Network for Greening the Financial System

Task force on Biodiversity Loss and Nature-related Risks

Review of global nature-economy models: Model 'ID Cards'

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Network for Greening the Financial System

Review of global nature-economy models: Model 'ID Cards'

Supplementary material to the NGFS Technical Document 'Recommendations toward the development of scenarios for assessing nature-related economic and financial risks'[1]

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As part of the Network for Greening the Financial System Taskforce on Nature Scenarios, findings summarized in Chapter 3 of the aforementioned NGFS Technical Document

Overview: The assessment of the following models was conducted through extensive reading of model documentation, and oral interviews, and written exchanges with the modelling teams. The findings are presented in the Model ID cards presented below. The selected assessment criteria in the ID Cards were mostly focusing on understanding the type of macroeconomic models and underlying assumptions, and the way the connection with biophysical aspects was performed. The interviews with the modelling teams aimed to help us understand better the functioning of the models and the typical questions they could provide an answer to. This also allowed us to understand the recent or ongoing developments of the modelling framework regarding biodiversity and nature issues, which cannot not necessarily be found in the models' documentation yet. Any errors in the tables below remain the responsibility of the authors.

1 This annex is also included in Kedward, Salin and Dunz (forthcoming), "Nature-Economy integrated assessment modelling: a review".

Contents

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1. GTAP-AEZ-InVEST model evaluation

GTAP-AEZ-InVEST		
GENERIC	**Aims of model**	1. How does a change in ecosystem services impact economic variables, such as GDP (i.e. deviations from exogenous growth path), economic welfare, returns on factors of production, and output of sectors? (**Physical risk**) 2. How do changes in economic policy affect the achievement of environmental and economic objectives? (**Transition risk**)
	Time horizon	Two-period comparative static model: produces economic projection for 2030 which is compared to 2021 projection (latter projected because latest GTAP data is 2014). No adjustment costs between two equilibrium points modeled
	Geographic scope	**Global coverage:** 37 aggregated regions (from GTAP database), sub-divided by 18 agro-ecological zones (AEZ), together creating 337 agro-ecological regions
	Environmental scope	• **Type of biodiversity:** terrestrial and marine (not comprehensive) • **Biodiversity pressures:** land use change through conversion of natural land into forests, pastures or agricultural land; climate change (in across certain physical and transition scenarios) • **Ecosystem services:** wild pollinators; timber from forestry; marine fishery stocks; carbon sequestration
	Type of macroeconomic model	**Structural computable general equilibrium (CGE)** model linked to high resolution spatially explicit ecosystem service models
	Inputs	**Data/assumptions from scenarios (forecasts/projections):** • Population & coarse LUC trends from SSP2 in 2030. The global population in 2030 is predicted to be 8.3 billion (Samir and Lutz 2017) • Temperature & precipitation projections from RCP4.5 in 2030 (currently not aligned with climate net zero 2050 scenarios) • Economic projections (income growth, TFP, trade patterns, rates of dev) from GTAP-AEZ projection 2014-21 **Other data inputs (historical data):** • Input-output flows on trade, capital stocks, savings, subsidies/tariffs/taxes from GTAP database • Spatial data on forest & agricultural land for 18 agro-ecological zones from AEZ database • High resolution maps with local-specific data on ecosystems from SEALs
	Description of model process	• **Four stage process:** 1. the CGE model GTAP-AEZ is used in a first round to model endogenous land-use change by 2030 based on economic demand (production input needs land as part of input factors) (GTAP-1) 2. these projections of regional land use (based on GTAP regional resolution) are then downscaled to a finer spatial resolution using the SEALS model 3. InVEST model uses this resolution data to model local impacts on ecosystem services 4. these ES impacts then input into second round GTAP run to model effects on 2030 economic activity (GTAP-2) • **Comparative static approach which compares two equilibrium states 2021 and 2030** (adjustment costs are not explicitly modelled)

