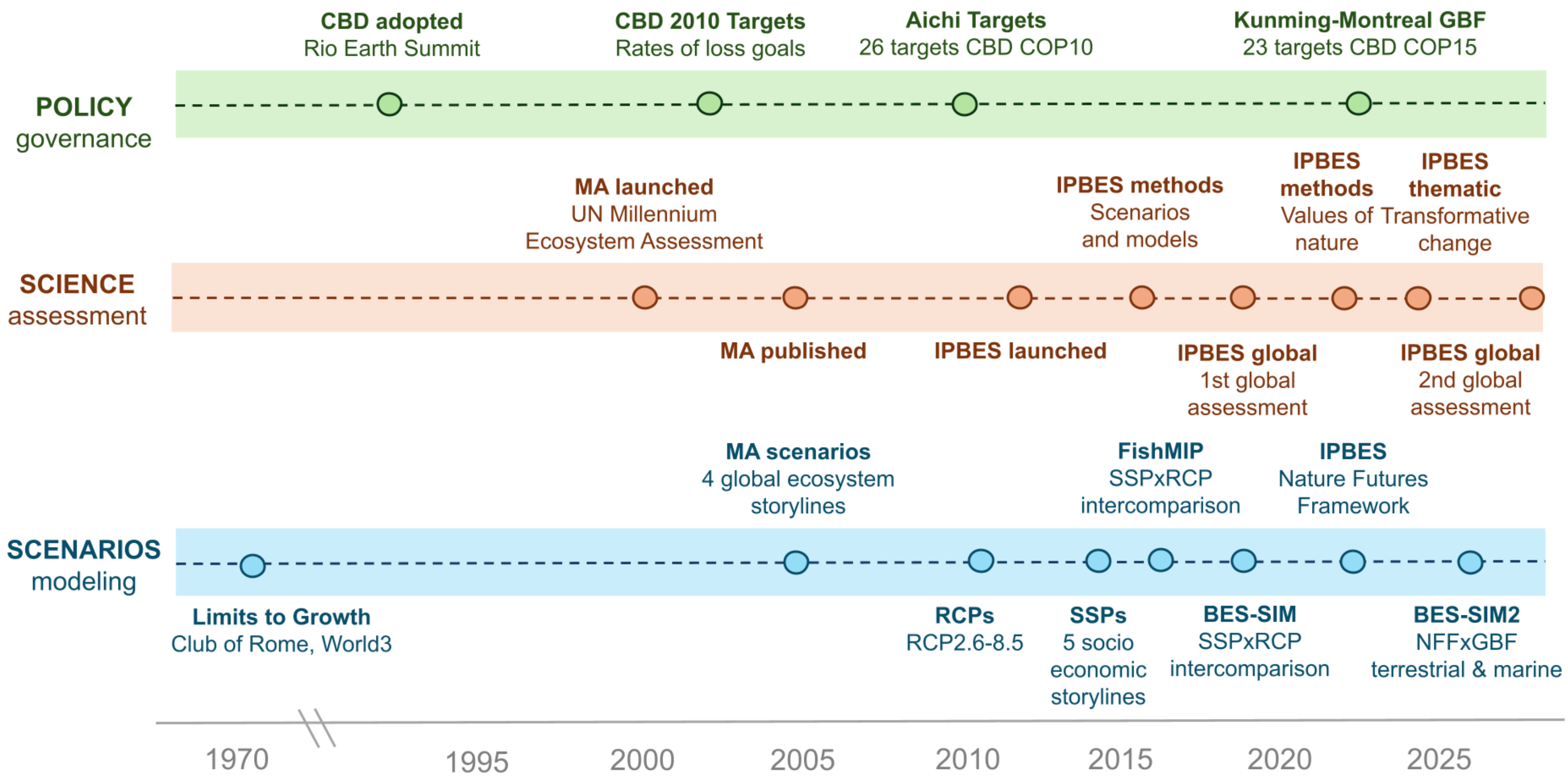

Figure 1. Chronogram of global policy (green), science (orange), and scenario (blue) initiatives focusing partly or in full on biodiversity and ecosystem services. Abbreviations are as follows: CBD = Convention on Biological Diversity; COP = Conference of the Parties; GBF = Global Biodiversity Framework; 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; SRES = Special Report on Emission Scenarios; RCP = Representative Concentration Pathways; SSP = Shared Socio-economic Pathways; AR = Assessment Report; BES-SIM = Biodiversity and Ecosystem Services Scenario-based Inter-Model comparison; NFF = Nature Futures Framework.

In the scientific collaboration space **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 their 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 (Tittensor et al. 2018; Lotze et al. 2019). The FishMIP ensemble suggested substantial trophic impacts from climate change, although as indicated above, 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 (2016) led to the **Biodiversity and Ecosystem Services Scenario-based Intercomparison of Models (BES-SIM)**, which informed the first global assessment of IPBES (2019) (Kim et al. 2018). Using harmonised land-use and climate inputs for three SSP-RCP combinations ranging low to high climate change to facilitate model intercomparisons across ten biodiversity and six ecosystem functioning and services models (though not all models could quantify climate-change impacts), BES-SIM projected continuing declines in terrestrial biodiversity and ecosystem services to 2050 across the pathways with substantial difference in the magnitude of change and geographic patterns (Pereira et al. 2024).

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

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 (Leclere 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 climate impacts were not considered (Leclere et al. 2020). Unlike SSPs, these scenarios had biodiversity goals, with some scenarios not permitting land-use changes that would have negative biodiversity impacts.

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' prioritizing intrinsic values where biodiversity thrives independently of human utility, 'Nature for Society' optimizing instrumental ecosystem services sustaining human wellbeing, and 'Nature for Culture' centering relational values and diverse ontologies recognizing nature as kin, teacher, and identity source. Importantly, these perspectives are not arranged hierarchically acknowledging mutually inclusive and reinforcing characteristics. Formally adopted by IPBES in 2022, the **NFF aligns closely with the CBD's 2050 vision of 'Living in Harmony with Nature', and shifts biodiversity change from being a passive outcome to being co-determinents for desired nature-positive futures** (IPBES 2025).

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, justice, agency and diverse knowledge systems** (Pereira et al., 2026, IPBES 2024-TCA). The **representation of biodiversity drivers has broadened beyond land-use and climate change**, although major gaps remain for exploitation, pollution, invasive alien species and interactions among drivers (Aschi et al., 2026, Lenzner et al. In review?), explicit dynamic scenarios of fishing as the only driver of marine biodiversity change in the global ocean (Maury et al. 2025) and underrepresentation of freshwater realm and cross-realm interactions (Kramer et al., 2023). The **growth-centric assumptions** embedded in sustainability scenarios (Otero et al., 2024), limited representation of **interlinkages and feedbacks between drivers** (Harrison et al. 2015), the weaving of **Indigenous and traditional knowledge** into quantitative workflows (McElwee et al., 2020), and the **translation of global scenario outputs into policy-relevant information** at national and sub-national scales (Rosa et al., 2017) **remain as key challenges**.

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). Following another decade of unmet ambitions, Parties adopted the **Kunming-Montreal Global Biodiversity Framework (KM-GBF)** in December 2022 (Figure 1), establishing four long-term goals spanning genes to ecosystems and nature's contributions to people, and 23 targets on broad-ranging biodiversity drivers in social and ecological systems (CBD Secretariat, 2022). The KM-GBF's **2050 vision of 'Living in Harmony with Nature' is operationalised through four 2050 'outcome' goals**. These relate to halting and reversing ecosystem loss and species extinction (Goal A), ensuring biodiversity is sustainably used 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**, grouped around three central themes, are set as the levers on the pathways towards achieving these goals, addressing biodiversity loss through reducing direct threats to biodiversity (T1-8), human-centered 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 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 review of collective progress'. In reality, parties tend to report mainly on national indicators and headline indicators but neglect others due to their complexity or absence of data or operational indicators for about 12% of the KM-GBF monitoring framework (Affinito et al. 2025). To date, the latest CBD global report documents government actions related to targets and how these might be delivering change. **However,** when it comes to the goals on biodiversity and ecosystem services outcomes, **it does not indicate whether the actions taken will lead to the achievement of the 2030 mission or 2050 goals** (CBD 2026 - global report).

Critical science-policy challenges remain informing national policies or monitoring global progress without the evidence base in the **current landscape of parallel processes without joint**

mechanisms (Leadley et al., 2022, McGowan et al., 2024; Perino et al., 2022). Achieving the global goals requires a **whole-of-society approach** with all societal actors as agencies of change (IPBES 2019, 2024-TCA). This means national governments, academics, private sectors, civil society, and Indigenous and local communities to co-produce **scale- and context-relevant evidence**, **integrating sources and interweaving knowledges** across monitoring, assessments, indicators, models, scenarios, and practice, that can inform actor- and sector-specific actions and their anticipated outcomes on biodiversity to support integrative and collaborative governance (Gonzalez et al., 2023; Kim et al., 2026; Moersberger et al., 2024). These include improving the interoperability among monitoring systems and models across domains, expanding access to biodiversity, environmental and ancillary data, and strengthening the integration of biodiversity, drivers, and response options relevant to the KM-GBF in ecological, social and economic dimensions of the models (Affinito et al., 2024; Purvis, 2025; Ferrier 2025).

