Integrative Biodiversity Science Informing Transformative Multiscale Governance through Diversifying Values of Nature in Scenarios and Models

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Key messages:

- Improved use of scenarios and models can contribute to enhancing 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) that incorporate diverse values of nature.
- Scenarios play critical roles in both global and national biodiversity governance and assessment processes. Qualitative narrative development can enable inclusive governance, while quantitative assessment can strengthen evidence-based decisions.
- Models can strengthen evidence through detection and attribution capabilities using ecological monitoring data at fine scales. Where feasible and appropriate, biodiversity-centric modeling frameworks should be developed that incorporate key drivers and interventions to improve biodiversity conservation with cross-sectoral policy coherence.
- Nature Futures Framework supports building futures through the human-nature relationship lens 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., model networks) are needed to respond to evolving societal needs, also considering the financial sector that demand climate and nature-related risk assessment and proactive mitigation/prevention.
- At the national level, governments need to coordinate and improve coherence across monitoring, modeling, 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 efficiency and conservation efficacy.

Keywords: scenarios, models, indicators, Global Biodiversity Framework, Nature Futures Framework, detection-and-attribution science, policy support

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History of Global Biodiversity Governance, Assessments and Scenarios

The intellectual foundations of biodiversity scenario modelling predate the Rio Convention by two decades. The Club of Rome's *Limits to Growth* introduced the World3 systems dynamics model, establishing the epistemological template of integrated, multi-variable, long-horizon projection that would later shape major environmental scenario exercises (Meadows et al., 1974) (Figure 1). Almost in parallel the development of the IMAGE model framework at PBL Netherlands emerged, providing one of the earliest platforms linking socioeconomic drivers to ecosystem outcomes at global scale and paving the way for integrated assessment models capturing a large range of facets of the global system and the quantification of future scenario projections (Rotmans, 1990; Stehfest, 2014).

The Convention on Biological Diversity, opened for signature in June 1992 and entering into force in December 1993, recognising biodiversity conservation as a common concern of humankind and establishing three objectives: conservation, sustainable use, and equitable benefit-sharing (UN 1992). However, its analytical infrastructure was weak. National biodiversity strategies were the primary delivery mechanism; quantitative scenario requirements were absent from the Convention text. Globally the Intergovernmental Panel on Climate Change (IPCC)'s Special Report on Emissions Scenarios (SRES, 2000) provided the first widely adopted global scenario framework intersecting with biodiversity concerns. However, designed for climate projection it treated land use – the dominant driver of biodiversity loss – only as a derived output rather than a primary policy lever (Nakićenović and Intergovernmental Panel on Climate Change, 2000). Spatially explicit biodiversity projection tools did not exist in this climate scenario space then. This changed with the Millennium Ecosystem Assessment (MA, 2001–2005) that represented the first systematic effort to project biodiversity and ecosystem services under alternative global futures explicitly linked to human well-being. Its four scenarios employed the storyline to simulation method, developed through participatory storyline construction followed by quantification using connected models for land use, freshwater, fisheries, and biodiversity indicators (MA, 2005).

A major limitation of the SRES approach was the coupling of climate forcing to socioeconomic assumptions, preventing modellers from independently varying climate and development futures. The Representative Concentration Pathways (RCPs), adopted for IPCC AR5, resolved this by decoupling radiative forcing targets from socioeconomic storylines (Van Vuuren et al., 2011). The subsequent Shared Socioeconomic Pathways (SSPs), formalised between 2012 and 2017, provided five sets of narratives across the two axes of climate mitigation and adaptation, with quantified projections of population, GDP, energy, and land use (O'Neill et al., 2017; Riahi et al., 2017). The SSP–RCP matrix became the de facto standard infrastructure for global environmental modelling and has since become the major scenario framework for biodiversity impact assessments (Kim et al., 2018). The major challenges with the SSPs for biodiversity science however was the absence of biodiversity policies by design and limited drivers considered beyond land use and climate change (e.g. resource exploitation, invasive alien species, pollution) (Kok et al., 2017; Rosa et al., 2017). This rendered the use of SSP-RCP scenarios in biodiversity science incomprehensive, hampering robust global biodiversity risk assessment, where biodiversity remained a passive recipient rather than an active mitigating agent for climate change (Alexander et al., 2023; Pereira et al., 2026).

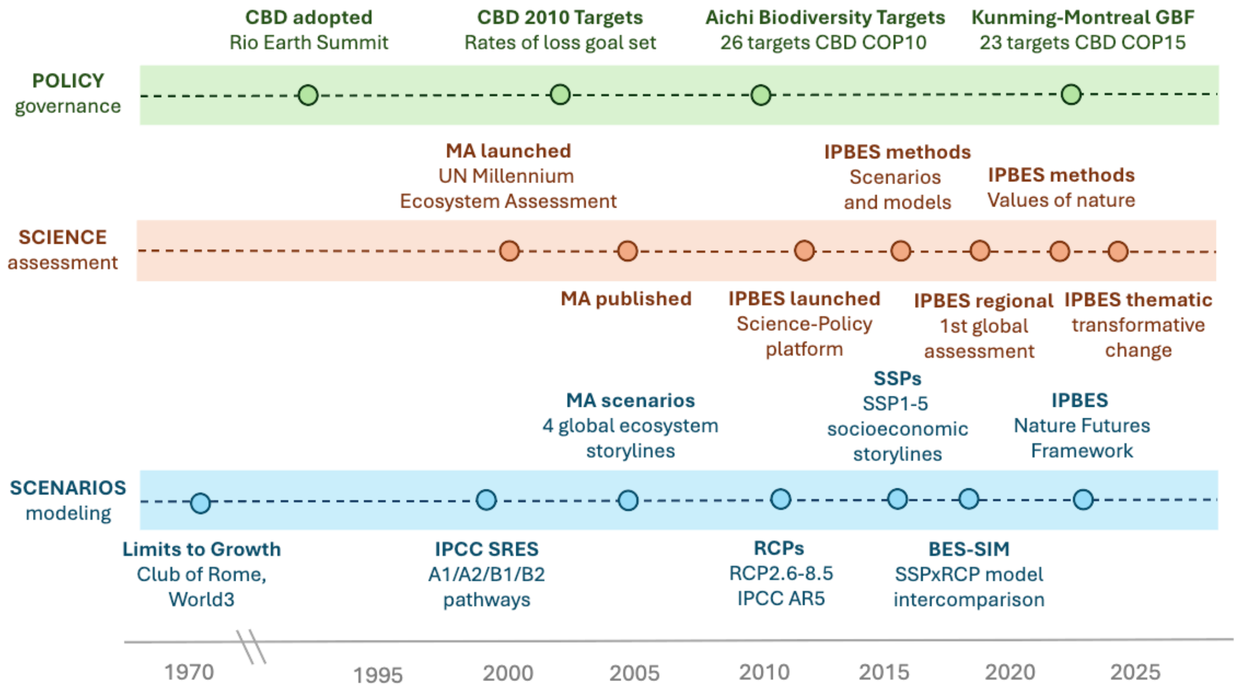


Figure 1. Chronogram of global policy (green), science (orange), and scenario (blue) initiatives focusing partly or in full on biodiversity and ecosystem services. Abbreviations are as follows: CBD = Convention on Biological Diversity; COP = Conference of the Parties; GBF = Global Biodiversity Framework;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

The Intergovernmental Science Policy Platform on Biodiversity and Ecosystem Services (IPBES) was established in 2012, modelled after the IPCC to conduct global assessments on biodiversity and ecosystem services (Larigauderie and Mooney, 2010). The IPBES methodological assessment on scenarios and models conducted the first comprehensive evaluation of biodiversity modelling for policy identified five major model families: correlative species distribution models; process-based ecological models; matrix-based habitat models; macroecological models; and integrated assessment models coupling socioeconomic drivers to ecosystem outcomes (IPBES, 2016). The assessment acknowledged several limitations, particularly that most global biodiversity models represented land use and climate change and only a few incorporated additional drivers and ecological processes such as species interactions or trophic dynamics (Weiskopf et al., 2022). Critically, it highlighted challenges in dealing with uncertainty in biodiversity and ecosystem service projections, driven by deficiencies in the spatial, environmental and thematic coverage of existing scenarios and models, and data that is underpinning them (Rosa et al., 2020). Further, there was limited development and application of alternative scenarios with innovative management and policy options for nature preventing proactive policy design in biodiversity conservation and sustainable development (Rosa et al., 2017).

Catalyzed by the IPBES Expert Group on Scenarios and Models, the BES-SIM project assembled ten biodiversity models and six ecosystem service models using harmonised inputs from the Land Use Harmonization Project (LUH2), applying three SSP–RCP combinations spanning low-pressure sustainability (SSP1×RCP2.6), regional rivalry (SSP3×RCP6.0), and high fossil-fuel trajectories (SSP5×RCP8.5) (Kim et al., 2018). The final synthesis projected that terrestrial biodiversity and ecosystem services deteriorated between 1900 and 2015 and are anticipated to continue declining to 2050 across all three scenario combinations, with the trajectory and geographic distribution of loss varying significantly by pathway (Pereira et al., 2024). BES-SIM catalysed the first model intercomparison exercise in biodiversity science, strengthened IPBES–IPCC linkages, and informed CBD post-2020 discussions on the importance of linking national biodiversity strategy and action plans (NBSAPs) with national reports (NRs) (Kim et al., 2026). Five core challenges were identified: (i) better integrating nature into development storylines; (ii) improving land-use resolution; (iii) linking species-level biodiversity to ecosystem service models; (iv) expanding representation of multi-dimensional biodiversity; and (v) incorporating time-series data for model validation (Pereira et al., 2024; Rosa et al., 2020).

A fundamental critique emerging from this body of literature was that all existing global scenario frameworks were designed to describe trajectories of human socioeconomic development, with biodiversity appearing only as an outcome. Additionally, existing scenarios largely extrapolate historically established trends of systems drivers without consideration alternative socioeconomic development pathways for sustainability. This extrapolation of historic trends of biodiversity pressures from the second half of the 20th century almost inevitably resulting in declining biodiversity projections as no mitigation of the pressures is anticipated (Kim et al., 2023; Pereira et al., 2026). In response to this critical gap, the Nature Futures Framework (NFF) was developed by the IPBES scenarios and models expert group between 2016 and 2019 (Lundquist et al., 2017). The NFF captures diverse positive values for human-nature relationships in a triangular space with three value perspectives: nature for nature, nature as culture, and nature for society (Pascual et al., 2017). This representation and structure was deliberately non-hierarchical, rejecting implicit primacy of instrumental over intrinsic or relational values and accommodating Indigenous and local knowledge alongside Western scientific paradigms (Pereira et al., 2020). Formally recognised by the IPBES Plenary in 2022, the NFF aligns with CBD's 2050 vision of living in harmony with nature, with a shift from projecting expected losses towards co-developing desirable futures (IPBES, 2025).

Across this thirty-year development, several structural trends emerged. There has been progressive upscaling from national single-taxon models to globally coordinated multi-model ensembles. Driver representation is slowly broadening from the near-exclusive focus on land-cover and climate change towards a still limited unilateral representation of exploitation, pollution, and invasive species within models and scenarios (Aschi et al., 2026). The framing is shifting from projection towards co-production, reflecting deeper engagement with questions of values, justice, and agency (Pereira et al., 2026). Persistent weaknesses include underrepresentation of marine and freshwater systems; growth-centric assumptions embedded even in sustainability scenarios; limited integration of Indigenous knowledge into quantitative workflows; and difficulty translating global outputs to sub-national decision scales (Kramer et al., 2023; McElwee et al., 2020; Otero et al., 2024; Rosa et al., 2017).