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GENERIC	**Outputs**	• **Economic variables:** 2030 projections of global & regional GDP; sectoral output/value added, productivity, and prices; regional import/export flows; employment; returns to capital, labor, land • **Biophysical variables:** projections on land use change and carbon emissions; composite biodiversity index per geographical area (combining species richness, endangered species, biodiversity hotspots & rare ecoregions
	Model access and useability	Not available for off-the-shelf usage. Access via World Bank / University of Minnesota
	References	Johnson, J.A., Ruta, G., Baldos, U., Cervigni, R., Chonabayashi, S., Corong, E., Gavryliuk, O., Gerber, J., Hertel, T., Nootenboom, C. and Polasky, S. 2021. *The Economic Case for Nature: A Global Earth-Economy Model to Assess Development Policy Pathways* [Online]. Washington, DC: World Bank. https://openknowledge.worldbank.org/handle/10986/35882
SCENARIOS	**Scenarios that can be explored with the model**	**Baseline scenario:** 2030 projections without accounting for losses of ES **Physical scenarios** (exploratory): • **BAU scenario:** 2030 projections accounting for losses of ecosystem services induced by land conversion because of economic growth • **Partial collapse scenario:** partial collapse of 3 ES (reduction in wild pollinators, loss of forests, marine fisheries collapse) **Transition scenarios:** • 5 policy screening scenarios of 4 mitigation responses & various combinations of them: (1) subsidies to farmers; (2) domestic forest carbon payments; (3) global forest carbon payments; (4) public spending on agri R&D • Another policy-screening scenario evaluating economic impacts of achieving the 30x30 Global Biodiversity Framework target
NATURE-ECONOMY ASPECTS	**Key economic and behavioral assumptions**	• Representative agent with utility and cost optimizing behavior • Substitutability between production factors assumed, but additional rigidities modelled to reduce possibilities of adjustment (sectoral elasticity of substitution parameters reduced by 50% (95^{th} percentile) • Perfect capital & labor mobility; imperfect (sluggish) land mobility • Technical change modelled as exogenous improvement to sectoral TFP • Imperfectly elastic land supply curves • Substitutability of domestic products with imports, based on Armington elasticity setup
	Key parameters	• **Elasticities of transformation for alternate land uses:** the base values come from GTAP-AEZ (2008), initially based on Choi (2004). Substitution between croplands: -0.5. Substitution between managed forestland, cropland and pastureland: -0.2 Rigid values = base values/2 • **Elasticities of substitution for supply response *and* consumer demand sensitivity to price changes:** To reflect the impact of real-world economic rigidities on the economic projections, a sensitivity analysis is conducted that draws on the literature. To account for these rigidities, substitution elasticities that govern industry supply responses and consumer demand sensitivity to price changes are reduced from their initial mean value estimates. To better gauge the magnitude of the shock on the global economy, the substitution elasticities that are part of the GTAP model are replaced; instead of the mean values (based on literature searches and validation studies), the values at the upper limits of the 95th percentile are used

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NATURE-ECONOMY ASPECTS	**Key parameters**	• **R&D-TFP Elasticities:** regional estimates based on Fuglie (2017), ranges 0.13-0.30 for key world regions • **Land supply curves:** maximum arable land and distance away from maximum • **Armington trade elasticity** used for substitution between imported and domestic inputs
	Sectors represented	• **57 commodities aggregated into 17 commodity groups.** Those relevant for agriculture, forestry, and fisheries are: paddyrice, wheat, crs grns, fruitveg, oilsds, sugarcrps, cotton, othercrps, forestsec, fishery, ruminant, nonruminant
	Financial aspects	• **No representation of financial sector;** no financial variables in model • **One price variable held fixed, all others valued relative to this numéraire.** Money is neutral (classical dichotomy)
	Nature-economy interactions	• **Physical risks:** land and natural resources included as factors in production function, with some degree of substitutability assumed possible (including via imports) • **Transition risks:** policies represented by exogenous adjustments to selected parameters - *Decoupled support to farmers modelled through removing inputs and output subsidies and reallocating them to owners of agricultural land as lump sum transfers* - *Domestic forest carbon payment modelled through limiting land supply while compensating landowners via increases in land subsidies* - *Global forest carbon payment modelled through payment made by high-income countries based on historical emissions and received by countries according to the avoided deforestation* - *Public spending on agricultural R&D modelled through exogenous increase to agriculture TFP and lumpsum transfers to landowner* - *30 by 30 target (protected areas) modelled through shift in the land supply curve*
	Interactions with climate change	• **Economic damages from climate not explicitly modelled in GTAP**, even in scenarios with a decline in carbon sequestration by forests. Instead, for the additional CO_2 emissions for BAU scenario (due to decrease in forests in BAU). the social cost of carbon, set at $171 per ton (Tol, 2008), proxies for marginal increase in economic damages per ton in a given year. Hence total economic impact of additional CO_2 emissions valued at a hit to output of $135 billion in 2030. Impacts on countries are allocated proportional to their population • No damage from climate affecting ecosystems nor economic factors of production
COMPLEXITY FEATURES	**Non-linearities**	• **Tipping points in physical scenarios modelled as exogenous shocks to relevant ecosystem services** • **Sensitivity analysis on the BAU scenario:** elasticities of substitution reduced by 50% to proxy for the decreased ability of economy to adjust to shock. Question remains whether it is possible to adapt the model to more extreme scenarios? (e.g., lack of substitutability case) – see summary above
	Feedback effects	• **Two-step modelling process proxies for feedback effects from environment to economy:** ES outcomes of 1^{st} model run are input back into 2nd model run to understand economic implications • **Damage effects indirectly accounted for via land price effects** (less land availability → higher input costs), plus exogenous climate damages (see above) • **Feedback between climate change and economic output proxied through the valuation of carbon emissions from land-use change** with an ad hoc social cost of carbon (see above)
	Treatment of network effects	• The GTAP multi-regional input-output table is underlying the GTAP CGE model, which provides linkages between sectors and regions. Price adjustments, via recursive supply and demand adjustments, determine new market equilibrium