To understand the evidence landscape on the modelling resources and to assess their scenario modelling and detection and attribution capabilities in informing the achievement of global biodiversity goals 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 models 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 and evaluated them against the 23 GBF targets, the value perspectives of the Nature Futures Framework, and detection and attribution capabilities with resource needs and aspirations (see Supplement Information, SI II and III for statistical and descriptive overview of model database and IV for model description) (Figure 2). This review brought models and modellers together into dialogue, building bridges across domains and communities, and gaining understanding on how each model is used and how biodiversity can be represented or linked to other models (Kim et al. 2025 - Defra report).

Given the broad scope of KM-GBF, **this review prioritized the broad coverage of all domains relevant for the framework with representative models that meet the review criteria** (KM-GBF and NFF relevance) and is not intended to be exhaustive or comprehensive, especially on ongoing and upcoming model developments (see SI I and Walkden et al. In review for methods). 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 GBF as biodiversity indicators (e.g. species richness, species abundance, Species Threat Abatement and Restoration, Living Planet Index) are most often derived from models, model outputs can be further considered in the GBF monitoring framework (e.g. ecosystem and natural capital data products in ARIES and ENCORE database), and because only an integrative assessment of GBF can inform on synergistic actions with minimized tradeoffs (e.g. systems models such as Felix and DIVERSE). The **domains** include biodiversity, ecosystems, ecosystem services, land, water, climate, energy, and economy. The **methods** include statistical/correlative, mechanistic/process-based, expert/knowledge-based, and in the vast majority of cases, mixed methods approaches.

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 given Goal A's emphasis on maintaining adaptive potential in wild and domesticated populations. Biodiversity models span multiple realms, taxonomic groups, and drivers: for instance, HexSim (Schumaker and Brookes, 2018) simulates spatial population dynamics, LPI (McRae et al., 2017) tracks population trends, GLOBIO (Schipper et al., 2020b) provides global mean species abundance, PREDICTS (De Palma et al., 2021) produces the Biodiversity Intactness Index (BII), and STAR (Mair et al., 2021) assesses threatened species and restoration potential.

At the **Goal A ecosystems level,** a dynamic global vegetation models such as LPJ-GUESS (Smith et al., 2014) predicts ecosystem responses to climate and land-use change while a foodweb model Madingley (Harfoot et al., 2014), Atlantis (Audzijonyte et al. 2020), and EcoOcean (Coll et al. 2023) integrates mechanistic processes across ecosystem functions. Ecosystem resilience can be informed by BILBI's Bioclimate Ecosystem Resilience Index while changes in the extent of natural ecosystems in LPJ-GUESS and FATE-HD (Isabelle et al., 2014) can inform broader land system modelling frameworks such as JULES (Best et al., 2011), LandSHIFT (Schüngel et al., 2022), and LandSymm (Arneth et al. 2023, Rabin et al. 2020).

For the **Goal B ecosystem services** (or nature's contributions to people), model-based data platform ARIES (Villa et al., 2014) uses Artificial Intelligence (AI) to support stakeholder-informed decision-making, while InVEST (Sharp et al., 2016) maps impacts on nature's contributions to people to support natural capital investment strategies. Economic models such as EXIOMOD (Bulavskaya et al., 2016a) assess sectoral environmental impacts, while ENCORE (Kiss-Dobronyi et al., 2021) supports cross-sectoral nature-related economic risk analyses.

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 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 agrochemical production 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 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 outcomes but remain oversimplified in multi-realm models (Müller Schmied et al., 2021). **These specialized tools are highly effective for screening policies within specific domains and generating actionable evidence for sectoral interventions. However, they are less suited to assessing the cross-sectoral synergies and trade-offs that are central to the KM-GBF.**

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. GLOBIOM/iBIOM (Havlík et al., 2011) evaluates species diversity under renewable energy and climate scenarios, while system dynamics frameworks such as World3 (Nebel et al., 2024) and JUNIPER (Ioannou et al., 2025) provide holistic perspectives on interactions among drivers and their implications for biodiversity. In the marine realm, DIVERSE-DBEM (Cheung et al. 2019) integrates marine biodiversity, ecosystem services, fisheries, climate change, and socioeconomic dynamics to assess marine biodiversity futures and evaluate the effectiveness and trade-offs of conservation and sustainable-use strategies across multiple sectors and scales, as do other marine ecosystem models such as Atlantis. In the terrestrial realm, MAgPIE is an example model that optimizes land-use to explore food system transformations and generate cascading biodiversity impacts through trade, technological change, and climate mitigation to support policy integration (T14).

However, integration imposes critical limitations: computational constraints necessitate 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 spatial resolution (~0.5° grids) and land-use classification of integrated models can limit their usefulness for addressing conservation problems at local scales, or related to shifts in land management rather than agricultural expansion. Most critically, integrated models focus largely on provisioning and regulating ecosystem services, with cultural services represented in only 25% of models. As a result, they underrepresent equity dimensions that are central to Targets 13, 21, 22, and 23. Limited expert-based and participatory modeling capabilities further constrain incorporation of Indigenous knowledge, diverse value perspectives and the whole-of-society and human rights-based approaches enshrined in Section C of the KM-GBF. Consequently, current model integration remains strongest in representing biophysical-economic system dynamics, while socio-cultural dimensions that are essential for just and legitimate biodiversity governance receive less attention.

The existing modeling landscape demonstrates substantial technical capacity to support the KM-GBF implementation, potentially by joining the latest integrated systems-level models with specialized domain-specific models or by developing new modelling frameworks that join the latest development of the models suited to respond to a question or a context. There however is ample room for model innovation given the rapidly evolving and accelerating risk landscape and societal needs that are both commonly shared and specific to places and circumstance. This requires flexible model development without the major model paradigm or unnecessary model lock-ins.

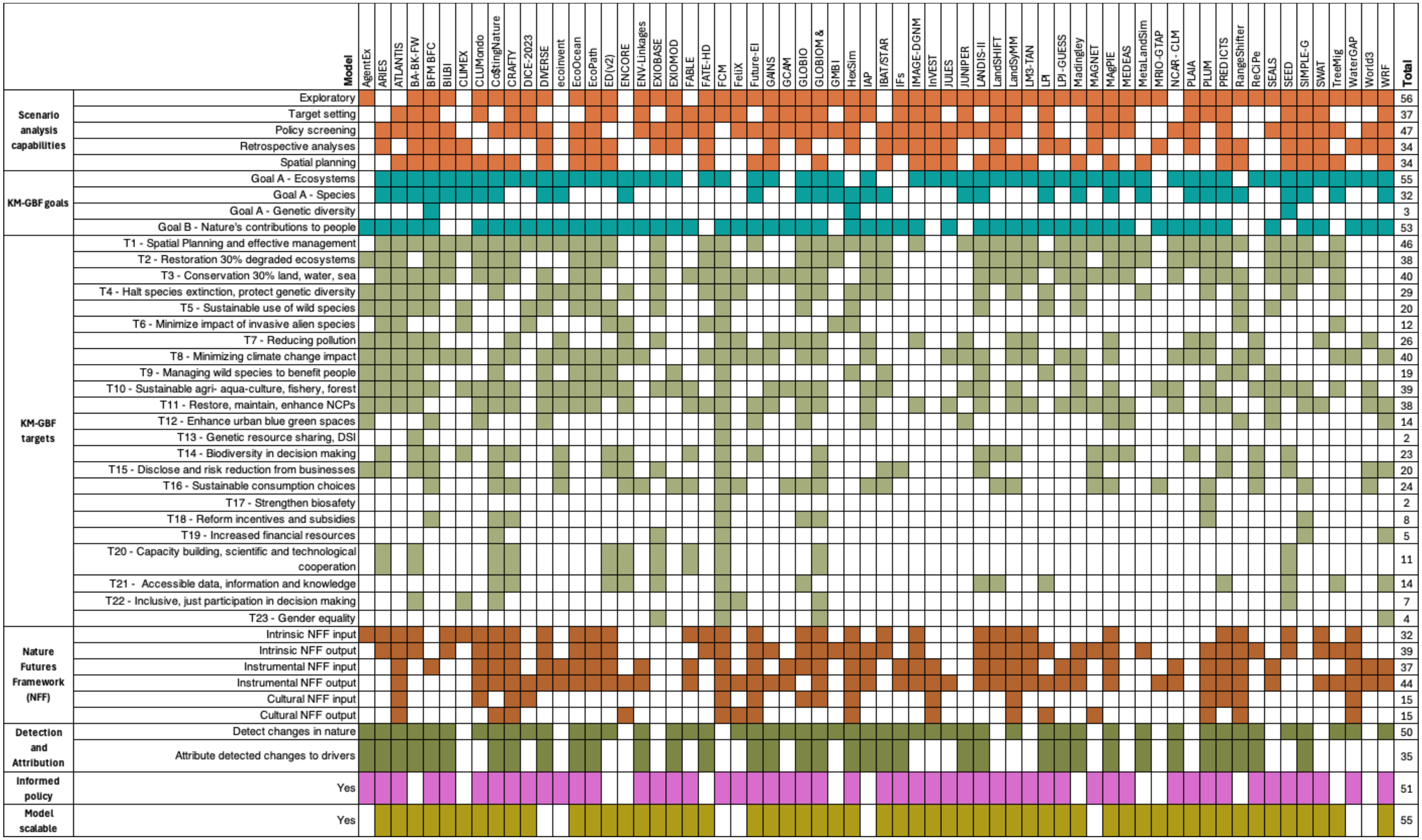

Figure 2. Summary of model capabilities on KMGBF, NFF, scenario analyses, and detection and attribution (see SI II-IV for more on the database and SI V for the full name of the model acronyms)

Improving Biodiversity Evidence Linking Monitoring to Modelling Futures

As of 26th August 2026, 89 of 196 Parties have not submitted an NBSAP aligned with the KM-GBF and 24 Parties have submitted no National Targets at all, and 56 Parties have not submitted a 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 (Immerzeel et al., 2026; CBD Secretariat, 2026). This suggests that **with only 4 years left to achieve the 2030 targets**, a sizeable 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** (CBD Secretariat, 2026).