Global Advancement in Modelling Targets and Goals of the Global Biodiversity Framework

Since the establishment in 1992, the CBD and its member states have continuously worked on establishing achievable biodiversity targets culminating in 2002 in the 2010 Biodiversity target aiming at a significant reduction in the rate of biodiversity loss (Butchart et al., 2010; Mace and Baillie, 2007). While this target was not met by 2010, it provided the foundation for subsequent refined targets like the Aichi Biodiversity targets adopted in 2010 at COP 10 in Nagoya (Tittensor et al., 2014). Following another decade of unmet biodiversity targets, the CBD adopted the Kunming-Montreal Global Biodiversity Framework (KM-GBF) in December 2022 (Figure 1), establishing four goals and 23 targets spanning genes to ecosystems, nature's contributions to people, and broad-ranging biodiversity drivers in social and ecological systems (CBD Secretariat, 2022). KM-GBF's 2050 vision – 'Living in Harmony with Nature' – operates through goals addressing protection/restoration, prosperity with nature, equitable benefit-sharing, and investment/collaboration. The four 2050 'outcome' goals are 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), securing sufficient financial, technical, and capacity-building means to implement the framework (Goal D). Twenty-three 2030 'action' targets address biodiversity loss through land/ocean spatial planning, protection and restoration (T1-3), species conservation (T4), sustainable use (T5), invasive species control (T6), pollution reduction (T7), climate adaptation (T8), human-centered management (T9-13), and enabling conditions including finance, knowledge, and governance (T14-23). Achieving these ambitions requires national policies informed by rigorous evidence, yet current approaches reveal critical gaps (McGowan et al., 2024; Perino et al., 2022). Member states utilize NBSAPs to monitor progress through three indicator categories but assess these individually without detecting or attributing changes to interventions or driver interactions, limiting evidence-based decision-making (Leadley et al., 2022).

Critical science-policy challenges and gaps persist in CBD's monitoring indicators, data and models that underpin them. They include interoperability across monitoring systems and models, including enhancing cross-national data accessibility for transnational conservation (Affinito et al., 2024). Comprehensive assessments of models representing ecological dynamics across nature, drivers, and responses relevant to KM-GBF remain essential but rarely put into practice (Purvis, 2025). Synergistic achievement of the global goals requires governments, academics, and civil society to co-produce NBSAPs with planning and monitoring tools, where models can strengthen standardized form of evidence through detection and attribution using fine-scale monitoring data, biodiversity-centric frameworks incorporating key drivers to improve cross-sectoral policy coherence, translate KM-GBF's transformative ambitions into measurable, adaptive, evidence-based implementation pathways to the 2050 vision (Gonzalez et al., 2023; Kim et al., 2026; Moersberger et al., 2024).

A vast landscape of KM-GBF-relevant models has been established to capture diverse facets of nature, its changes and underlying drivers. These models integrates different ecological, social-ecological and earth systems facets and operate at varying spatial, temporal and sectoral scales, each with its own advantages and limitations. The full scale of their capabilities, complementary strengths, limitations, and opportunities across realms, drivers, and nature's facets for implementing the KM-GBF through scenario-based approaches however remains tenuous (Kim et al., 2025). Here we assess models that can inform Goals A (Protect and Restore) and B (Prosper with Nature) and evaluate them on 23 targets to provide a representative assessment on their capacity (see Walkden et al. In Prep. for methodological description of the review).

We developed a living model database comprising 65 models to date that can inform the KM-GBF goals and targets across genetic, species, ecosystem, and socioeconomic dimensions (Figure 2, Supplementary Information I and II for statistical and descriptive overview and IV for model description). Goal A (Protect and Restore) can be informed by 32 models focusing on species-level objectives – 3 on genetic diversity, 6 on ecosystem connectivity, and 12 on ecosystem integrity. Goal B (Prosper with Nature) can be addressed through 53 models quantifying nature's contributions to people – 26 on provisioning, 16 on regulating, and 18 on cultural services. Overall, target coverage varies considerably: highest 46 models on target 1 (spatial planning and effective management), 41 models on target 8 (climate change impacts), 40 models on target 3 (30% area-based conservation) and target 10 (sustainable agriculture, aquaculture, fishery, forestry), 39 models on target 11 (restoration and enhancement of nature's contributions), and 38 models on target 2 (30% ecosystem restoration). Coverage is critically limited for target 13 (genetic resource sharing) and target 17 (biosafety) with two models and target 23 (gender equality) with four models.

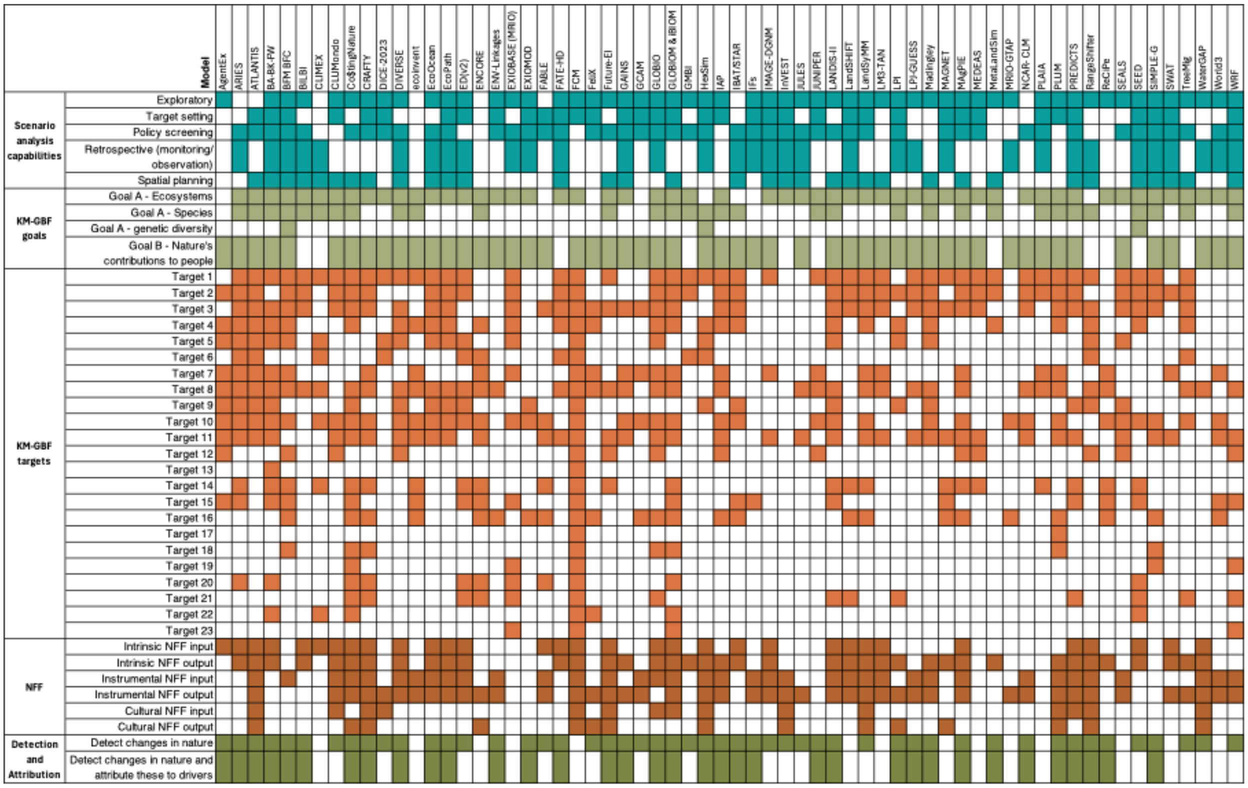


Figure 2. Summary of model capabilities on KMGBF, NFF, scenario analyses, and detection and attribution.

On the Goal species-level, extinction risk and abundance are informed by distributional models and pressure-reduction frameworks. At genetic diversity level, SEED (Fournier De Lauriere et al., 2023) uniquely develops 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, taxa, and drivers: HexSim (Schumaker and Brookes, 2018) simulates spatial population dynamics, LPI (McRae et al., 2017) tracks population trends, GLOBIO (Schipper et al., 2020b) provides global means species abundance, BILBI models compositional turnover, and IBAT/STAR (Mair et al., 2021) assesses threatened species. Specialized models address specific domains: PREDICTS (De Palma et al., 2021) uses abundance-distribution and pressure-reduction approaches, TreeMig (Lischke et al., 2006) for forest landscape dynamics, PLAIA (Stegmann et al., 2022) for plastic pollution impacts, and EcoOcean (Coll et al., 2020) for marine food webs under anthropogenic pressures.

On the Goal A ecosystems level, models include LPJ-GUESS (Smith et al., 2014), a dynamic global vegetation model predicting climate and land-use responses, and Madingley (Harfoot et al., 2014), integrating mechanistic processes across ecosystem functions. Ecosystem connectivity is informed by BILBI's (Hoskins et al., 2020) protected area assessments and Future-EI (Black et al., 2024) and LandSyMM's (Rabin et al., 2020) natural versus non-natural land cover comparisons. Resilience metrics can emerge from BILBI's bioclimate ecosystem resilience index and ENCORE's (UNEP-WCMC and NCFA, 2020) risk assessments, while LPJ-GUESS (Smith et al., 2014) and FATE-HD (Isabelle et al., 2014) project natural ecosystem area in vegetation models to inform land systems modelling frameworks such as JULES (Best et al., 2011) and LandSHIFT (Schüngel et al., 2022).

Ecosystem service models employ social-ecological assessment approaches: ARIES (Villa et al., 2014) uses artificial intelligence for stakeholder-informed decision support, while InVEST (Sharp et al., 2016) maps global change impacts on nature's contributions for natural capital investment strategies. Economic modelling resources like EXIOMOD (Bulavskaya et al., 2016a) assess sectoral environmental impacts, and ENCORE (Kiss-Dobronyi et al., 2021) is used for cross-sectoral nature-related economic risk analyses. As part of integrated assessment models, GLOBIOM/iBIOM (Havlík et al., 2011) evaluate 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 driver interlinkages and impacts on biodiversity. This diverse modeling landscape demonstrates substantial technical capacity for informing the KM-GBF implementation while revealing critical gaps requiring targeted development in areas such as genetic diversity, biosafety, and equity.

Specialized models provide essential depth for targeted KM-GBF implementation challenges, offering precision and mechanistic understanding within specific domains that integrated models do not yet have. TreeMig for example focuses exclusively on forest landscape dynamics under climate change, delivering fine-scale spatial and temporal resolution critical for Target 2 (ecosystem restoration) and Target 4 (species recovery) in forest systems, enabling forest managers to evaluate species-specific migration corridors and restoration site suitability with taxonomic and ecological details absent from broader frameworks. Similarly, PLAIA's agrochemical production-pollution focus provides the chemical sector specificity essential for operationalizing Target 7 (pollution reduction), tracing nitrogen and pesticide pathways from manufacturing through application to ecosystem contamination with supply-chain granularity that integrated agricultural models cannot achieve with aggregated pollution as a single driver. WaterGAP's dedicated focus on water resources, flows, and storage enables the evaluation of freshwater targets (T3, T10, T11) through hydrological processes – groundwater depletion, seasonal flow regimes, dam operations – that influence aquatic biodiversity outcomes but remain oversimplified in multi-realm models (Müller Schmied et al., 2021). These specialized tools excel at screening policies within their domains, providing actionable evidence for sector-specific interventions, yet these models are limited in assessing cross-sectoral synergies and trade-offs central to the KM-GBF.