2. REMIND-MAgPIE model evaluation

		REMIND	MAgPIE	REMIND-MAgPIE
GENERIC	**Aims of model**	Model aims to determine cost-efficient mitigation strategies (and the associated climate policy effort, represented in a carbon price) required to attain an exogenously prescribed climate target, or calculate the emission trajectory based on prescribed policies. It can also include the damages from climate change on the economy (but in a rather coarse way – see below)	Model aims to simulate the impact future food, energy and material demand (based on the GDP and population dynamics) on water requirements and supply patterns on (spatially explicit) land use scale, including agricultural production and food prices, and on ecosystem services (e.g. biodiversity, pollination, soil erosion). It can also assess the impacts of climate change and climate mitigation policies, or other land policies (e.g. protected areas), on land-use maps, agricultural production, commodity prices, and ecosystem services (see for example Leclère et al. 2020, Jeetze et al. 2023). The model features a modular setup, allowing to activate or deactivate specific modules when conducting different analyses	REMIND-MAgPIE is primarily designed to assess feasibility of mitigation options, considering energy, land-use and macroeconomic feedback effects. The focus lies less on assessing macroeconomic impacts, although they can be included as well. Aims to determine efficient strategies to attain an exogenously prescribed climate target ('cost-effectiveness' mode), while explicitly accounting for land-use GHG emissions and mitigation possibilities (via bioenergy and carbon sequestration potential). The model can also be used to assess effects of climate mitigation strategies on land-use and agriculture
	Time horizon	2005 up to 2150. Default time step is 5yrs until 2060 and then 10yrs until 2110 and then 20yrs after that	For future projections, 5-10 year time steps. The model is initialized for the year 1995 and usually runs until 2100, or until 2150 when coupled with REMIND	2005 to 2100, 5 year time steps until 2060, 10 year time steps after that
	Geographic scope	Global level. Each country is assigned to one of 12 economic regions: CAZ (Canada, Australia and New Zealand; CHA (China); EUR (European Union); IND (India); JPN (Japan); LAM (Latin America); MEA (Middle East and north Africa); NEU (non-EU member states); OAS (other Asia); REF (reforming countries); SSA (Sub-Saharan Africa); USA (United States)	Global level. Each cell of the geographic grid (0.5° x 0.5°) is assigned to 1 of standard 12 economic world regions: CAZ (Canada, Australia and New Zealand; CHA (China); EUR (European Union); IND (India); JPN (Japan); LAM (Latin America); MEA (Middle East and north Africa); NEU (non-EU member states); OAS (other Asia); REF (reforming countries); SSA (Sub-Saharan Africa); USA (United States). It is possible chose different regional definitions, depending on the assessment, and not always use 12 standard regions	REMIND-MAgPIE uses the same geographic regions as REMIND

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		REMIND	MAgPIE	REMIND-MAgPIE
GENERIC	**Geographic scope**	For a number of variables, a country-downscaling is available via the NGFS scenario explorer, but these variables are currently focused on the energy system rather than land use or nature-related variables. The land use variables will be downscaled in the next phase of the NGFS Transition Risk Scenarios project	Most of MAgPIE's economic outputs are returned at the regional level. Physical outputs are returned at the cluster level (~1000 spatial clusters) which can be disaggregated on to 0.5 degree. MAgPIE also has a developed link to the SEALS model, which disaggregates physical results to the 300m x 300m level	
	Environmental scope	**Type of biodiversity:** not explicitly modelled **Biodiversity pressures included:** As an energy-economy IAM, there is no explicit nature/biodiversity module. Climate change is the primary pressure modelled (but no explicit link with biodiversity loss) – GHG emissions translate into temperature changes and chronic climate damages (Nordhaus style) but impacts of climate on biodiversity aren't modelled **Ecosystem services:** water for secondary energy production can be computed – the water consumption and withdrawal associated with the energy mix (depending on type of energy used and type of cooling) can be calculated in a post-processing of REMIND. It is not part of the optimization. REMIND does not account for constraints on water quality or quantity	**Type of biodiversity:** terrestrial focus. Available land types: cropland, pasture area, forest (managed and unmanaged), settlements, other land (non-forest natural vegetation, set-aside arable land, deserts). Can model **species abundance** (Biodiversity intactness index) associated to different types of land uses, with additional weighting on areas that harbour a high amount of rare species with a limited geographical range, to account for the spatial heterogeneity of biodiversity **Biodiversity pressures:** land use and land use change, climate change **Ecosystem services:** Provisioning of food and fibre commodities, provisioning of water for secondary energy production. Agricultural yields also depend on physical properties of soil (fertility), climate conditions, terrain type, water availability (see model inputs and process below). At present the biodiversity module is not explicitly linked to these	As per MAgPIE
	Type of macroeconomic model	Ramsey-type optimal growth model where intertemporal welfare is maximized	Global, spatial, partial equilibrium model of land-use sectors, operating in recursive dynamic mode	REMIND-MAgPIE is an inter-temporal optimization model, solving for the perfect-foresight equilibrium of the world economy between the years 2005-2100. REMIND and MAgPIE are soft-coupled, where each model is run alternately until a joint convergence is reached (see model process below)