This is a shared challenge in biodiversity science where evidence synthesis research has progressed, however, only slowly given complexity in measuring, detecting changes, and inferring causal changes. **Detection and attribution science forms the foundation of biodiversity evidence base** by establishing causal links between environmental drivers and observed biodiversity changes, enabling rigorous evaluation of policy interventions and management actions essential for KM-GBF implementation (Gonzalez et al., 2023; Tekwa et al., 2023, Schrodt et al. 2025, Dunley et al. 2025). Detection involves identifying biodiversity changes relative to baselines or null models, while attribution establishes the causal contribution of one or more drivers to detected 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 for tracking progress toward international biodiversity outcomes and designing effective interventions. **Progress monitoring through National Reports fundamentally depends on this capacity.**

In this context, scenarios and models can support building a joint evidence base through collaboration between science and policy communities. Retrospective scenarios combining observations with models enable evaluation of whether implemented policies produced attributed outcomes or if observed changes stem from exogenous drivers independent of interventions – distinguishing policy success from unusual external pressures or policy failure. This attribution is essential for adaptive management: adjusting strategies based on evidence of what worked, what failed, and why. Detection and attribution frameworks are also being woven into model intercomparison projects (Blanchard et al. 2024).

This review builds on **two key roles of the models – explanatory and predictive**. Explanatory and predictive models serve distinct but interdependent functions in supporting biodiversity assessment. Models fitted to temporal data are better positioned to distinguish genuine drivers of change from variables that are simply spatially correlated with those drivers, and to capture dynamic processes – such as phenotypic plasticity – that are hard to detect from spatial data alone (Ferrier 2016). Critically, using **explanatory modelling** to analyse new observations generated by ongoing monitoring initiatives provides a powerful means of testing earlier projections, thereby supporting the adaptive refinement of the models that underpin policy and decision-making over time (Ferrier, 2016). **Predictive modelling** plays a complementary role: it need not rely solely on correlative data analysis, but can also be built from deductive relationships grounded in expert knowledge, and spatial prediction – either derived inductively or deductively – can make a vital contribution to planning and management applications that require complete geographic mapping of biodiversity values, such as the prioritisation and selection of new protected areas (Ferrier, 2016). **This dual role of modelling – as a basis for both explanation and prediction, across monitoring and planning – underlies the whole-landscape framework of KMGBF.** The detection and attribution science become a prerequisite for priority mapping, interactive scenario evaluation, site-based assessment, and monitoring and reporting of the whole-landscape conservation status (Ferrier and Drielsma 2010).

A **fundamental technical challenge limiting comprehensive attribution** is disentangling the ecosystem complexity and numerous non-linear interacting driver effects on biodiversity to accurately infer individual driver impacts (Bowler et al., 2020; Redlich et al., 2022). Most models consider single drivers or simple pairwise interactions because complex multi-driver models produce increasingly uninterpretable results, obscuring causal mechanisms essential for policy diagnosis (Ou et al. 2026). This **complexity-interpretability trade-off** manifests in complementary model strengths: complex models (species distribution models) can forecast biodiversity patterns representing many interacting drivers, valuable for retrospective policy evaluation and exploratory scenarios examining possible futures, but offer limited causal transparency. Conversely, simpler causal models attributing changes to specific drivers provide explicit estimations of intervention impacts critical for target-seeking and policy-screening scenarios but sacrifice predictive comprehensiveness. This tension emphasizes designing monitoring systems supporting complementary modeling approaches serving distinct policy objectives – prediction for agenda-setting and review, attribution for intervention design and implementation.

Joint modeling that integrates the latest domain-specific model advancement offers pathways overcoming these limitations. In this model database, 45 models (69%) work jointly with others, enabling cross-domain integration where, for instance, economic and behavioral drivers influence biodiversity through land cover patterns. ENV-Linkages projects economic scenarios that MAGNET (Kavallari et al., 2014) translates into agricultural production changes, which IMAGE allocates spatially, enabling GLOBIO to attribute biodiversity impacts – a sequential attribution chain linking distant economic policies to proximate biodiversity outcomes. LPJ-GUESS facilitates integration through standardized outputs (e.g., Net Primary Productivity) readily coupled with models (e.g. IAP2, LandSHIFT, CRAFTY, TreeMIG, PLUM), SIMPLE-G communicates with the global hydrological model (Water Balance Model) at 5 arc-min resolution to assess groundwater resilience to macroeconomic shocks (Haqiqi et al., 2026), demonstrating how variable standardization could enhance interoperability and enable aggregation of local-national indicators into global indicators. Another approach is the integration of 'plug-in' mini-models into existing ecosystem models, such as the plug-in fleets and markets models from the Ocean System Pathways (OSP) that allow dynamic redistribution of fishing effort and feedbacks between the ecological and socioeconomic systems (Maury et al. 2025).

To improve the detection and attribution science in biodiversity, there are several key requirements. **Aligning monitoring with continuously collected, standardized data on biodiversity and drivers** would facilitate more efficient detection and attribution across drivers, realms, and data-poor regions (Gonzalez et al., 2026; Purvis, 2025). This would, in turn, support model updating and improvement by translating observed pressure-response outcomes into newly parameterised dynamics. Furthermore, AI may improve model documentation, programmatically facilitating the integration of models and reducing development time and improving reliability/reproducibility through better adoption of software-development practices such as unit-testing. **Model validation and calibration** also emerge as critical bottlenecks constraining policy application. In our database, 60% of models (39 models) have undergone independent validation, while at least 20 models highlight **data availability as a key challenge**. Limited studies directly link drivers to outcomes, insufficient in regular updates with observational data, and constrained by capacity processing available data. **Spatio-temporal and taxonomic biases in biodiversity data at all scales** increase uncertainty in output variables, with 78% of models (51 models) listing improved data availability as a primary requirement to model advancement.

Progressing detection and attribution capabilities in biodiversity science requires **partnership between science and policy and monitoring and modeling 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 System of Environmental-Economic Accounting (SEEA) (Gil et al., 2026). **Modeling 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.**

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 scenario 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.

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 (2016), we evaluated model capabilities across **five scenario types aligned with different stages of the policy cycle**: 1) **exploratory scenarios**, which examine plausible futures based on alternative driver trajectories and support agenda-setting; 2) **target-seeking scenarios,** which identify intervention pathways towards agreed goals and inform policy design; 3) **policy-screening scenarios**, which compare the outcomes of alternative interventions and support implementation; 4) **retrospective scenarios**, which evaluate past policies to identify gaps between objectives and outcomes; and 5) **spatial planning scenarios**, which are particularly important for biodiversity conservation across multiple policy stages (IPBES, 2016).

Scenario analysis utilises models to explore plausible futures or attribute outcomes to past actions, supporting evidence-based biodiversity policy across the policy cycle. **For the GBF globally, models inform target feasibility assessment**: Can proposed 2030 targets be achieved given observed driver trajectories and known pressure-response relationships? Attribution of historical biodiversity changes to specific drivers grounds target-setting in empirical reality rather than aspirational declarations. **For the NBSAPs nationally, intervention scenario analyses evaluate which policy combinations most effectively achieve multiple targets** while minimizing trade-offs – precisely the capacity detection-attribution models provide through target-seeking and policy-screening scenarios. At implementation scales, **spatial planning scenarios identify conservation, restoration, and sustainable use areas** based on attributed risk-benefit-cost gradients, ensuring interventions address actual causal drivers rather than symptomatic biodiversity declines. This, however, requires **a long-time horizon accounting for the short-term governance planning and the longer-term biodiversity outcome** (Essl et al., 2015).

The gap between normative policy goals and quantitative model outputs is most evident in efforts to represent value pluralism (Black et al., 2024). The **NFF demonstrates how qualitative narratives and quantitative modeling can work together** rather than develop along parallel tracks (IPBES, 2025). Narrative development articulates **societal visions:** Nature for Nature scenarios prioritize protected area expansion and reduced demand for products associated with habitat conversion; models operationalize these ambitions through conservation targets such as 30% protection under Target 3 and dietary shift assumptions that reduce agricultural land pressure (Von Jeetze et al., 2025). Nature for Society scenarios modify demands for food, fibre and housing, while maintaining provisioning services; models translate these objectives through ecological intensification parameters and service flow constraints (Godfray et al., 2010). Nature for Culture scenarios employ spatial layers identifying culturally valued landscapes developed through stakeholder consultations (Dou et al., 2023); models integrate these as constraints preventing conversion of sacred sites, traditional use areas, or ceremonial landscapes. **These narratives establish normative targets and intervention logics that models can operationalize through parameter settings and constraints** (Dou et al., 2023; Siebert et al., 2019). This translation manifests concretely in scenario design. Civil society organizations contribute participatory scenario development that incorporates diverse knowledge systems and plural values. However, current modeling capacity systematically underrepresents cultural and relational dimensions, particularly the perspectives of Indigenous People and local communities that are essential for equitable outcomes embedded within the GBF.