Integrated models such as MAgPIE (Dietrich et al., 2019), DIVERSE (Cheung et al., 2021), and IMAGE-GLOBIO (Schipper et al., 2020a) demonstrate widely used capacity for holistic KM-GBF assessment by representing dynamic systems interactions on multiple 'action' targets and 'outcome' goals for coherent policy analyses with co-benefits and risks. MAgPIE exemplifies this integration by informing nine targets through coupled land-use optimization that simultaneously projects agricultural production (Target 10), climate mitigation (Target 8), species habitat (Target 4), nitrogen pollution (Target 7), and spatial planning outcomes (Target 1), revealing how food system transformations generate cascading biodiversity impacts mediated by international trade, technological change, and climate feedbacks – system dynamics essential for Target 14's policy integration. This comprehensive scope enables exploratory scenarios assessing whether proposed interventions collectively achieve Goal A (biodiversity protection and restoration) while maintaining Goal B (sustainable production and consumption), quantifying trade-offs where protection conflicts with production or identifying synergies where agroforestry simultaneously enhances biodiversity and yields. However, integration imposes critical limitations: computational tractability necessitates simplified representations of processes that specialized models resolve mechanistically (e.g. forest succession dynamics in MAgPIE versus TreeMig, marine food web complexity in DIVERSE versus EcoOcean). The broad spatial resolution (0.5° grids) aggregates heterogeneity crucial for site-level implementation, and coupled complexity obscures attribution of outcomes to specific drivers or interventions complicating policy diagnosis. Most critically, integrated models' current focus on provisioning and regulating ecosystem services – with cultural services represented in only 25% of models – systematically underrepresents equity dimensions central to Targets 13, 21, 22, and 23. While limited expert-based and participatory modeling capabilities constrain the integration of Indigenous knowledge and diverse value perspectives fundamental to KM-GBF's Article 8(j) and whole-of-society approach, current model integration emphasizes biophysical-economic system dynamics while marginalizing social-cultural dimensions essential for just and legitimate biodiversity governance.

Scenario Analyses to Inform Multiscale Policy Implementation inclusive of Value Plurality

Scenario analysis enables models to explore plausible futures or attribute outcomes to past actions, supporting evidence-based biodiversity policy across the policy cycle. In accordance with the scenario types defined in the IPBES Scenarios and Models methodological assessment (2016), we evaluated model capabilities on five scenario types aligned with policy stages: 1) exploratory scenarios examine unrestrained plausible futures based on driver trajectories, supporting agenda-setting; 2) target-seeking scenarios explore intervention pathways toward common goals, informing policy design; 3) policy-screening scenarios compare outcomes of contrasting interventions, guiding implementation; 4) retrospective scenarios review past policies to identify gaps between objectives and outcomes, enabling policy evaluation; and 5) spatial planning scenarios with particular importance to biodiversity conservation across policy stages (IPBES, 2016) (Figure 3).

KM-GBF explicitly recognizes diverse values of nature, positioning human-nature relationships centrally while embracing diverse worldviews, stakeholders, and priorities for coherent, forward-looking policy implementation (IPBES, 2022). These values underpin the new scenario framework of IPBES – the Nature Futures Framework (NFF) – aiming to inspire the generation of new scenarios and models that proactively inform policy and management actions toward nature-positive futures (IPBES, 2025). While indicators measure the proximal KM-GBF progress, scenarios and models can be instrumental for planning through exploratory analyses of synergistic policy options in NBSAPs and reporting progress with impact assessment in National Reports, strengthening the evidence rigor by linking observations to forecasting (Kim et al., 2026; Leung and Gonzalez, 2024). This integration transforms biodiversity governance from reactive monitoring to anticipatory, adaptive, and transformative implementation grounded in pluralistic values and robust projections of alternative pathways toward the 2030 targets and 2050 goals in 'Living in Harmony with Nature' (Kim et al., 2023; Visseren-Hamakers et al., 2021).

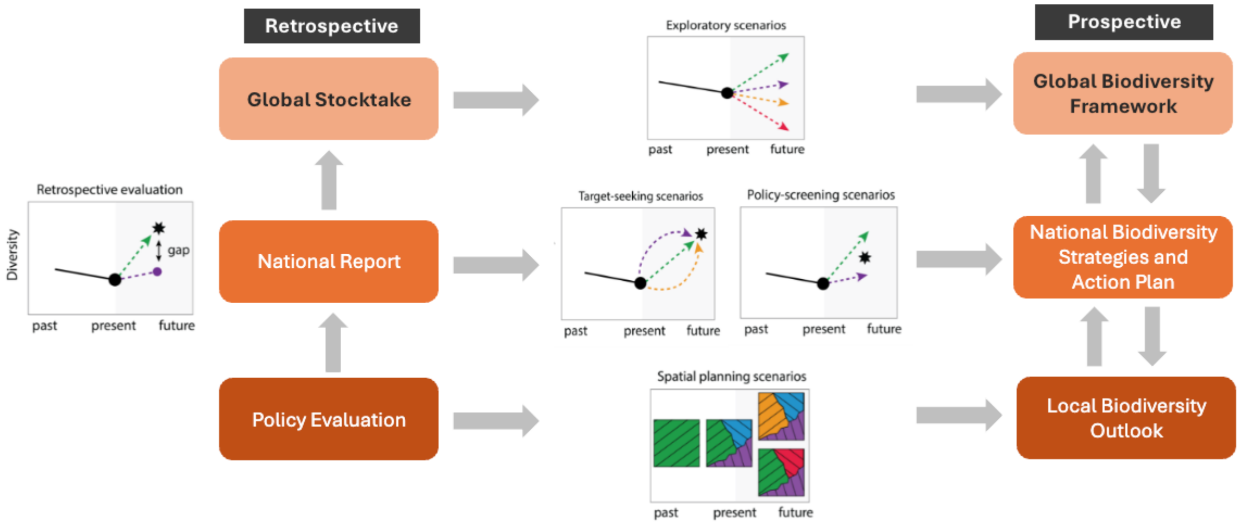


Figure 3. Scenarios typology across the policy cycle (top) across the regional scale in achieving the KM-GBF (bottom) from retrospective evaluation to exploratory, target seeking, policy screening scenarios and spatial planning with particular importance in biodiversity conservation. Abbreviations are: GBF = Global biodiversity Framework; GBO = Global Biodiversity Outlook; NBSAP = National Biodiversity Strategy and Action Plan; LBO = Local Biodiversity Outlook.

Models inform the KM-GBF policy cycle differently across spatial scales, from global agenda-setting to national implementation. For the design of global policy frameworks, systems-level 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, and World3 assess interactions among population, economy, energy, water, land, food, carbon, climate, and biodiversity, evaluating interventions including carbon taxation, land protection, afforestation, fertilizer regulation, dietary shifts, and education policies as integrated scenarios. These holistic frameworks identify global targets achievable through coordinated action while revealing synergies and trade-offs across sectors.

Specialized spatial models complement systems models with fine-resolution projections. BILBI identifies optimal protection and restoration areas globally by mapping habitat conditions under anthropogenic pressures, directly informing Targets 2 and 3 (30% restoration and conservation). CLIMEX (Kriticos et al., 2021) simulates species distributions, phenology, and abundance under climate scenarios and invasive species interventions, supporting Targets 6 and 8. Marine models EcoOcean and EcoPath (Christensen and Walters, 2004) project climate change and fishing effort impacts on primary productivity and stocks, testing marine protected area effectiveness for Targets 3, 5, and 10. Freshwater model LM3-TAN (Lee et al., 2014) predicts nitrogen-carbon dioxide interactions affecting water and air pollution, informing Target 7. Systemic scenario-model integration can enhance KM-GBF achievement through causality frameworks, detection-and-attribution science, and evidence-based indicators for policy planning and evaluation.

Globally, collaborative model development can support achievable target design with implementation guidance. Nationally, governments can coordinate monitoring, modeling, indicator development, and scenario programs, bridging scientific and implementation agencies to co-develop scenarios reflecting national priorities and the state of nature in NBSAPs and National Reports (Figure 3). For the design of NBSAPs, policy-screening and target-seeking scenarios can identify intervention portfolios using nationally calibrated models, data and local knowledge. At implementation scales, spatial planning models can identify priority conservation, restoration, and sustainable use areas, aggregating outcomes as monitoring indicators. For progress evaluation in National Reports, retrospective analyses combine observations with models for detection-attribution analysis, assessing policy effectiveness to inform adaptive management (Figure 3).

Integrating diverse values of nature – intrinsic (nature thriving independently), instrumental (human benefits from nature), and relational/cultural (Indigenous rights, traditional stewardship, cultural connections) – enables equitable consideration of locally relevant interventions balancing competing priorities: government interests in agricultural productivity and food security, Indigenous Peoples practicing traditional management, and conservationists identifying high biodiverse areas for protection assessing land-use impacts on biodiversity and resilience. Models in the database demonstrate varying capacities to integrate the NFF values – intrinsic, instrumental, and relational/cultural – as scenario inputs and outputs, revealing both capabilities and critical gaps for value-inclusive KM-GBF implementation.

At input level, 51% of models (33/65) can parameterize intrinsic values through biodiversity state variables including species richness, population abundances, and ecosystem extent serving as conservation priority criteria. BILBI exemplifies this by incorporating spatial variation in biodiversity composition as intrinsic value inputs, enabling scenarios where protection prioritizes compositionally unique areas independent of human utility. Similarly, ATLANTIS (Audzijonyte et al., 2019) parameterizes intrinsic values through species presence/absence and abundance metrics, allowing marine scenarios to evaluate interventions based on ecosystem integrity goals (Goal A) rather than solely fisheries yields.

Instrumental values appear in 38 models (58%) at input level, primarily through ecosystem service dependencies and economic production parameters. InVEST parameterizes instrumental values via pollination service dependencies, crop production requirements, and water purification demands, enabling scenarios testing agricultural intensification pathways that maintain critical regulating services while meeting food security targets (Targets 10, 11). GLOBIOM (Havlík et al., 2011) incorporates instrumental values through agricultural commodity demands, timber production quotas, and bioenergy targets, allowing scenarios to explore trade-offs between biodiversity conservation (Goal A) and sustainable production (Goal B) under alternative consumption patterns and technological trajectories. These instrumental parameterizations enable Target 16 (sustainable consumption) scenarios that quantify how sustainable dietary shifts reduce land conversion pressures while maintaining nutrition security.

Cultural values present the starkest limitation: only 23% of models (15/65) can incorporate cultural dimensions at input level. CLUMondo (Van Asselen and Verburg, 2012) represents cultural values through spatial maps of landscape with cultural importance based on expert and stakeholder consultations, enabling scenarios where land allocation respects culturally significant sites alongside productivity and biodiversity criteria. CRAFTY's (Murray-Rust et al., 2014) agent-based model allows parameterizing diverse land manager values – profit-seeking, stewardship ethics, traditional practices – creating scenarios revealing how cultural motivations shape landscape outcomes differently than economic optimization alone would predict. However, these representations remain simplified proxies rather than comprehensive integration of Indigenous cosmologies, relational values, or diverse cultural knowledge systems central to Target 22 (Indigenous participation) and Goal C (equitable benefit-sharing).

At output level, value representation strengthens: 61.5% (40/65) produce outputs considerable as intrinsic value (e.g. species persistence, ecosystem integrity), 69% (45/65) generate instrumental values (e.g. ecosystem service flows, economic production), but only 25% (23/65) provide cultural value outputs. ATLANTIS scenarios project distribution of culturally important species under fishing regulations, enabling evaluation of whether management maintains species central to Indigenous and local community identities. Co$tingNature (Mulligan et al., 2020) outputs recreation values and aesthetic landscape metrics, quantifying cultural service changes under development scenarios. However, most cultural outputs are oriented on provisioning services or monetary values rather than measuring impact of stewardship, spiritual connections, or traditional knowledge emphasized in the NFF.