The model database informs that at the global level, systems models integrate cross-sectoral dynamics: ENV-Linkages (Chateau et al., 2014), FeliX (Ye et al., 2024), Fuzzy Cognitive Map (FCM) (Sarmiento et al., 2024), JUNIPER, World3, REMIND-MAgPIE (Bodirsky et al. 2025), and GTAP-AEZ (Cisneros-Pineda et al., 2025), as examples, to assess interactions among population, economies, energy, water, land, food, climate, and biodiversity, while evaluating interventions such as carbon pricing, land protection, afforestation, fertilizer regulation, dietary change, and education as integrated scenarios. These models help identify feasible and achievable policy pathways while revealing synergies and trade-offs across sectors. The DeFRA-funded BioFutures project used the LandSyMM joint modelling framework to simulate global land use futures under NFF scenarios (NfN, NfS, NaC; Burns et al In Prep). Each of the scenarios achieved the 2030 KM-GBF 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 goals to meet the KM-GBF 2050 vision.

At the national level, policy-screening or target-seeking scenarios can be used in NBSAP development to identify effective intervention portfolios using nationally calibrated models, data and local knowledge. For example, the RESTORE+ project used a nationally adapted GLOBIOM 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 (RESTORE+, 2017; 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 (Saito et al., 2019; PANCES, 2020). The latest follow-on of PANCES uses the NFF in scenario and model development. However, such examples remain rare (in contrast to climate policy) and neither approach is yet widespread.

At implementation scales, spatial planning models can identify priority areas for conservation, restoration, and sustainable use, with outputs contributing directly to monitoring indicators. The Korean Nature Futures project is applying an integrative biodiversity-climate-society feedbacks modelling framework with sustainability scenarios simulated in land use optimization model

(SEALS) using national biodiversity, ecosystem services, climate risk and socioeconomic data, then land-air feedbacks simulated in climate model (WRF) to assess combined land and climate impact on biodiversity and ecosystem services using Species Distribution Models (SDMs) and InVEST models. The scenarios were citizen developed using the NFF and the models were calibrated by national data to compare the risks and benefits of the SSP (business-as-usual) scenarios to four Nature Futures scenarios in 2050 (Kim et al. 2026, In prep). The model outputs will be derived as indicators to inform how different scenarios support the achievement of national goals and targets of GBF, SDG, NDC, and LDN. These model-based scenario analyses can inform the planning of NBSAPs with spatial prioritization, policy screening, and target setting. These planning tools will improve its rigour when observations and effect measures are integrated in models to support detection and attribution assessments of policy effectiveness through the retrospective analyses in NRs, strengthening adaptive management and learning.

Further, integrating diverse values of nature – intrinsic, instrumental, and relational/cultural – can support more equitable consideration of locally relevant interventions. This allows different priorities to be considered simultaneously, including government concerns regarding agricultural productivity and food security (**instrumental**), Indigenous Peoples' traditional management practices (**relational**), and the typical conservation priorities of biodiversity protection and ecosystem resilience (**intrinsic**). Models in the database show varying capacities to represent these value perspectives as both scenario-specific inputs and outputs. EcoOcean, GLOBIO, and PREDICTS demonstrate existing capacity to support KM-GBF implementation whilst reflecting intrinsic values in their outputs of biomass, abundance trends and predicted biodiversity intactness; while Co$tingNature, MRIO-GTAP and NCAR-CLM can reflect instrumental values by quantifying the supply and demand of ecosystem services, ecological footprint across countries, cities and sectors, and the availability of critical resources. These examples demonstrate promising pathways for operationalising value pluralism, while also highlighting the need for more systems approaches to representing multiple value perspectives in biodiversity modelling. However, a critical gap remains in reflecting rational and cultural values for truly value-inclusive modeling capacity.

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 traditional ecological knowledge into modelling workflows, and developing equity-focused metrics that assess how benefits and burdens are distributed among different groups. Models such as CRAFTY, FCM and FABLE (Jones et al., 2023) demonstrate potential pathways forward through agent-based and participatory approaches respectively. However, achieving genuine value pluralism will require continued methodological innovation and stronger links to formal planning and policy processes. This is particularly important for relational values, which are often difficult to quantify yet remain fundamental to the transformative and equitable vision of the KM-GBF.

Globally, collaborative scenario and model development – scientists collaborating with other scientists to combine/further improve models, or scientists with stakeholders to enhance their policy relevance and uptake – can support the design of achievable targets and provide guidance for implementation. **Nationally, governments can coordinate monitoring, modelling, indicator, and scenario programmes**, bringing together scientific and implementation agencies to co-develop scenarios that reflect national priorities and the state of nature. Indicators in NBSAPs and National Reports can strengthen the evidence base by linking observations with forecasting and impact assessment (Kim et al., 2026; Leung and Gonzalez, 2024). Together, these approaches can help **shift biodiversity governance from reactive monitoring towards more anticipatory, adaptive, and transformative decision-making,** grounded in plural values and robust pathways towards the

2030 targets and 2050 Vision of 'Living in Harmony with Nature' (Kim et al., 2023; Visseren-Hamakers et al., 2021).

Scenario and 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, opening the path for model ensembles and intercomparison projects 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 (see Table 1). The review identifies **five broad classes of input data that cut across the modeling 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, 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 (Stadler et al., 2018). 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, FeliX, GLOBIO, JUNIPER, MAgPIE, and PLUM can simultaneously reduce livestock production demands, alter land use patterns, decrease nitrogen loading, and modify drivers of biodiversity change across terrestrial and freshwater systems. 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 & Oyinlola 2019).

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. FABLE, GLOBIOM & iBIOM), and ecosystem models (e.g. Madingley, NCAR-CLM (Lawrence et al., 2019), ED, 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 modeling 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 (e.g. BILBI, Future-EI, GLOBIO, LandSHIFT, LandSyMM, SEALS) to operate from a common spatial baseline while producing more comparable biodiversity metrics (Von Jeetze et al., 2023). **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, RangeShifter), validating abundance projections (e.g. LPI, PREDICTS, GLOBIO), and parameterizing trophic interactions (e.g. EcoPath, EcoOcean, Madingley). **Together, 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 (Tittensor et al. 2018, Lotze et al. 2019) and BES-SIM (Kim et al. 2018, Pereira et al. 2023), which prescribe or standardize both input data and output metrics and formats while still allowing sufficient flexibility for the diverse range of ecological models that form the ensemble. This enables intercomparability among individual models with heterogeneous inputs and producing heterogeneous outputs with varying definitions and resolutions, as well as providing estimates of spread and inter-model variability, which provides a more robust basis for informing international MEAs. Indeed, such model intercomparisons have already informed outputs such as the IPBES Global Assessment Report (IPBES 2019), the IPCC Special Report on the Ocean and Cryopshere in a Changing Climate (IPCC 2019), and the IPCC AR6 report (IPCC 2022). **Agreement among models and observations can increase confidence in projections, whereas divergence may signal uncertainty related to differences in drivers included or underlying data.**

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-state 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 to be quantified. Essential Biodiversity Variables and Essential Ecosystem Service Variables provide **standardization frameworks that align monitoring protocols** with model requirements, enabling model outputs to contribute more directly to KM-GBF indicators while reducing the need for semantic translation. **Improvement in model interoperability** – including harmonized input-output specifications, standardized data formats and workflow management systems – could transform current multilateral collaborations into more systematic model ecosystems (Table 1).

There is a role for individual model outputs to inform sustainable transitions through scale-specific and policy-relevant applications. **At the global scale,** for instance, MAgPIE was used to provide an integrated perspective of how dietary transitions could drive changes across conservation values (intrinsic vs. instrumental), GHG emissions and socioeconomic outcomes (von Jeetze et al., 2025). **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 (e.g. WaterGAP, SWAT, 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.

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. At the local scale, BILBI identifies optimal allocations of protection and restoration areas that maximize biodiversity representation by implementing targets 2 and 3 (30% protected areas) using fine-resolution habitat condition data, and has been applied in countries such as Australia and Brazil to support conservation prioritization, while CRAFTY's agent-based framework simulates heterogeneous land manager decision-making across a range of land users. Such models can assess how policy interventions influence land use outcomes under different social 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 KMGBF targets. Achieving synergy across the many scales of multilateral environmental agreements – linking biodiversity commitments under the KMGBF, 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. Model intercomparison projects may further help in this multi-scale context by developing frameworks for input and output data interoperability and intercomparison. **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 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) has drawn sectoral ministers into a long-term convening space, embedding biodiversity considerations into cross-government dialogue (link). South Africa has gone further, establishing a legal mandate requiring biodiversity impact assessment within sectoral development processes such as mining (link). Japan's National Ecosystem Assessment, together with its Japan Biodiversity Outlook and Local Biodiversity Outlook scenario projects, has explicitly adopted GBF, IPBES, and SDG frameworks (Saito et al. 2019). The UK has meanwhile developed cross-sectoral, government-informing scenario projects – such as EVAST and ERAMMP – that similarly operationalize this policy-science integration nationally (link). **Together, these examples underscore the critical importance of national coordination efforts convening diverse projects and initiatives to tackle these intertwined challenges coherently rather than piecemeal, as well as the need for models operating at all scales from local to global.**

Table 1. Key model input requirements and inputs and output relevant for KMGBF across 65 model database

Input Requirements	Inputs and outputs relevant for KMGBF Targets	Outputs relevant for KMGBF 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 options	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 (number of trees, by functional group)
Species traits	**Targets 4–5 Species recovery & Wildlife**	Gross and 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
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 b/t 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	CO_2 concentration, GHG emission	
Local context and knowledge	Bioclimatic Ecosystem Resilience Index	

Summary and Future Directions

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 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. Transforming currently largely isolated modeling 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 i**mproved coordination across diverse agencies for change and mainstreaming of biodiversity** across all aspects of society to advancing research frontiers bridging biodiversity science with economic and financial decision-making.