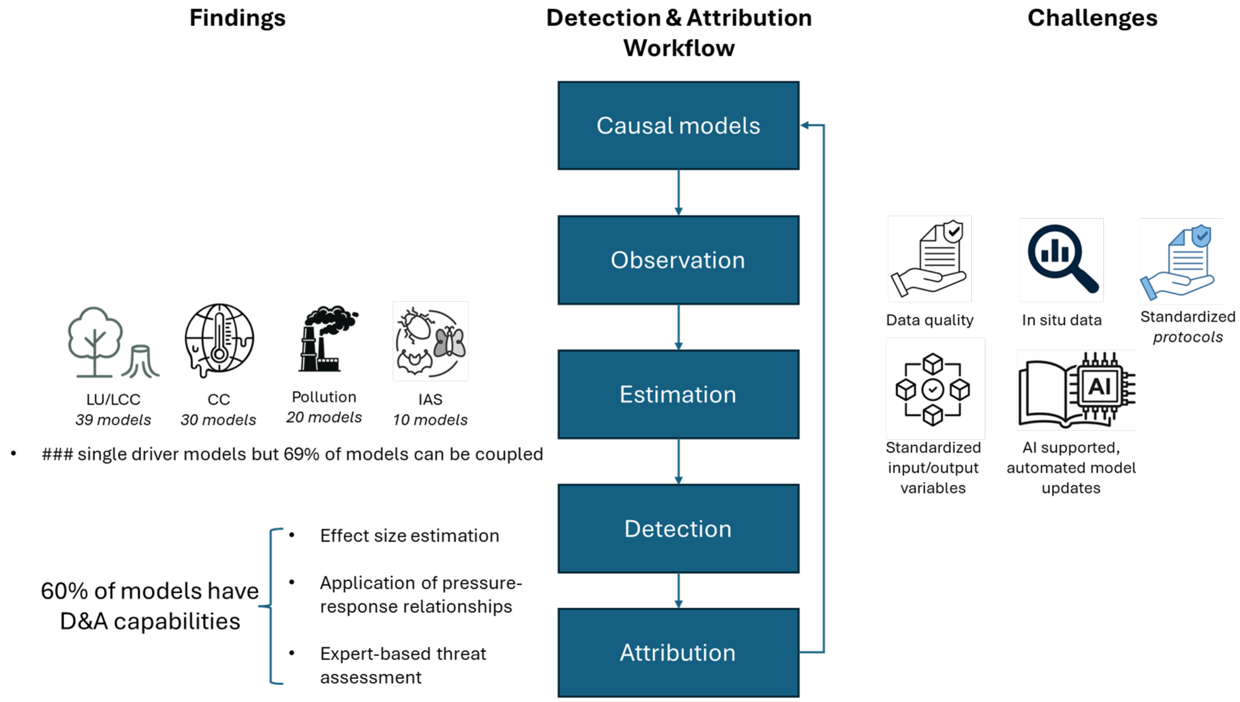
Comprehensive multi-value scenarios remain limited. ARIES (Martínez-López et al., 2019) demonstrates integration potential through semantic modeling linking intrinsic biodiversity metrics, instrumental service flows, and cultural values within a unified framework for national natural capital accounting in the Philippines, Nigeria, and Senegal. LandSyMM couples GLOBIO (intrinsic biodiversity), PLUM (Rabin et al., 2019) (instrumental services and trade), and CRAFTY (agent values including stewardship) enabling scenarios simultaneously tracking biodiversity integrity, food production, and diverse land management behaviors – approximating value pluralism. Future-EI projects intrinsic (biodiversity intactness), instrumental (agricultural productivity), and cultural (landscape heterogeneity as aesthetic proxy) outcomes jointly, supporting scenarios exploring whether nature-positive futures can harmonize multiple values or require negotiating trade-offs among value-holding communities.

Critical development needs emerge: expanding cultural value parameterization from spatial proxies to participatory scenario co-creation with Indigenous Peoples and local communities, integrating traditional ecological knowledge as formal model components rather than external validation, and developing equity metrics quantifying whether scenarios distribute benefits and burdens fairly across communities holding different values. Models like CRAFTY and FABLE (Jones et al., 2023) demonstrate pathways through agent-based and participatory approaches respectively, but systematic value pluralism requires methodological innovation and integration with formal processes (e.g. local and national planning tools) beyond current model capabilities, particularly for relational values resisting quantification yet fundamental to KM-GBF's transformative and equitable vision.

Detection and Attribution Science to Improve the Evidence Base for Biodiversity Policy

Detection and attribution science forms the cornerstone of evidence-based biodiversity policy 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). Detection involves identifying biodiversity changes relative to baselines or null models, while attribution quantifies the statistical contributions of multiple causal factors to observed outcomes – a dual capacity critical for tracking progress toward international biodiversity outcomes and designing effective interventions (Figure 4). Progress monitoring through National Reports fundamentally depends on detection-attribution capacity. 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.

For the KM-GBF implementation, detection and attribution science enables evidence-based policy cycles at multiple scales. 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. Nationally, NBSAPs require intervention scenario analyses evaluating 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. For example, evaluating whether 30% protection (Target 3) can simultaneously advance species recovery (Target 4), maintain ecosystem services (Target 11), and support sustainable production (Target 10) requires models attributing biodiversity outcomes to spatial protection patterns while accounting for climate change (Target 8) and pollution (Target 7) interactions. 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).



Figures 4. Detection and Attribution framework (Gonzalez et al 2023) with key findings per step (left panel) and key challenges per step (right panel)

Among the 65 models reviewed, 54% (35 models) possess detection and attribution capabilities, representing substantial technical capacity for causal inference. These models employ diverse methodological approaches: statistical estimation of effect sizes linking pressures to biodiversity outcomes (e.g. BILBI, RangeShifter (Bocedi et al., 2021), FATE-HD), application of published pressure-response relationships (e.g. GLOBIO, HexSim), and expert-based threat assessments (e.g. IBAT/STAR, Co$tingNature). While a robust formal methodology for detection and attribution grounded in causal inference principles has recently been proposed (Gonzalez et al. 2023), only few models have implemented this comprehensive framework, revealing a methodological frontier requiring systematic advancement. The current detection and attribution capacity provides substantial foundation, but systematic gaps in driver coverage (particularly indirect drivers like governance, finance, and behavior central to Targets 14-23), limited cultural value attribution constraining equity evaluation (Targets 22-23), and inadequate validation for causal inference in social-ecological systems key to KM-GBF.

Models with detection-attribution capacity demonstrate a broad coverage across KM-GBF Goals A and B, enabling the assessment of interventions addressing Targets 1-3 (spatial planning, ecosystem restoration, protected areas) and their implications for multiple biodiversity facets. BILBI, Future-EI, and BA-BK-FW (Martins et al., 2023) evaluate how land and sea use changes associated with protection and restoration impact species diversity within ecosystems (Goal A – Ecosystems), projecting compositional turnover and habitat condition under alternative spatial allocation strategies. IBAT/STAR and RangeShifter assess threat reduction and management actions from protection towards preventing species extinctions (Goal A – Species), quantifying persistence probabilities and population viabilities under conservation scenarios. Co$tingNature tracks the consequences of habitat change for nature's contributions to people including pollination services (Goal B – NCP), revealing trade-offs between biodiversity protection and agricultural productivity. HexSim uniquely simulates how pressure alleviation shapes genetic diversity (Goal A – Genetics), the least-represented dimension of Goal A. This ensemble enables intervention scenario analyses – target-seeking and policy-screening – evaluating possible effects of policy interventions and solution-oriented pathways to specific biodiversity goals while informing spatial resource allocation to regions identified at greatest biodiversity loss risk or greatest restoration opportunities given ecological and environmental states.

Driver coverage reveals systematic biases constraining holistic causal inference. The coverage is strong on land use (54 models) and climate change (55 models), reflecting their recognized dominant impacts and availability of spatially-temporally explicit data models and data. Conversely, comparatively fewer models inform sea-use change (21 models), invasive alien species (13 models), or pollution (32 models), preventing the comprehensive evaluation of the full driver-outcome interactions influencing biodiversity responses to environmental change. This imbalance creates evidence gaps potentially rendering interventions ineffective or detrimental in specific contexts where underrepresented drivers dominate. For example, Target 6 (invasive alien species management) receives limited model support despite invasives' severe impacts in island and freshwater systems (Roy et al., 2024), while Target 7 (pollution reduction) lacks fine-scale attribution capacity linking specific pollutants to biodiversity outcomes essential for targeted regulatory design.

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. This complexity-interpretability trade-off manifests in complementary model strengths: complex models with many interacting drivers (species distribution models) excel at forecasting biodiversity patterns, invaluable 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 (Gonzalez et al., 2023; Zurell et al., 2025).

Joint modeling offers promising pathways overcoming single-model complexity limitations while maintaining interpretability. 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 GLOBIOM 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 (Net Primary Productivity) readily coupled with models (e.g. IAP2, LandSHIFT, CRAFTY, TreeMIG, PLUM), demonstrating how variable standardization could enhance interoperability and enable aggregation of local-national indicators into global indicators. The current input-output heterogeneity across models hampering information flow can be improved with employment of the Essential Biodiversity Variables (EBVs; H. M. Pereira et al., 2013) and Essential Ecosystem Service Variables (EESVs; Balvanera et al., 2022) as standardizing frameworks for integrative modelling and model intercomparison in biodiversity science, similarly to Essential Climate Variables (ECVs) in climate science (Kim et al., 2026, 2018; Pereira et al., 2024)

Validation and calibration also emerge as critical bottlenecks constraining policy application. Sixty percent of models (39 models) have undergone independent validation, with data availability presenting persistent challenges. 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.

The standardized monitoring protocols regarding data collected, combined with misalignment in input-output variables across models, will improve coordinated detection-attribution efforts (Figure 4). 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; Kim et al., 2026; Purvis, 2025). Further, AI may provide valuable automation for model updating, potentially accelerating validation cycles, and enabling continuous learning from emerging observations. Improving detection and attribution science requires partnership between monitoring and modeling communities developing sampling protocols that are achievable, funded, and deliver primary purposes alongside scenario and policy needs. 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.

Streamlining Scenario-based Biodiversity Information for Transformative Governance

Using scenarios and models in the KM-GBF implementation requires inter-sectoral governance harmonizing datasets across modelling domains to ensure interoperability. The 65-model database reveals systematic patterns in data requirements, output variables, and integration opportunities that demand coordination (see Table 1). Review identifies five classes of fundamental data transversing 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-specific traits and histories, food web structures, environmental preferences, soil properties, trophic interactions, and ecosystem conditions; (3) social and economy data comprising demographic and economic projections, policy assumptions, management strategies, sociocultural values, and human behavioral parameters; (4) spatial pressures 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 requirements such as observational data for calibration and validation, baseline conditions, statistical relationships, transfer functions, service demands, local expert knowledge, and systems interaction information. Substantial variation exists in sources, types, and resolutions even for common inputs, creating coordination challenges and harmonization opportunities.

Model inputs demonstrate inherent interdependencies requiring coordinated scenario design and parameter setting. Agricultural yields and fertilizer/pesticide applications jointly determine nitrogen and phosphate runoff patterns (modeled in PLAIA, LM3-TAN, SWAT (Bieger et al., 2017)), while trade extent and commodity prices interact with production and consumption patterns and GDP growth trajectories (captured in MAgPIE, GLOBIOM & iBIOM, EXIOBASE (Stadler et al., 2018)). These coupled dynamics requires joint parameterization where intervention assumptions propagate through model chains – for instance, dietary shifts toward plant-based consumption (e.g. in FABLE, FeliX, GLOBIO, JUNIPER, MAgPIE, PLUM) simultaneously reduce livestock production demands, alter land use patterns, decrease nitrogen loading, and modify biodiversity pressures across terrestrial and freshwater systems. Alignment between input data and modeled outputs emerges when parameterizing actions corresponding to NBSAP interventions across model domains through scenario approaches for spatial planning, policy screening, or target-seeking exercises.

Climate data exemplifies optimization potential: meteorological inputs (e.g. temperature, precipitation, radiation) required by vegetation models (e.g. LPJ-GUESS, FATE-HD, TreeMig), land systems models (e.g. MAgPIE, FABLE, GLOBIOM & iBIOM), and ecosystem models (e.g. Madingley, NCAR-CLM (Lawrence et al., 2019), ED) can be standardized from common sources (e.g. CMIP6), reducing duplication and ensuring consistency across coupled modeling chains. Similarly, land use/land cover data – the most common input (21 models) – benefits from harmonization around products like ESA-CCI Land Cover or national land maps, enabling models (e.g. BILBI, Future-EI, GLOBIO, LandSHIFT, LandSyMM, SEALS (Von Jeetze et al., 2023)) to operate from identical spatial baselines while producing comparable biodiversity metrics. Biodiversity observation data from GBIF, eBird, and national monitoring programmes can jointly calibrate species distribution models (e.g. CLIMEX, HexSim, RangeShifter), validate abundance projections (e.g. LPI, PREDICTS, GLOBIO), and parameterize trophic interactions (e.g. EcoPath, EcoOcean, Madingley), transforming fragmented data collection into coordinated model infrastructure.