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 (CBD 2026) 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'.

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. Consequently, the active development of model-based scenarios supports the evaluation of contrasting intervention portfolios sketching out intervention 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. This will only be possible through simultaneous development of new sectoral and context specific models capturing the specificities of systems and targets as well as intercomparison projects that support integration of multi-model approaches into one coherent platform and language. In addition, crucially, 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** (Kim et al., 2023; Nicholson et al., 2019). Existing infrastructure can deliver on parts of these needs, however, targeted developments along the data to decision pipeline are needed as well as improved coordination and mainstreaming of biodiversity.

From Fragmented Data to Causal Understanding

Evidence-based policy fundamentally depends on causal understanding: which interventions produce which outcomes, through which mechanisms, over which timescales (Ferraro et al., 2019).

Detection and attribution science 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 modeling 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 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 modeling, 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. Multimodel-development across sectoral scales and spatial extents will be crucial to establish such 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. The lack of such semantic synchronization currently also hampers the technical synchronization across different models, e.g., through Model Intercomparison Projects, 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. 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 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 predictive 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 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 modeling centers** – analogous to meteorological services that maintain operational weather forecasting systems – to embed evidence-based support within government planning processes.

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., 2026; Zurell et al., 2026). Climate science's Coupled Model Intercomparison Project (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). Such MIPs already exist in the marine ecosystem modelling space (e.g., FishMIP) with terrestrial initiatives being developed (e.g., BES-SIM2). 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 parallel development of novel integrated models and frameworks to foster innovation and maintain the capacity to adapt biodiversity model infrastructure to evolving societal questions**, keeping in mind community standards as outlined above. Having both modelling approaches – model intercomparison and model innovation – in place will help prevent unnecessary model lockins and account for complexity-interpretability trade-offs, where predictive multi-driver models' causal transparency and domain-specific attribution models are complemented.

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 modeling 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 agencies aligning funding and incentives around shared evidence; across knowledge systems incorporating diverse values of nature into formal projections; and across domains connecting biodiversity science to climate, energy, health, food and water systems and to economic and financial decision-making. 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.

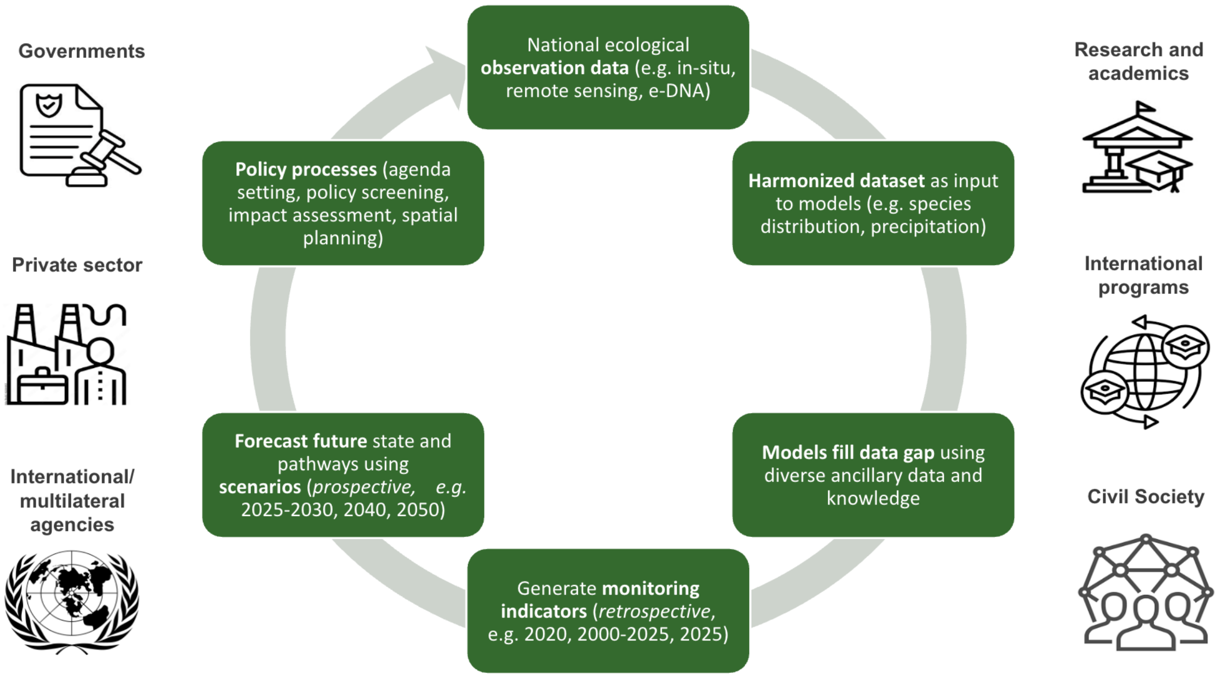

Figure 3. Data to decision flow from monitoring to data harmonization, modelling, indicator development, scenario design and modelling, and policy processes with a broad range of agencies of change across society.

Frameworks, Typologies, and Glossary

Global biodiversity framework

- Goals
- Targets

Monitoring

Modelling

- Explanatory
- Predictive

Prediction vs. projection

Measures

- Data
- Variables
- Indicators

Detection and attribution

Counterfactual analyses (ex-post)

Scenario analyses (ex-ante)

- Retrospective
- Exploratory
- Target-seeking
- Policy-screening

Spatial planning

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(v3): Ecosystem Demography (v3)
ENCORE: Exploring Natural Capital Opportunities, Risks and Exposure
EXIOMOD: EXtended Input-Output MODel
FABLE: Food, Agriculture, Biodiversity, Land-Use and Energy
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 Assessment Model GCAM
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-DGNM: IMAGE-Dynamic Global Nutrient Model
InVEST: Integrated Valuation of Ecosystem Services and Tradeoffs
JULES: Joint UK Land Environment Simulator
LandSyMM: the Land System Modular Model
LM3-TAN: Land Model (LM3)-TAN (Terrestrial and Aquatic Nitrogen)
LPI: Living Planet Index
MAGNET: Module Applied General Equilibrium Tool
MAgPIE: Model of Agricultural Production and its Impact on the Environment
MEDEAS: pymedeas/MEDEAS
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
SWAT: Soil and Water Assessment Tool
WaterGAP: Water - Global Assessment and Prognosis
WRF: Weather Research and Forecasting

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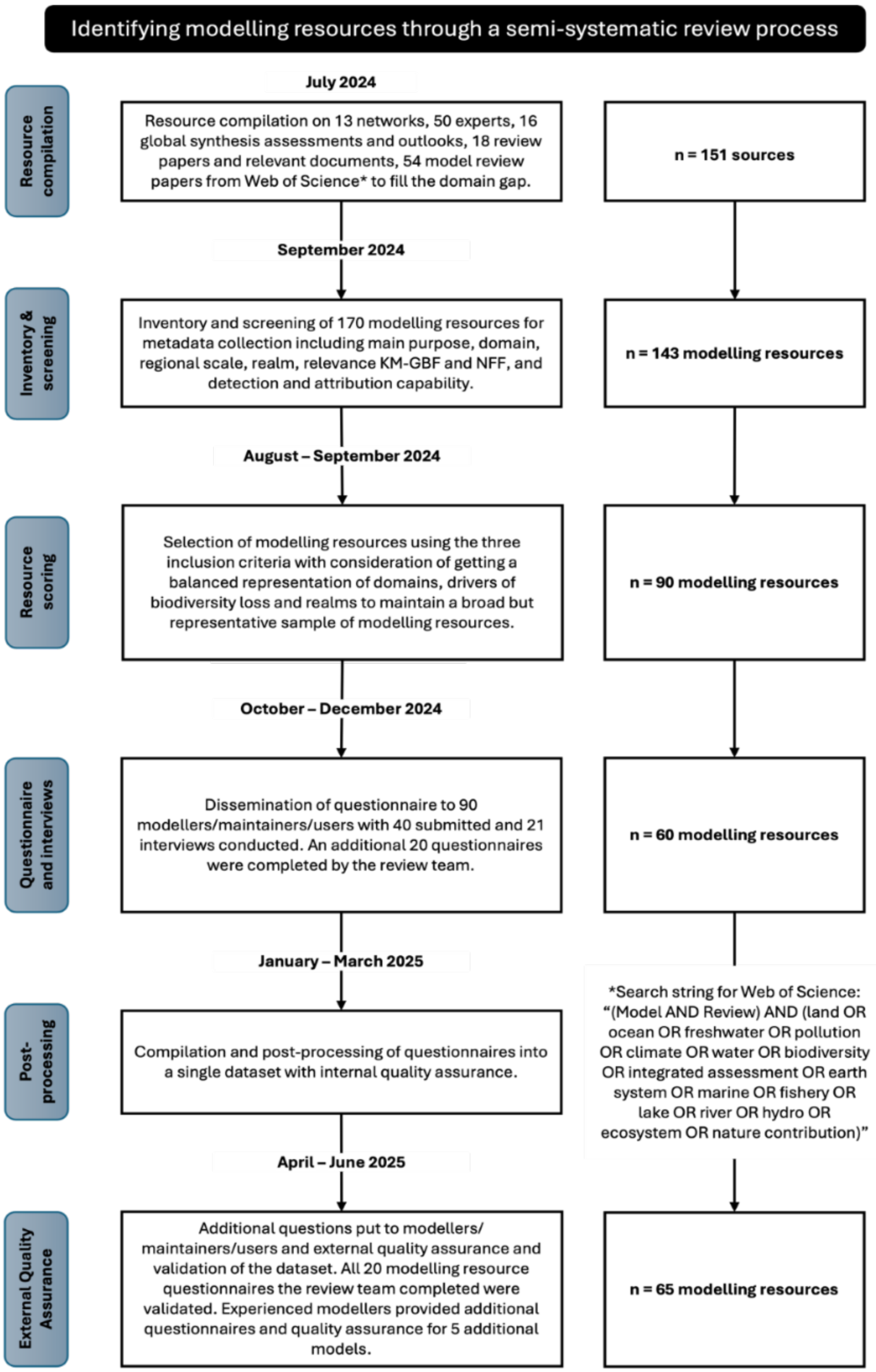
Supplementary Information

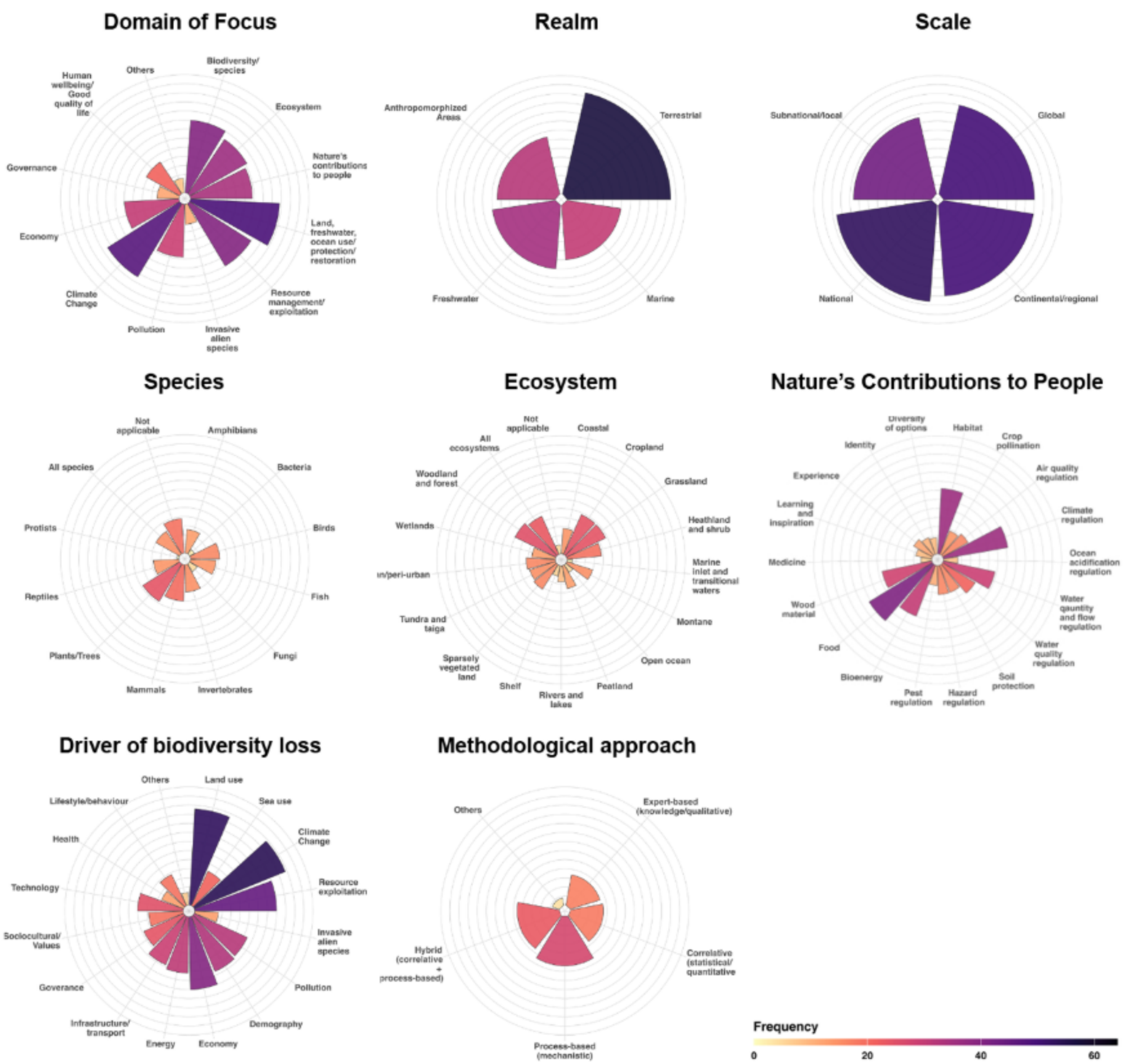
I. Review protocol

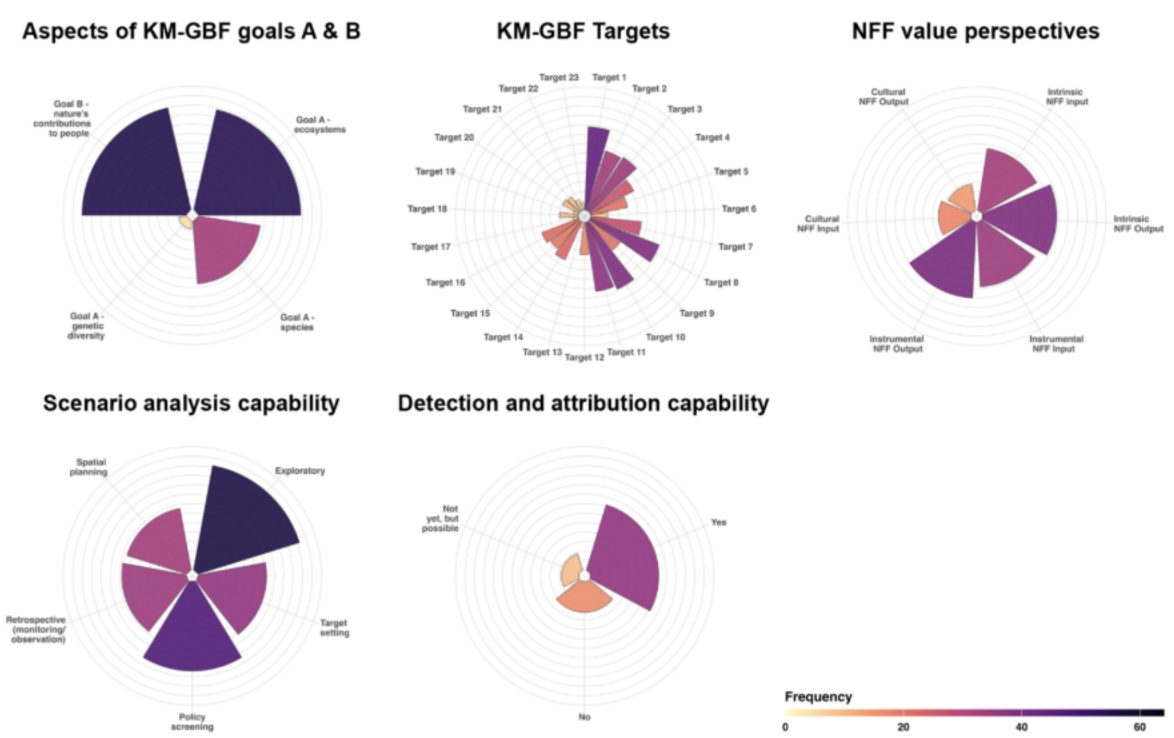


II. Descriptive data of the model database

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 adopted targets.