While models require heterogeneous inputs and produce heterogeneous outputs with varying definitions and resolutions, use of standardizing frameworks at both input and output levels optimize efficient data exchange and comparison. Biomass outputs – produced by 13 models including ED (Ma et al., 2022), FATE-HD, LPJ-GUESS, Madingley, and NCAR-CLM – can be crossvalidated against satellite observations (e.g. GEDI, ICESat-2) and flux tower measurements, with model agreement indicating robust projections and divergence signaling structural uncertainty. Species abundance projections from GMBI (Savage and Renton, 2014), PREDICTS, GLOBIO, LPI, and Madingley employ different methodological approaches (e.g. statistical response functions, mechanistic population dynamics, pressure-state relationships) yet target conceptually aligned metrics, enabling multi-model comparison analogous to climate science's CMIP framework where the model ensemble quantifies projection uncertainty.

Model outputs inform sustainable transitions through scale-specific applications demonstrating concrete policy relevance. At global scales, MAgPIE's projections of agricultural land expansion under alternative dietary scenarios (current trends versus plant-based shifts) coupled with species' area-of-habitat calculations quantify biodiversity-food system trade-offs can inform international assessments and negotiations. FABLE pathways – developed by 24 country teams using harmonized methods – illustrate national-scale applications where governments employ standardized modeling to design NBSAPs balancing food security, biodiversity conservation (Targets 1-3), and climate mitigation (Target 8), with bottom-up national projections validated against top-down global constraints to set national commitments within planetary boundaries.

Regional transboundary applications emerge in marine systems where EcoOcean and EcoPath project management of fishing effort and expansion of marine protected areas (Target 3) across shared ecosystems like the Mediterranean or Coral Triangle, informing regional fisheries organizations on quota allocations achieving sustainable yields (Target 10) while preventing species collapses (Target 4). Freshwater models (e.g. WaterGAP, SWAT, LM3-TAN) operate at basin scales spanning national boundaries, projecting nitrogen and pesticide pollution under agricultural intensification scenarios (Target 7) and evaluating upstream-downstream equity in water quality degradation – critical for international river basin agreements.

Local-scale applications utilize spatial planning capabilities. BILBI identifies optimal protection and restoration site allocations maximizing biodiversity representation within 30% conservation targets (Targets 2-3) using fine-resolution habitat condition data, deployed nationally in Australia and Brazil for conservation prioritization. CRAFTY's agent-based framework simulates heterogeneous land manager decisions – profit-seeking industrial farmers, stewardship-oriented smallholders, and traditional practitioners. The models can inform how policy interventions (subsidies modifiable in models such as FeliX, GLOBIO, IFs (Hughes, 2016), MAgPIE; taxes in CRAFTY, DICE-2023 (Barrage and Nordhaus, 2024)) can assess the impact of land use outcomes for different composition of local actor for context-specific NBSAP design.

Table 1. Key model input data requirements and key model output metrics for KMGBF across 65 model database

Input Requirements	Output relevant for KMGBF Targets	Output 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	Different management options	Extinction risk or rate
Cloud, radiation	Bioenergy production	Biodiversity Vulnerability Index
Nature	Agricultural, urban, industrial land	Area of habitat for species
Biotic factors	**Target 2 Ecosystem restoration**	Species richness
Abiotic factors / biogeography	Ecological footprint per capita	Keystoneness index
Soil properties	**Target 3 Protected / conserved areas**	Species Threat Abatement and Restoration
Species demography / Life history	Area based protection measures to reduce emission	**Goal A Ecosystems**
Species distribution	River discharge surface runoff, nutrient in streams	Biomass (number of trees, by functional group)
Species traits	Changes in forest areas	Gross and Net primary productivity (GPP, NPP)
Ecosystem structure and conditions	**Targets 4–5 Species recovery & Wildlife**	Mean species abundance
Baseline state / reference area	Climate impact on species distribution	Area of natural ecosystems
Biodiversity trend and response data	Potential climate and habitat suitability for species	Mixed trophic level impact
Ecological footprint	Species Threat Abatement and Restoration (STAR)	Biodiversity Habitat Index
People / Economy	Biodiversity vulnerability index	Habitat loss, fragmentation
Human population density	Change in economically important species	Ecosystem connectivity
Agriculture traits	Change in culturally important species	Bioclimatic Ecosystem Resilience Index
Demands / supply	**Target 6 Invasive Alien Species**	Intactness
Trade/stocks and flows, prices	Spread of IAS	**Goal B Nature's contributions to people**
Gross domestic product (GDP)	**Target 7 Pollution**	Human health
National accounting data	Generic waste production	Water use
Perceived condition b/t human nature systems	Fertilizer, pesticides	Nitrogen runoff
Service proportional human welfare	Nitrogen deposition, leaching, runoff	Water regulation and quality
Spatial pressures	Phosphorous erosion, leaching, runoff	Pollination
Water use	Soil carbon, removal, erosion control	Crop and livestock productivity
Mariculture sites	Soil formation, protection, decontamination	Pest and pathogens regulation
Protected areas	Concentration of major pollutant	Carbon pools
Land use	Change in carbon pools	Heat fluxes
Agricultural yields	Damage to ecosystems	Climate regulation
Food per capita	**Target 8 Climate**	
Pollution and emission	Temperature	
Methodological requirements	Precipitation	
Baseline conditions	Climate regulation, carbon storage	
Statistical relationships	Solar radiation, humidity, air pressure	
Thresholds as boundary conditions	Heat fluxes	
Local context and knowledge	CO2, GHG emission	
	Bioclimatic Ecosystem Resilience Index	

Sectoral transitions leverage technology and behavioral interventions can be modeled as well. Pollution reduction (Target 7) through green energy transitions (e.g. BFM BFC (van Rooij and Arets, 2016), GAINS (Höglund-Isaksson et al., 2020), IFs, JUNIPER, WRF (Skamarock et al., 2008)), energy-efficient production (e.g. BFM BFC, IFs), and pollution control technologies (e.g. BA-BK-FW for marine systems, PLAIA for plastics, SWAT for pesticides). Models can simulate extraction reduction via fisheries management (e.g. EcoOcean, EcoPath) scenarios, consumption changes through EXIOBASE and IFs assessing harmful sector impacts (e.g. EXIOMOD (Bulavskaya et al., 2016b), GAINS), and trade pattern shifts (e.g. GLOBIO, MAgPIE) redistributing environmental pressures globally. Agricultural transformation pathways combine spatial interventions – protected area expansion (e.g. BILBI, CRAFTY, EcoOcean, EcoPath, Future-EI, GLOBIOM & iBIOM, LPI, Madingley, MAgPIE, PLUM, SEALS), restoration (e.g. BILBI, CLUMondo, FABLE, GLOBIOM & iBIOM, MAgPIE, NCAR-CLM, SEALS, SIMPLE-G (Haqiqi and Hertel, 2025), WRF), sustainable intensification (e.g. CRAFTY, FABLE, FeliX, GAINS, NCAR-CLM) – with behavioral shifts in diet and food waste (e.g. FABLE, FeliX, GLOBIO, JUNIPER, MAgPIE, PLUM) and education (e.g. FeliX), demonstrating multi-lever sustainability pathways.

Cross-model data needs reveal priorities for monitoring investment and methodological innovation. Time series biodiversity data emerges as the most frequently cited limitation with 51 models identifying improved data availability as primary development constraint. Spatial resolution mismatches between global models (e.g. 0.5° grids common in MAgPIE, GLOBIOM & iBIOM, GLOBIO) and local implementation needs (e.g. site-specific conservation decisions, landscape configuration in MetaLandSim (Mestre et al., 2016)) require downscaling methods and fine-resolution validation data. Behavioral and sociocultural parameters – essential for agent-based models (e.g. CRAFTY, HexSim) and behavioral change scenarios (e.g. FeliX diet shifts, consumption patterns in EXIOBASE) – lack systematic data collection infrastructure, relying on correlational additions from fragmented surveys rather than comprehensive monitoring such as the Food and Agricultural Organization (FAO) can provide with national administrative data. Transfer functions and statistical relationships parameterizing pressure-response dynamics (e.g. GLOBIO's mean species abundance relationships, PREDICTS' mixed-effects models) require expanded empirical studies across taxonomic groups, realms, and biogeographic regions to reduce taxonomic and geographic bias and uncertainty. Finally, Indigenous and local knowledge integration requires not only technical capacity (e.g. participatory modeling methods demonstrated in CLUMondo stakeholder consultations) but also governance frameworks respecting CARE principles – Collective benefit, Authority to control, Responsibility, Ethics – ensuring knowledge sovereignty while enabling inclusive and multi-evidence-based NBSAP development addressing Target 22 (Indigenous participation) and Goal C (equitable benefit-sharing) currently underdeveloped by existing modeling infrastructure.

Summary and Future Directions

The Kunming-Montreal Global Biodiversity Framework envisions transformative change by 2030 and 2050, yet achieving these ambitions requires more than political commitment – it demands systematic evidence infrastructure connecting observation to projection, projection to policy design, and policy implementation back to adaptive monitoring (Figure 5). The cyclical framework linking national ecological observation, harmonized datasets, modelling, indicator development, scenario simulations, and policy planning with scenarios provides this architecture. However, current practice fragments these activities across institutions, disciplines, and scales. The 65-model database reveals substantial technical capacity spanning genetic to ecosystem levels, yet this capacity remains underutilized for coordinated policy support (Kim et al., 2025). Transforming isolated modeling exercises into coherent evidence infrastructure requires addressing four fundamental challenges: establishing causal understanding across scales, coordinating diverse agencies for change and coordination, integrating qualitative values with quantitative projections, and advancing research frontiers that bridge biodiversity science with economic and financial decision-making.

From Fragmented Data to Causal Understanding Across Scales

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 ecological processes, monitoring programs, and policy cycles (Cumming et al., 2006; Essl et al., 2015). Monitoring operates annually to decadally – national forest inventories repeat every 5-10 years – while policy functions in 1–5-year cycle through National Reports and NBSAP revisions. Meanwhile, ecological responses unfold across decades to centuries: forest succession, genetic diversity shifts, trophic reorganizations. Models must therefore project simultaneously across near-term 2030 targets validated against emerging observations and multi-decadal 2050 goals incorporating legacy effects in biodiversity outcomes.

Spatial coordination presents parallel challenges. Global models provide planetary boundaries and international context but operate at coarse resolutions masking local heterogeneity where conservation actions materialize. National models translate global scenarios to domestic contexts but require downscaling to site-specific implementation (Hoskins et al., 2016). Regional models addressing transboundary ecosystems – Amazon Basin, Coral Triangle, Great Lakes – remain critically underdeveloped (only 11% of database) despite many biodiversity challenges transcending national jurisdictions (Kuempel and Suárez-Castro, 2024; Liu et al., 2020). The solution lies not in choosing single "correct" scales but in nested architectures: global boundary conditions constrain national projections, whose bottom-up aggregation validates whether collective commitments achieve planetary targets, revealing ambition gaps requiring enhanced action or resource mobilization. This nesting also enables cross-scale feedbacks – local land use decisions aggregate to national patterns influencing regional climate, which iteratively alters local agricultural suitability decades later, as example.