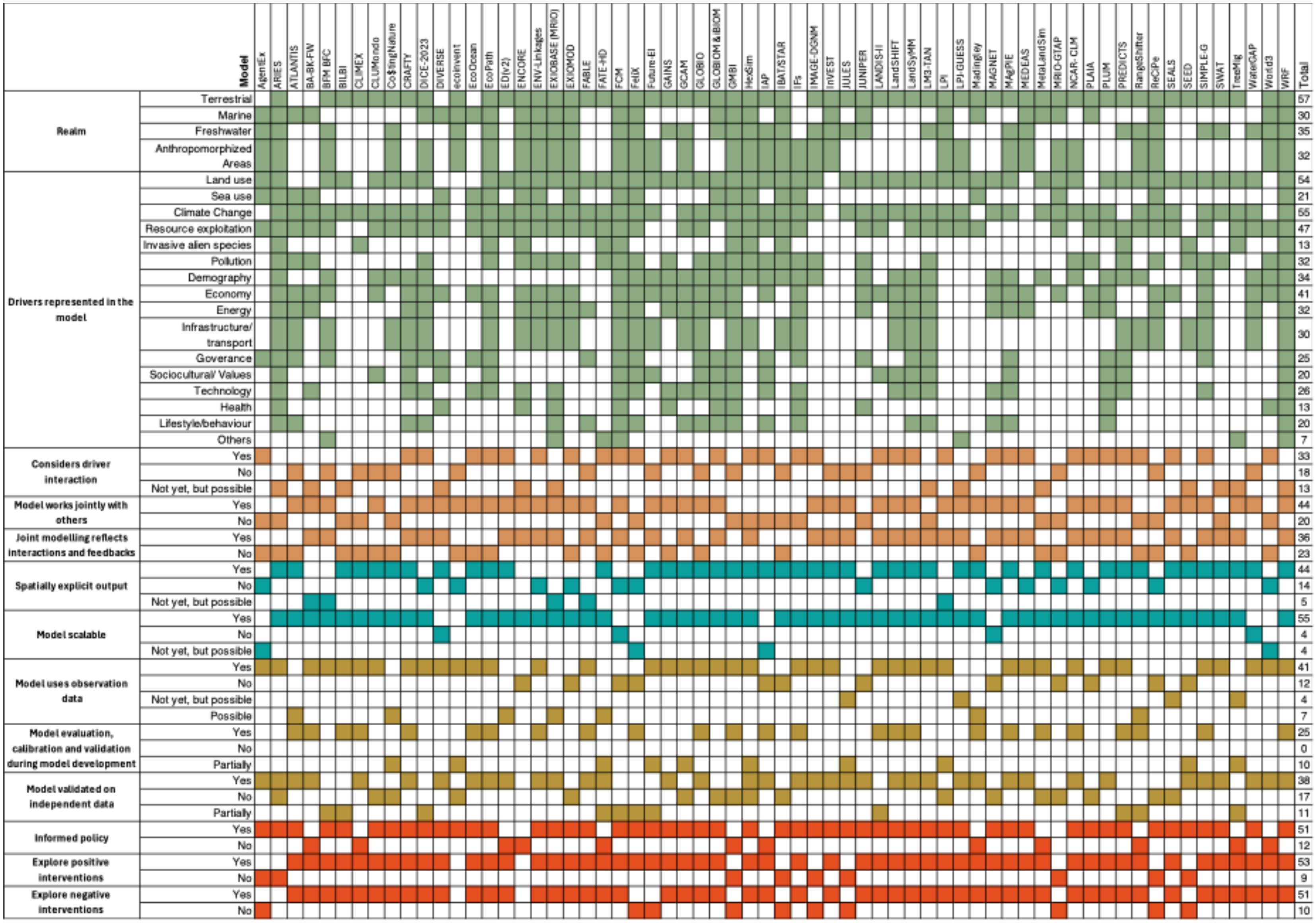
KM-GBF Goal / Target	Number of Models
Goal A Species	32
Goal A Ecosystems	55
Goal A Genetic diversity	3
Goal B Nature's Contribution to people	53
Target 1 Spatial planning and effective management	46
Target 2 Restoration 30% degraded ecosystems	38
Target 3 Conservation 30% land, water, seas	40
Target 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


Domain of Focus
Biodiversity/ species
Ecosystem
Nature's contributions to people
Land, freshwater, ocean use/ protection/ restoration
Resource management/ exploitation
Invasive alien species
Pollution
Climate Change
Economy
Governance
Human wellbeing/ Good quality of life
Others
Realm
Terrestrial
Marine
Freshwater
Anthropomorphized Areas
Scale
Global
Continental/regional
National
Subnational/local
Species
Amphibians
Bacteria
Birds
Fish
Fungi
Invertebrates
Mammals
Plants/Trees
Reptiles
Protists
All species
Not applicable
Ecosystem
Coastal
Cropland
Grassland
Heathland and shrub
Marine inlet and transitional waters
Montane
Open ocean
Peatland
Rivers and lakes
Shelf
Sparsely vegetated land
Tundra and taiga
Wetlands
Woodland and forest
All ecosystems
Not applicable
Nature's Contributions to People
Habitat
Crop pollination
Air quality regulation
Climate regulation
Ocean acidification regulation
Water qauntity and flow regulation
Water quality regulation
Soil protection
Hazard regulation
Pest regulation
Bioenergy
Food
Wood material
Medicine
Learning and inspiration
Experience
Identity
Diversity of options
Driver of biodiversity loss
Land use
Sea use
Climate Change
Resource exploitation
Invasive alien species
Pollution
Demography
Economy
Energy
Infrastructure/ transport
Goverance
Sociocultural/ Values
Technology
Health
Lifestyle/behaviour
Others
Methodological approach
Expert-based (knowledge/qualitative)
Correlative (statistical/ quantitative
Process-based (mechanistic)
Hybrid (correlative + process-based)
Others
Frequency
0
20
40
60



Aspects of KM-GBF goals A & B
Goal B - nature's contributions to people
Goal A - ecosystems
Goal A - genetic diversity
Goal A - species
KM-GBF Targets
Target 1
Target 2
Target 3
Target 4
Target 5
Target 6
Target 7
Target 8
Target 9
Target 10
Target 11
Target 12
Target 13
Target 14
Target 15
Target 16
Target 17
Target 18
Target 19
Target 20
Target 21
Target 22
Target 23
NFF value perspectives
Cultural NFF Output
Intrinsic NFF input
Cultural NFF Input
Intrinsic NFF Output
Instrumental NFF Output
Instrumental NFF Input
Scenario analysis capability
Spatial planning
Exploratory
Retrospective (monitoring/ observation)
Target setting
Policy screening
Detection and attribution capability
Not yet, but possible
Yes
No
Frequency
0
20
40
60

III. Overview of model capabilities



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

Gap 1. Bridging the invasive alien species modeling 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 (Roy et al., 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.

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, and BIOMOD offer distribution modeling capabilities to understand potential future spread and impacts of invasive alien species. However, these approaches remain purely correlational, only informed using, 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 importance in determining whether spreading species pose invasion risks including potential impacts, suggesting hybrid data-expert approach as pragmatic way forward (Essl et al., 2020). Nevertheless, data on impacts of invasive alien species are increasingly becoming available at global scale (Bacher et al., 2025; Diagne et al., 2020).

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. The critical frontier lies in impact modeling: recent developments including the first global impacts evidence database enabling spatially explicit impact projections, though context dependency and impact diversity presenting challenges (Bacher et al., 2025; Henriksen et al., 2024). Economic cost modeling demonstrates one approach, though transferability assumptions require scrutiny (Hulme et al., 2024; 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 already exist (Jiménez et al., 2025).

Integrating IAS into global biodiversity models such as GLOBIO (Schipper et al., 2020b) 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 50% reduction in Red List species impacts by 2030, yet lacks standardized baselines for introduction and establishment rates (McGeoch et al., 2023). Historic data gaps across taxonomic groups compound these challenges.

Development priorities emerge across scales. Species-level modeling requires expanded trait databases, dispersal observations, and demographic parameters, enabling mechanistic projections beyond expert opinion, while maintaining expert knowledge integration for risk assessment. Global modeling 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 modeling 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 modeling.

Gap 2. Linking economy models with biodiversity models for post growth 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 modeling 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 (Otero et al., 2024).

The modeling database reveals emerging capacity for biodiversity-economy integration but highlights critical development needs. SIMPLE-G (Haqiqi and Hertel, 2025) 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., 2023b). 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 prep.).

Fundamental to this integration is a Global-to-Local-to-Global 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; Liu et al., 2013). The model database demonstrates this multi-scale architecture through models like FABLE (Jones et al., 2023) linking global boundaries to 24 national contexts, MAgPIE (Dietrich et al., 2019) coupling global agricultural markets with 0.5° land allocation, and EXIOBASE (Stadler et al., 2018) tracking 163 industries across

49 regions. However, realizing the full potential requires incorporating governance heterogeneity at finer scale: 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), and ENV-Linkages (Chateau et al., 2014) demonstrate this through carbon pricing, subsidies and taxes, trade regulations, and protected area designations. Yet broader policy spaces – universal basic income enabling post-growth transitions, working time reductions decoupling wellbeing from GDP, circular economy regulations reducing resource throughput – remain largely unexplored. Evaluating transformative pathways requires models projecting outcomes under fundamentally different economic logics rather than incremental modifications of business-as-usual growth (Otero et al., 2024).

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 with ecoinvent'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).

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 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 post-growth 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 spatial models with local and national data with region or global as boundary conditions as relevant.]

National biodiversity indicators can simultaneously inform policy progress at multiple scales – tracking whether actions advance nature's state nationally while guiding subnational spatial planning, implementation and evaluation (Ly et al., 2023; McGeoch et al., 2023). Yet current indicator-model integration reveals fundamental coordination gaps limiting evidence-based and scenario-based design of NBSAPs and rigorous retrospective evaluation in National Reports for conservation and policy efficacy (Purvis, 2025; Zurell et al., 2025). The model database demonstrates the KM-GBF relevant capacity for indicator projection: Living Planet Index (LPI) (McRae et al., 2017), Red List Index (RLI) (Cazalis et al., 2024, 2022), Species Threat Abatement and Restoration (STAR) (Mair et al., 2021), Mean Species Abundance (MSA) (Schipper et al., 2020a), Biodiversity Intactness Index (BII) (De Palma et al., 2021), among others. These complementary metrics each offer distinct and synergistic roles across ecological context and scales. Developing a coordinated evidence infrastructure requires understanding of differentiated 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; MSA and BII estimate compositional intactness relative to pristine baselines under scenarios. Models inform spatial planning by projecting these metrics under alternative interventions. BILBI (Hoskins et al., 2020) optimizes protection-restoration allocations maximizing biodiversity conservation with governance constraints. GLOBIO projects MSA under land use scenarios. STAR identifies cost-effective threat reduction portfolios.

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, 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).

A fundamental 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 – limiting capacity to project future trends under alternative scenarios. Consistent monitoring simultaneously recording population states and driver intensities enables 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 providing information across policy-relevant scales, enabling 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 National Reports as tools for designing and implementing KM-GBF and other multilateral environment agreements (Kim et al., 2023). 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 rivaling 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), Nature for Society prioritizing ecosystem service provision (MSA-ecosystem function linkages), and Nature for Culture centering 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 modeling and diverse ways of stewarding nature.

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 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 plaform for model intergartions using artificial intelligence (AI) to develop open, safe, and accurate methods for sharing and linking scientific models, and datsets, 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 aspect such as level of compliance to regulations. The model consist of a deterministic biogeochemical whole ecosystems so 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 emmisison, water use and nitrogen and phosphorous emmmission to water of a company or product, combining these value 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.
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. Environmental Modelling & Software 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

Model	Model Full Name	Objective	Reference
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 phonology 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. Glob Change Biol, 18: 3125-3148.
Co$tingNature	Co$tingNature	The Co$ting Nature V3 is a web based policy-support tool for natural capital accounting and analysis of the ecosystem services provided by natural environments. It focuses on costing nature (understanding the resource, e.g. the land area, and the opportunity cost of protecting nature to produce ecosystem services) as opposed to valuing nature (i.e. how much someone is willing to pay for it), though the tool does support economic valuation and has the necessary tools for this.	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, Remote Sensing of Environment, Volume 239, 2020, 111671, ISSN 0034-4257
CRAFTY	Competition for Resources between Agent Functional TYpes	Simulation of land use change and ecosystem service provision	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. Environmental Modelling and Software, 59, 187–201.
DICE-2023	DICE-2023	The DICE model (Dynamic Integrated model of Climate and the Economy) estimates the SCC and evaluate 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.	

Model	Model Full Name	Objective	Reference
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.
ED(v3)	Ecosystem Demography (v3)	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), Geosci. Model Dev., 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.	
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	Stadler et al. "EXIOBASE 3: Developing a Time Series of Detailed Environmentally Extended Multi-Regional Input-Output Tables." Journal of Industrial Ecology 22, no. 3 (2018): 502–15.

Model	Model Full Name	Objective	Reference
		sustainability questions of the EU and its main trading partners as well as for major global economies.	
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 involment 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 backgrounds. An FCM consists of biophyicals models combined with qualitive data.	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
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. Environmental Modelling & Software 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. Reg Environ Change 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.	Short-Lived Climate Forcers. IPCC Sixth Assessment Report Working Group I, Climate Change 2021: The Physical Science Basis. ; Technical potentials and costs for reducing global anthropogenic methane emissions in the 2050 timeframe –results from the GAINS model
GCAM	Global Chnage Assessment Model 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 conists of a global energy-economic-agriculture-land use market equilibrium model linked with a simple climate model, with an optional destender model to downscale land-use change prediction to user define scales.	Calvin, Katherine, et al. "GCAM v5. 1: representing the linkages between energy, water, land, climate, and economic systems." Geoscientific Model Development 12.2 (2019): 677-698.
GLOBIO	GLOBIO	The GLOBIO model assesses impacts of future policy pathways and scenarios on terrestrial biodiversity at regional and gobal 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. Glob Change Biol. 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, renewable energy deployment, agriculture and forestry management and climate change. It is achieved in iBIOM modeling platform by coupling the semi spatial explicit economic equilibrium land use model GLOBIOM to models of species diversity, fresh water dynamics (quantity and quality), renewable energy deployment and agriculture and forestry management, and responses to climate change.	Petr Havlík, Uwe A. Schneider, Erwin Schmid, Hannes Böttcher, Steffen Fritz, Rastislav Skalský, Kentaro Aoki, Stéphane De Cara, Georg Kindermann, Florian Kraxner, Sylvain Leduc, Ian McCallum, Aline Mosnier, Timm Sauer, Michael Obersteiner, Global land-use implications of first and second generation biofuel targets, Energy Policy, Volume 39, Issue 10, 2011, Pages 5690-5702, ISSN 0301-4215.
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. Ecological Modelling, 272, 394-409. .

Model	Model Full Name	Objective	Reference
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. Landscape Ecology 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. *Nature Climate Change*, 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. *Climatic Change,* 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. Nat Ecol Evol 5, 836–844 (2021).
IFs	International Futures	The IFs model to support the exploration of long-term global future for 183 countries. It links responses to user defined scenario across economic, demographic, education, health, environment, technology, domestic governance, infrastructure, agriculture, energy and environment.	Hughes, Barry B. 2015. "International Futures (IFs) and integrated, long-term forecasting of global transformations." Futures 81: 98-118.
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. Journal of Advances in Modeling Earth Systems, 12, e2019MS001796.
InVEST	Integrated Valuation of Ecosystem Services and Tradeoffs	The InVEST model supports the 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 conisist 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, Science of The Total Environment, Volumes 569–570, 2016, Pages 1418-1426, ISSN 0048-9697

Model	Model Full Name	Objective	Reference
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, Geosci. Model Dev., 4, 677–699, , 2011.
JUNIPER	JUNIPER	The JUNIPER is a systems dynamic model capable of estimating water, energy, agricultural production (food), transportation, health impact (life expectancy), biodiversity (red List Index) and GHG emissions outcomes. It draws on spatial and statistical datasets and can quantify the interlinkages among components in the modelling framework.	
LANDIS-II	LANDIS-II	The LANDIS-II is a forest succession model capable of predicting how forest and scrub land will response to different future scenarios based on response to abiotic factors (including future climate) and human interventions. It predicts trees 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. Ecological Modelling 201 (3-4): 409-419.
LandSHIFT	LandSHIFT	The 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 continental scale 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-use model as it provides a link between the human dimensions of global land-use changes (including economic drivers) with global-scale simulations of climate, the water cycle, biodiversity risk, and other global change processes and issues. It couples a regional prediction of land use demand with downscale land use change at roughly 9x9 km resolutions.	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, .
LandSyMM	LandSyMM: the Land System Modular Model	The LandSyMM is an integrated framework that provides predictions of future land use under alternative futures (scenarios) and the resulting impacts on outputs (food, fiber, social, biodiversity). It is coupled with process based models to provide spatially explicit prediction, which include a socio-economic, land-use model (PLUMv2), 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; Rabin, S. S., Alexander, P., Henry, R., Anthoni, P., Pugh, T. A. M., Rounsevell, M., and Arneth, 2020. A.: Impacts of future agricultural change on ecosystem service indicators, Earth Syst. Dynam., 11, 357–376
LM3-TAN	Land Model (LM3)-TAN (Terrestrial and Aquatic Nitrogen)	The LM3-TAN model predicts the combined terrestrial effects of anthropogenic N inputs, atmospheric CO2, 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.

Model	Model Full Name	Objective	Reference
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 to 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
LPJ-GUESS	LPJ-GUESS	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. Biogeosciences. 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. – PLoS Biol.
MAGNET	Module Applied General Equillibrium 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 level of country or region and thus are not spatially explicit. It is a gobal macro-economic model with focus on bioeconomy and land use.	Woltjer, G. B. et al. (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., Strefler, 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. Nature Food, 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, inculding limits and impact of land use for renewable energy production, energy scarcity, climate change impacts, materials scarcity and socioeconomic issues inculding the creation and quaility 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', Renewable and Sustainable Energy Reviews, 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, Environmental Modelling & Software, 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. Journal of Advances in Modeling Earth Systems, 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, MethodsX, Volume 9, 2022, 101666, ISSN 2215-0161, .
PLUM	Parsimonious Land Use Model	Global land use and food system modelling	Rabin, S.S., Alexander, P., Henry, R., Anthoni, P., Pugh, T.A.M., Rounsevell, M., Arneth, A., 2020. Impacts of future agricultural change on ecosystem service indicators. Earth System Dynamics 11, 357–376.
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).

Model	Model Full Name	Objective	Reference
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 JMJ (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 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 end point include human health, ecosystem quality, resource scarcity. Environmental mechanisms include climate change, ozone depletion, ionizing radiation, fine particular 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 difine a 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	SIMPLE-G	The SIMPLE-G is a gridded economic equilibrium model which provides spatially explicit prediction of land use change, water used, labor demands and commodity prices. It allows for global trade within the framework.	Haqiqi and Hertel (eds.), SIMPLE-G: A Gridded Economic Approach to Analysis of Sustainability of the Earth's Land and Water Resources; Springer, 2024.
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 model predicts forest succession, capable of modelling both natural and plantation forest. It is ideally suited to predicting change in	Lischke, H., Zimmermann, N.E., Bolliger, J., Rickebusch, S. & Loffler, T.J. (2006) TreeMig: A forest-landscape model for

Model	Model Full Name	Objective	Reference
		forest species and structural diversity over extended time periods (100yrs) dure to climate change.	simulating spatio-temporal patterns from stand to landscape scale. Ecological Modelling, 199, 409-420.
WaterGAP	Water - Global Assessment and Prognosis	The WaterGAP m odel compute 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 forcasting and the prediction of impact on weather of changes in landuse, GHG emmisison and climate. It provide accurate numerical weather predictions and atmospheric simulation tool for both reserach and operational forcasting.	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.