Aligning Diverse Agencies of Change Around Shared Evidence Infrastructure

Coordination challenges often stem from the absence of integrative or systems-based approaches to governance and financing across agencies, rather than from technical constraints. Governments designing NBSAPs and submitting National Reports require operational decision support but often lack in-house modeling capacity, relying on external consultancies producing disconnected assessments rather than sustained evidence systems (Lindenmayer and Likens, 2010). The solution requires joint national ecological monitoring and modeling centers –

analogous to meteorological services maintaining operational weather prediction – embedding evidence-based support within government planning processes.

Multilateral institutions (CBD, IPBES) synthesize model-based evidence into policy-relevant assessments but lack integrative monitoring and modelling frameworks (Gonzalez et al., 2026; Zurell et al., 2026). Climate science's Coupled Model Intercomparison Project is a demonstrative example: standardized experiments enable ensemble projections quantifying structural uncertainty across approaches, transforming "which model is correct?" into "what do models collectively tell us?" with explicit confidence intervals (Touzé-Peiffer et al., 2020). This review reveals that biodiversity science possesses comparable capacity – with shared input sources, input to output exchangeable across models, and comparable output variables – but lacks institutional coordination mechanisms to bridge communities and support collaboration and co-production.

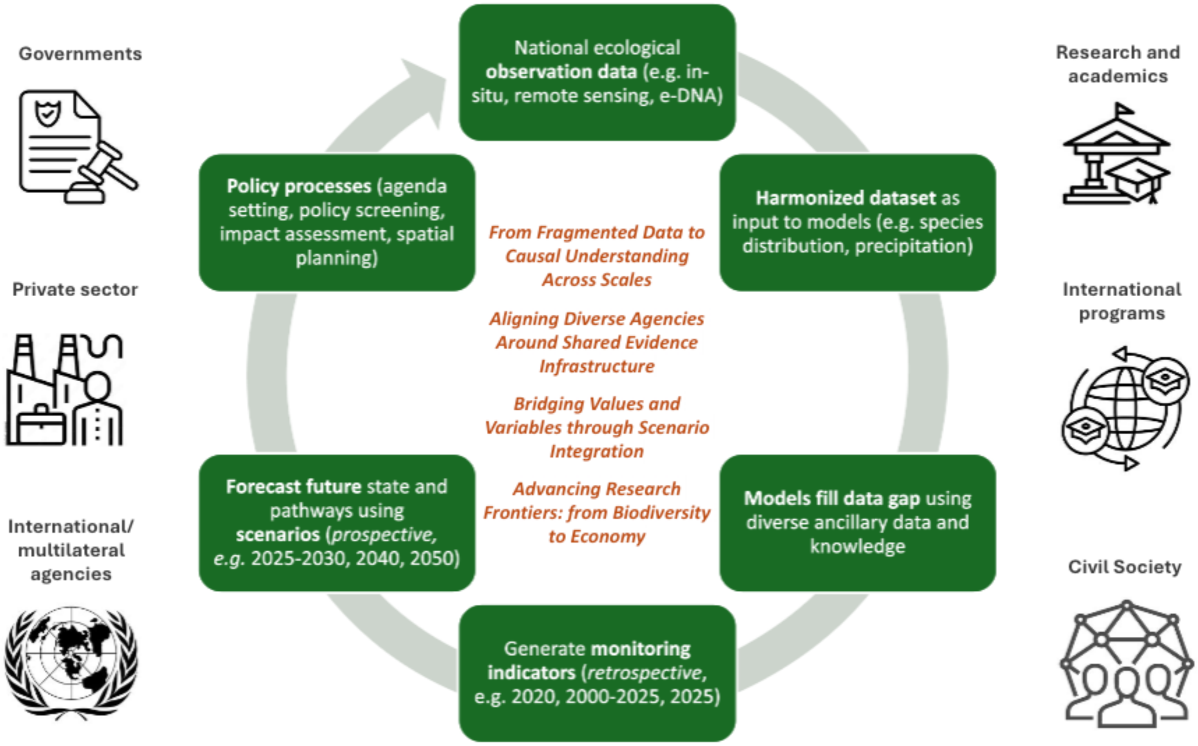


Figure 5. Data to decision flow from monitoring to data harmonization, modelling, indicator development, scenario design and modelling, and policy processes with a broad range of agencies of change across society.

Research institutions developing models face sustainability challenges: project-based funding supports novel development but often without long-term maintenance, validation against observations, or documentation for user communities. The majority of modelers cite data availability as primary limitation, yet monitoring investment remains disconnected from modeling needs rather than co-designed to serve both scientific understanding and operational prediction. This disconnect perpetuates the cycle where insufficient data limits model reliability, undermining confidence in model-based advice, reducing policy uptake, and ultimately justifying continued monitoring-modeling separation.

Private sector engagement introduces new coordination opportunities and challenges. Natural capital accounting, biodiversity-related financial disclosures, and supply chain risk assessments require linking biodiversity to corporate balance sheets – a frontier where ecological models must couple with multi-regional input-output frameworks, life cycle assessments, and computable general equilibrium models. This integration reveals financial materiality of nature loss, translating ecological concepts into fiduciary language corporate boards and sovereign investors understand. Civil society organizations contribute participatory scenario development incorporating diverse knowledge systems and plural values, yet current modeling capacity systematically underrepresents cultural and relational dimensions, particularly Indigenous People and local community perspectives essential for equitable outcomes and Target 22 implementation.

Bridging Values and Variables through Scenario Integration

The gap between normative policy goals and quantitative model outputs manifests most acutely in value pluralism (Black et al., 2024). The NFF demonstrates how qualitative narratives and quantitative modeling can synergize rather than remain in parallel tracks (IPBES, 2025). Narrative development articulates societal visions: Nature for Nature prioritizing intrinsic values where biodiversity thrives independently of human utility, Nature for Society optimizing instrumental ecosystem services sustaining human wellbeing, Nature for Culture centering relational values and diverse ontologies recognizing nature as kin, teacher, and identity source. These narratives establish normative targets and intervention logics that models operationalize through parameter settings and constraints (Dou et al., 2023; Siebert et al., 2019).

This translation manifests concretely in scenario design. Nature for Nature scenarios prioritize protected area expansion and reduced consumption demands for nature-converting products; models operationalize this through conservation targets (30% protection under Target 3) and dietary shift assumptions reducing agricultural land pressure (Von Jeetze et al., 2025). Nature for Society modifies food, fiber, housing density, and population demands to maintain provisioning services; models translate this into sustainable intensification parameters and service flow constraints (Godfray et al., 2010). Nature for Culture employs spatial layers identifying culturally valued landscapes developed through stakeholder consultations (Dou et al., 2023); models can integrate these as constraints preventing conversion of sacred sites, traditional use areas, or ceremonial landscapes.

Policy screening scenarios evaluate contrasting intervention portfolios emerging from narrative divergence: protection emphasis versus sustainable intensification versus traditional management systems. Target-seeking scenarios reverse the logic: given normatively defined 2030 targets (e.g. zero extinctions, halved pollution, 30% protection), models identify intervention pathways revealing whether dietary shifts alone suffice or require complementary technology changes and financial mechanisms. Retrospective scenarios enable policy review by attributing observed changes to implemented actions versus external drivers – distinguishing policy success from fortuitous trends, essential for adaptive management. This scenario typology spanning the policy cycle – from agenda-setting through design, implementation, monitoring, to review – requires models supporting multiple approaches rather than specializing in single types (Kim et al., 2023; Nicholson et al., 2019).

Advancing Research Frontiers: from Biodiversity to Economy

Coordinated evidence infrastructure must extend beyond traditional biodiversity science into domains where decisions materialize. The biodiversity-finance frontier exemplifies this imperative. Corporate supply chains depend on ecosystem services vulnerable to biodiversity loss – pollination for agriculture, water regulation for manufacturing, coastal protection for infrastructure – yet corporate risk assessments rarely quantify these dependencies or vulnerabilities (Chaplin-Kramer et al., 2019; Johnson et al., 2023a). Integrating spatial biodiversity models with economic frameworks enables tracing supply chain exposure: trade flows identify sourcing regions, land use models project habitat conversion under commodity demand scenarios, biodiversity models translate conversion to species loss and service degradation, which feedback to productivity declines in production functions – completing the loop revealing financial materiality for disclosure frameworks and credit ratings.

Similarly, cross-sectoral model development improves biodiversity representation in climate systems, freshwater hydrology, and marine dynamics, enabling integrated assessment of climate-biodiversity-development pathways rather than parallel independent evaluations (McElwee et al., 2024). This integration proves essential as interventions produce cascading effects: renewable energy expansion (climate mitigation) requires land for solar and wind facilities (biodiversity pressure), renewable materials substitution (plastic reduction) increases agricultural land demand (habitat loss), dietary shifts (health and emissions) alter fisheries pressure (marine biodiversity) (Kim et al. In prep.). Isolated sectoral models miss these trade-offs and synergies that integrated frameworks can assess.

From Aspiration to Implementation

Realizing this vision requires concrete investments across technical, institutional, and governance dimensions. Technically, semantic synchronization enables ensemble approaches where multiple models producing common indicators inform single KM-GBF goal elements through inter-model means with quantified uncertainties. Essential Biodiversity Variables and Essential Ecosystem Service Variables provide standardization frameworks aligning monitoring protocols with model requirements, enabling model outputs to directly populate KM-GBF indicators with reduced semantic translation. Model interoperability improvements – harmonized input-output specifications, standardized data formats, workflow management systems – can transform current multilateral collaborations into systematic model ecosystems.

Institutionally, sustained funding for model evaluation, calibration, and validation using national datasets and expert knowledge must parallel new model development. National modeling centers embedding evidence within government planning cycles replace disconnected consultancies with sustained capacity. Expanding stakeholder engagement through participatory modeling ensures diverse policy pathways, reflecting plural values strengthening legitimacy alongside credibility. Coordination mechanisms – e.g. model innovation, model intercomparison, IPBES-CBD joint assessment, capacity-building programs – can join fragmented efforts into coherent infrastructure.

Ultimately, this review reveals that the modeling capacity exists. What remains absent is coordination – across scales linking local implementation to global targets, across agencies aligning funding and incentives around shared evidence, across knowledge systems explicitly reflecting 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 can transform KM-GBF from aspirational declaration to evidence-grounded reality, enabling the rigorous, inclusive, equitable nature-positive futures the framework envisions. The technical foundation exists based on the 65-model database reviewed; the imperative now is initiating and sustaining collaboration and institutional commitment to operationalize this capacity for transformative change.

Glossary

Global biodiversity framework
Retrospective / ex-post analyses
Prospective / ex-ante analyses
Scenarios
Exploratory scenarios
Intervention scenarios (e.g. target-seeking, policy-screening)
Scenario framework
Narratives or storylines
Storyline-to-simulation
Models
Indicators
Monitoring
Detection and attribution
Prediction
Projection

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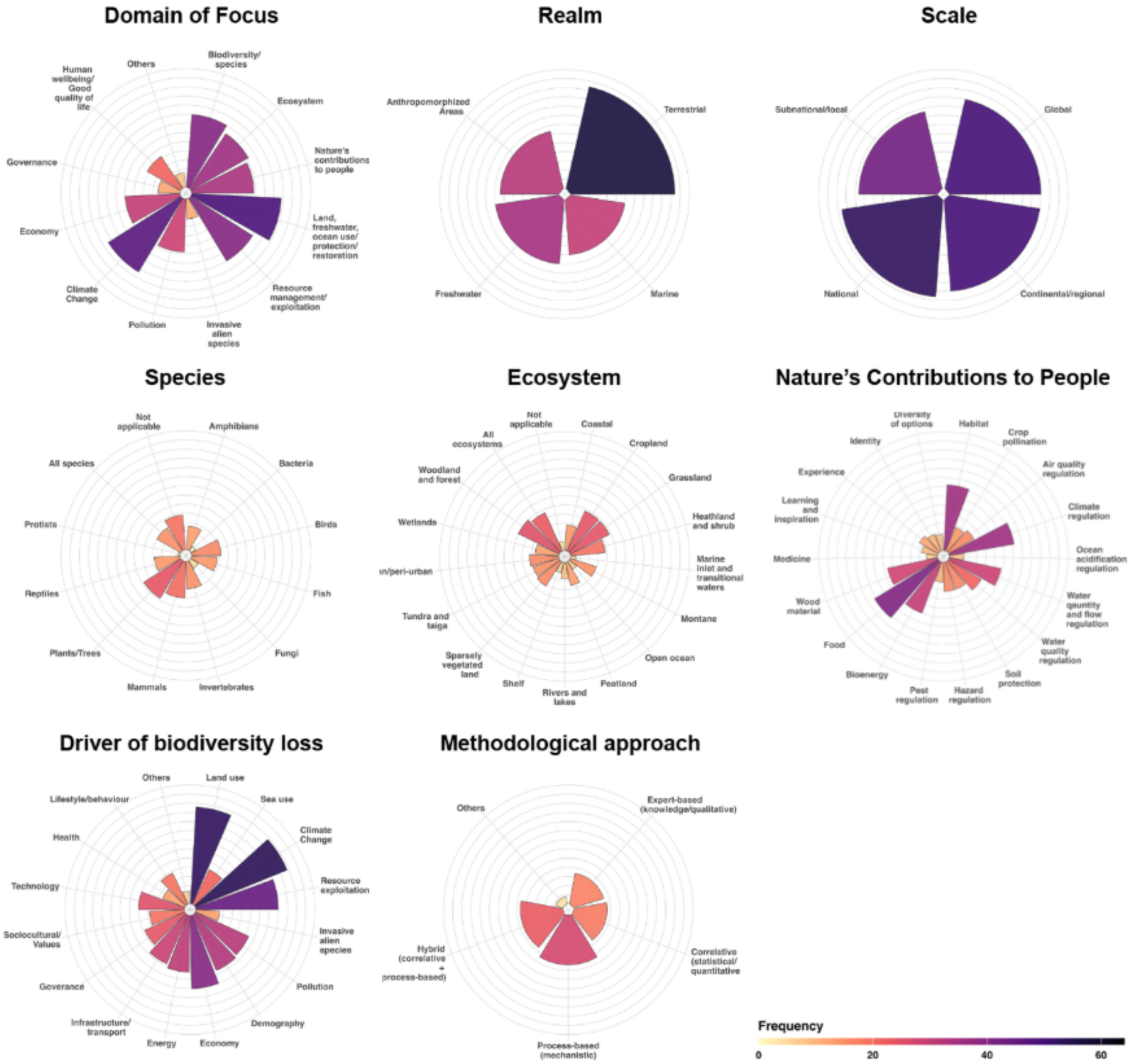
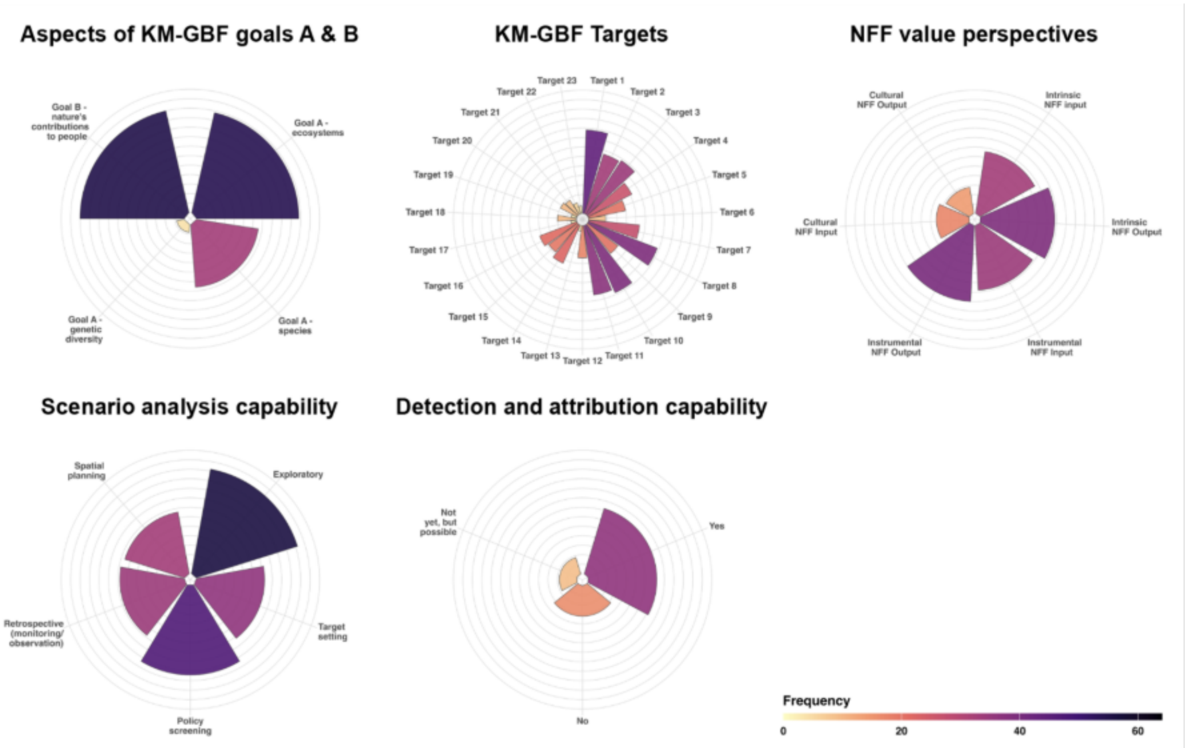
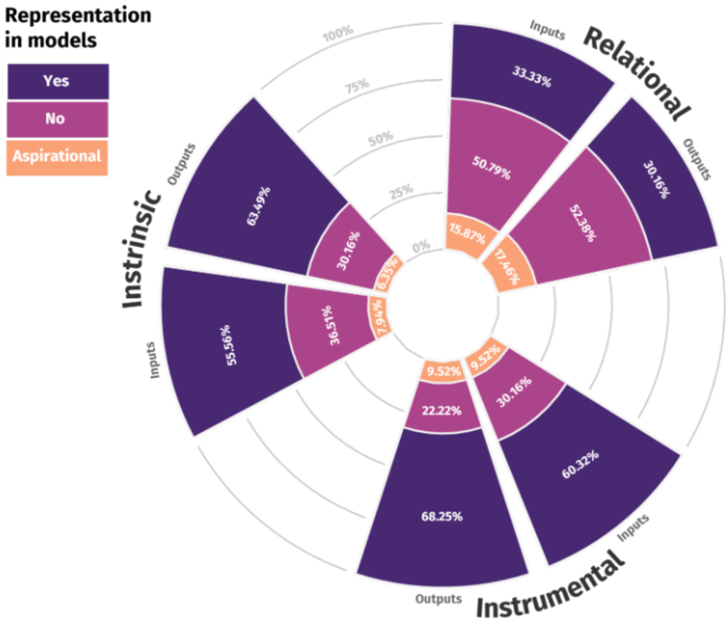
Supplementary Information

I. Meta-level overview of models



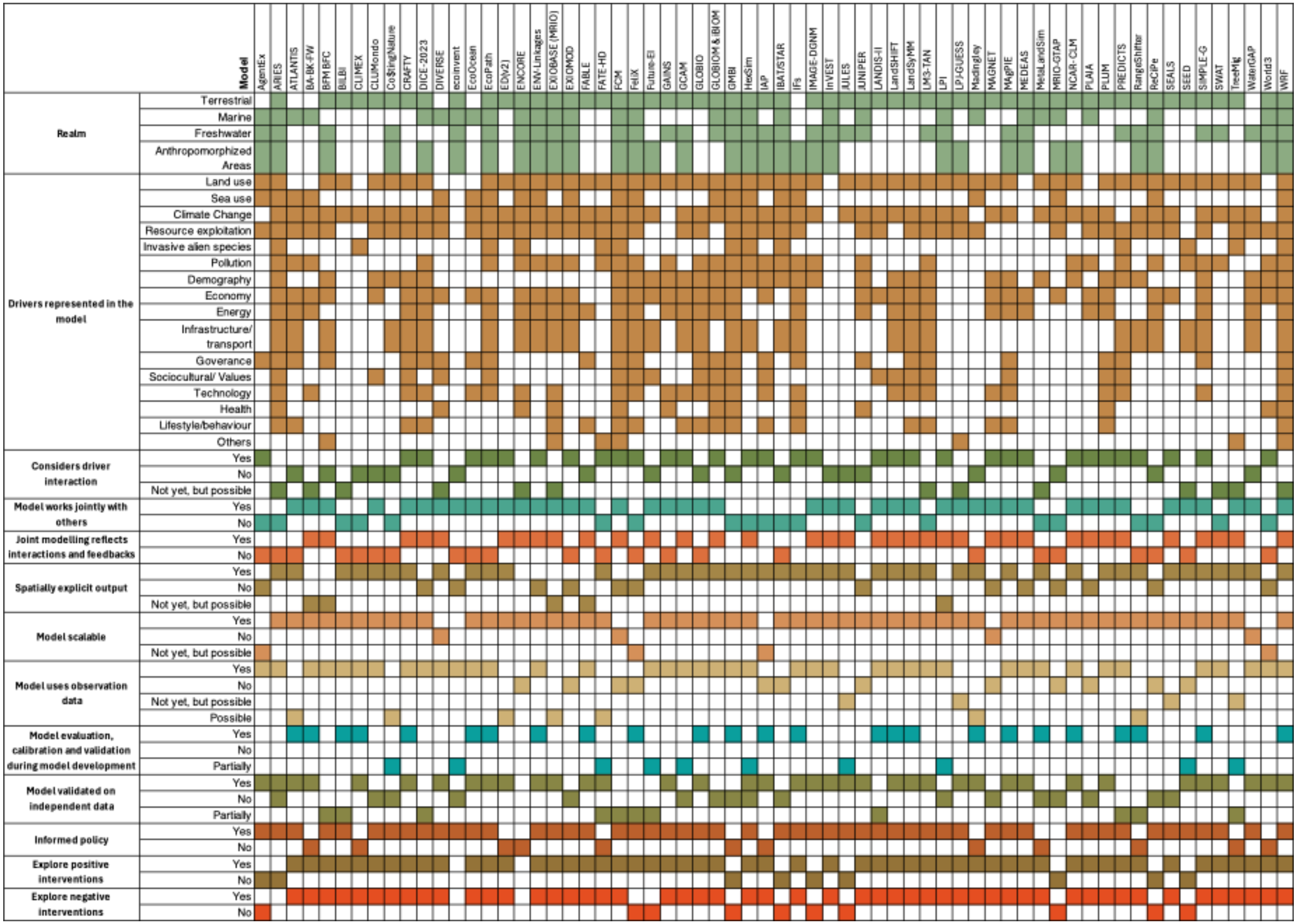


Aspects of KM-GBF goals A & B
Goal B - nature's contributions to people
Goal A - ecosystems
Goal A - genetic diversity
Goal A - species
KM-GBF Targets
Target 23
Target 1
Target 22
Target 2
Target 21
Target 3
Target 20
Target 4
Target 19
Target 5
Target 18
Target 6
Target 17
Target 7
Target 16
Target 8
Target 15
Target 9
Target 14
Target 10
Target 13
Target 12
Target 11
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



Representation in models
Yes
No
Aspirational
100%
75%
50%
25%
0%
Relational
Inputs
33.33%
50.79%
15.87%
Outputs
30.16%
52.38%
17.46%
Instrumental
Inputs
60.32%
30.16%
9.52%
Outputs
68.25%
22.22%
9.52%
Instrinsic
Inputs
55.56%
36.51%
7.94%
Outputs
63.49%
30.16%
6.35%

II. Summary of model capabilities



	Model	AgentEx	ARIES	ATLANTIS	BA-BK-FW	BFM BFC	BILBI	CLIMEX	CLUMondo	Co$tingNature	CRAFTY	DICE-2023	DIVERSE	ecoinvent	EcoOcean	EcoPath	ED(v2)
Realm	Terrestrial		■			■	■	■	■	■	■	■		■		■	■
	Marine	■	■	■	■							■	■	■	■	■	
	Freshwater	■	■			■				■				■		■	
	Anthropomorphized Areas	■	■			■				■		■		■		■	
Drivers represented in the model	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					■											
Considers driver interaction	Yes	■									■	■			■	■	■
	No			■		■		■	■	■				■			
	Not yet, but possible		■		■		■						■				
Model works jointly with others	Yes			■	■	■			■		■	■	■	■	■	■	■
	No	■	■				■	■		■							
Joint modelling reflects interactions and feedbacks	Yes				■	■					■	■	■				■
	No	■	■	■			■	■	■	■				■	■	■	
Spatially explicit output	Yes		■	■			■	■	■	■	■		■		■	■	■
	No	■										■		■			
	Not yet, but possible				■	■											
Model scalable	Yes		■	■	■	■	■	■	■	■	■	■			■	■	■
	No												■				
	Not yet, but possible	■															
Model uses observation data	Yes	■	■		■	■	■	■	■		■	■	■	■	■	■	
	No																
	Not yet, but possible																
	Possible			■						■							■
Model evaluation, calibration and validation during model development	Yes			■	■		■	■			■				■	■	
	No																
	Partially									■				■			
Model validated on independent data	Yes	■	■	■	■			■			■		■		■	■	■
	No		■						■	■				■			
	Partially					■	■					■					
Informed policy	Yes	■	■	■		■	■		■	■	■	■	■	■	■	■	
	No				■			■									■
Explore positive interventions	Yes			■	■	■	■	■	■	■	■	■	■		■	■	■
	No	■	■														
Explore negative interventions	Yes			■	■	■	■	■	■	■	■	■	■		■	■	■
	No	■															

	Model	ENCORE	ENV-Linkages	EXIOBASE (MRIO)	EXIOMOD	FABLE	FATE-HD	FCM	FeliX	Future-EI	GAINS	GCAM	GLOBIO	GLOBIOM & iBIOM	GMBI	HexSim	IAP
Realm	Terrestrial	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■
	Marine	■	■	■	■			■	■					■	■	■	
	Freshwater	■	■	■	■			■	■		■	■		■	■	■	■
	Anthropomorphized Areas	■	■	■	■			■	■	■		■			■	■	■
Drivers represented in the model	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			■			■	■									
Considers driver interaction	Yes		■		■		■	■	■		■	■		■		■	■
	No					■				■			■		■		
	Not yet, but possible	■		■													
Model works jointly with others	Yes	■	■	■	■	■		■		■	■	■	■	■			
	No						■		■						■	■	■
Joint modelling reflects interactions and feedbacks	Yes	■	■	■		■		■		■		■		■		■	
	No				■		■		■		■		■				
Spatially explicit output	Yes						■			■	■	■	■	■	■	■	■
	No		■		■			■	■								
	Not yet, but possible			■		■											
Model scalable	Yes	■	■	■	■	■	■			■	■	■	■	■	■	■	
	No							■									
	Not yet, but possible								■								■
Model uses observation data	Yes		■			■				■	■	■	■	■	■	■	
	No	■			■			■	■								■
	Not yet, but possible																
	Possible			■			■										
Model evaluation, calibration and validation during model development	Yes		■			■			■				■		■		■
	No																
	Partially						■			■		■				■	
Model validated on independent data	Yes		■	■		■	■				■		■			■	■
	No				■							■		■	■	■	
	Partially						■	■	■	■							
Informed policy	Yes		■	■	■	■		■	■	■	■	■	■	■		■	
	No	■					■								■		■
Explore positive interventions	Yes		■	■	■	■	■	■	■	■	■	■	■	■		■	■
	No														■		
Explore negative interventions	Yes		■	■	■	■	■	■			■	■	■	■		■	■
	No								■	■					■		

	Model	IBAT/STAR	IFs	IMAGE-DGNM	InVEST	JULES	JUNIPER	LANDIS-II	LandSHIFT	LandSyMM	LM3-TAN	LPI	LPJ-GUESS	Madingley	MAGNET	MAgPIE	MEDEAS
Realm	Terrestrial	■		■	■	■	■	■	■	■	■	■	■	■	■	■	■
	Marine	■			■		■					■		■			■
	Freshwater	■		■	■	■	■				■	■				■	■
	Anthropomorphized Areas	■	■	■	■							■	■			■	■
Drivers represented in the model	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												■				
Considers driver interaction	Yes		■	■				■	■	■		■			■	■	■
	No	■			■	■	■							■			
	Not yet, but possible										■		■				
Model works jointly with others	Yes			■	■	■		■	■	■		■	■	■	■	■	■
	No	■	■				■				■						
Joint modelling reflects interactions and feedbacks	Yes			■	■	■		■	■	■	■	■	■		■	■	■
	No	■												■			
Spatially explicit output	Yes	■	■	■	■	■		■	■	■	■		■	■		■	
	No						■								■		■
	Not yet, but possible											■					
Model scalable	Yes	■	■	■	■	■	■	■	■	■	■	■	■	■		■	■
	No														■		
	Not yet, but possible																
Model uses observation data	Yes		■	■	■			■	■	■	■	■				■	■
	No	■					■								■		
	Not yet, but possible					■							■				
	Possible													■			
Model evaluation, calibration and validation during model development	Yes		■					■	■	■				■		■	
	No																
	Partially					■						■					
Model validated on independent data	Yes		■	■	■	■	■		■	■	■		■	■		■	■
	No	■										■			■		
	Partially							■									
Informed policy	Yes	■	■	■	■	■	■	■	■	■	■	■	■		■	■	■
	No													■			
Explore positive interventions	Yes		■		■		■	■	■	■	■	■	■	■	■	■	■
	No	■		■		■											
Explore negative interventions	Yes		■		■		■	■	■	■	■	■	■	■	■	■	■
	No	■		■		■											

	Model	MetaLandSim	MRIO-GTAP	NCAR-CLM	PLAIA	PLUM	PREDICTS	RangeShifter	ReCiPe	SEALS	SEED	SIMPLE-G	SWAT	TreeMig	WaterGAP	World3	WRF
Realm	Terrestrial	■	■	■	■	■	■	■	■	■	■	■	■	■		■	■
	Marine	■	■		■				■							■	■
	Freshwater						■	■	■			■	■		■	■	■
	Anthropomorphized Areas		■	■				■	■							■	■
Drivers represented in the model	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													■			■
Considers driver interaction	Yes			■	■	■	■	■		■		■				■	
	No		■						■						■		
	Not yet, but possible	■									■		■	■			■
Model works jointly with others	Yes			■	■	■	■			■	■	■		■	■		■
	No	■	■					■	■				■			■	
Joint modelling reflects interactions and feedbacks	Yes			■	■	■	■			■		■	■	■			■
	No	■	■					■	■		■					■	
Spatially explicit output	Yes	■		■		■	■	■		■	■	■	■	■	■		■
	No		■		■				■							■	
	Not yet, but possible																
Model scalable	Yes	■	■	■	■	■	■	■	■	■	■	■	■	■			■
	No														■		
	Not yet, but possible															■	
Model uses observation data	Yes	■		■		■	■					■	■		■	■	■
	No		■		■				■		■						
	Not yet, but possible									■				■			
	Possible							■									
Model evaluation, calibration and validation during model development	Yes	■		■			■	■				■					■
	No																
	Partially										■			■			
Model validated on independent data	Yes			■		■					■	■	■		■	■	■
	No	■	■		■				■	■							
	Partially						■	■						■			
Informed policy	Yes			■	■	■	■		■	■	■	■	■		■		■
	No	■						■						■		■	
Explore positive interventions	Yes	■		■	■	■	■	■		■		■	■	■	■	■	■
	No		■						■		■						
Explore negative interventions	Yes	■		■	■	■	■	■		■		■	■	■	■	■	■
	No		■						■		■						

III. 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 (Kim et al., 2026).

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.
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.	
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 sustainability questions of the EU and its main trading partners as well as for major global economies.	Stadler et al. “EXIOBASE 3: Developing a Time Series of Detailed Environmentally Extended Multi-Regional Input-Output Tables.” Journal of Industrial Ecology 22, no. 3 (2018): 502–15.
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 act ivities 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 land use policy scenarios on agricultural land use (type of crops and total area, not spatially explicit), food security, water use, climate mitigation, and biodiversity conservation. With land amount of land "where natural processes predominate" used as a proxy for biodiversity. It is designed primarily to be allow co-development of national scale pathways for sustainable land use and food systems with policy makers.	Jones, S.M., Smith, A.C., Leach, N. et al. Pathways to achieving nature-positive and carbon–neutral land use and food systems in Wales. Reg Environ Change 23, 37 (2023).
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	Isabelle B, Damien G, Wilfried T. FATE-HD: a spatially and temporally explicit integrated model for predicting

		into account external drivers such as disturbance regimes, and environmental variations.	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).
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. .
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 (IAP1) 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 brings together and intergares existing models (inculding Watergap, LPJGuess).	Harrison, P.A., Holman, I.P., Cojocaru, G. et al. Combining qualitative and quantitative understanding for exploring cross-sectoral climate change impacts, adaptation and vulnerability in Europe. Reg Environ Change 13, 761–780 (2013).
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
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, 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.
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	Harfoot, M. B. J. et al. 2014. Emergent global patterns of ecosystem structure and function from a mechanistic general ecosystem model. – PLoS Biol.

		concepts and processes to predict the structure and function of the ecosystems at various levels of organization for marine or terrestrial.	
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 supports the prediction and optimisation of terrestrial land allocation based on future scenarios. 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 and bioenergy demand. It takes into account regional economic conditions, technological developments, production costs and spatially explicit data on potential crop yields land and water constraints. The model consists of a global land use allocation model, connected to the grid-based dynamic vegetation model LPJmL.	Dietrich, J. P., Bodirsky, B. L., Humpenöder, F., Weindl, I., Stevanović, M., Karstens, K., Kreidenweis, U., Wang, X., Mishra, A., Klein, D., Ambrósio, G., Araujo, E., Yalew, A. W., Baumstark, L., Wirth, S., Giannousakis, A., Beier, F., Chen, D. M.-C., Lotze-Campen, H., & Popp, A. (2019). MAgPIE 4 – a modular open-source framework for modeling global land systems. Geoscientific Model Development, 12(4), 1299–1317.
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.
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,	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.

		frequency of forest fire, air quality, terrestrial carbon storage, and water fluxes.	
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	The PREDICT is a modelled database supports the predictions of the impact on terrestrial biodiversity (species abundance, richness and diversity) of changes in land use and land management (intensification). 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 rather than global ecosystem health. The model consists of a database rather than a model, containing data on the composition of species communities across a gradient of land use and land use intensities collected form published literature.	De Palma, A., Hoskins, A., Gonzalez, R.E. et al. Annual changes in the Biodiversity Intactness Index in tropical and subtropical forest biomes, 2001–2012. Sci Rep 11, 20249 (2021).
RangeShifter	RangeShifter	The RangeShifter is a spatially-explicit, individual-based simulation platform that allows modelling species' range dynamics, such as expansion and shifting, and patch connectivity by linking complex local population dynamics and dispersal behaviour, while also taking into account inter-individual variability and evolutionary processes. It is highly flexible in terms of the spatial resolution and extent, and regarding the complexity of the considered ecological processes. Due to its modular structure, the level of detail in demographic and dispersal processes can be easily adapted to different research questions and available data.	Bocedi G, Palmer SCF, Malchow AK, Zurell D, Watts K, Travis 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 forest species and structural diversity over extended time periods (100yrs) dure to climate change.	Lischke, H., Zimmermann, N.E., Bolliger, J., Rickebusch, S. & Loffler, T.J. (2006) TreeMig: A forest-landscape model for 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.