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		REMIND	MAgPIE	REMIND-MAgPIE
GENERIC	**Inputs**	**Data/assumptions from scenarios (forecasts/projections):** *SSP2 (middle-of-the-road) used to help calibrate default scenarios, in particular the parameters of the CES production function* • Population (total & working age) projections from IIASA • GDP projections from OECD (see key assumptions below) • Energy efficiency parameters in the CES production function calibrated to projections from EDGE2 model **Other data inputs (historical data):** • IEA data (from 2014) for energy trade, energy technology characteristics. Also used to calibrate the conversion efficiencies	**Data/assumptions from scenario forecasts/ projections:** • Future scenarios on GDP and population growth (e.g. all SSPs) • Explicit information on pasture productivity, crop yields under both rainfed and irrigated conditions, water availability and terrestrial carbon content is provided by the global gridded crop model LPJmL (von Bloh et al., 2018) **Other data inputs (historical data):** • Regional and country data from base year 1995 on population, GDP, food energy demand, food self-sufficiency ratios from SSP and FAO • Crop yields and pasture productivity are calibrated at the regional level to meet the observed cropland and pasture area as reported by FAO (FAOSTAT 2020) • Average production costs per sector and region (from GTAP database) • Geographically explicit data on biophysical conditions from the grid-based dynamic vegetation model LPJmL which has 0.5° resolution, e.g. potential crop yields, water availability, carbon densities of different vegetation types	As per REMIND and MAgPIE standalone
	Description of model process	**Macroeconomic core:** • The macro-economic core of REMIND in each region is a Ramsey-type optimal growth model, where the inter-temporal welfare of one representative agent in each region is maximized, with utility function depending on per-capita consumption of a homogeneous good	• Recursive dynamic logic where optimal land use output from one timestep is used as initial land parametrization in the next time step	**REMIND connection to MAgPIE:** • Standalone mode': REMIND takes reduced-form emulators from original MAgPIE to represent emissions from land-use change and agriculture (CO_2, N_2O, CH_4), bioenergy supply, land based mitigation options …/…

		REMIND	MAgPIE	REMIND-MAgPIE
GENERIC	**Description of model process**	• Macro-economic production factors are capital, labor, and final energy (CES prod function, with nested CES for final energy types, produced with several types of primary energy) • Economic output is used for investments in the macro-economic capital stock as well as consumption, trade, and energy system expenditures. There is a trade-off in the model between consuming now or investing, so that output and consumption are larger in the following period. This arbitrage is balanced by the interest rate (determined by time preference and intertemporal elasticity of substitution). There is no explicit investment function but investment is driven by available savings, which are determined by the intertemporal optimal consumption decision, driven by the Ramsey-Keynes rule • Market equilibrium computed either as Pareto optimal solution where global welfare is maximised (assuming all externalities internalized) OR as a non-cooperative Nash solution where welfare is optimised at regional level without internalizing interregional externalities	**Economic processes:** • Model allocates spatially explicit land uses by minimizing total cost of production and so that supply is equal to food & bioenergy demand globally • Food demand endogenously modelled from GDP scenario (e.g. SSPs) and based on population properties (age groups, BMI, etc), diets, waste. Bioenergy demand obtained from dedicated coupled scenario runs with REMIND or from other scenario databases • Potential costs of production include type of production system (e.g., rainfed or irrigated), technologies (intensification), converting land, relocation of production/trade • Land use allocation is guided by LPJmL data on vegetation growth, crop water demand, water availability as well as MAgPIE implemented endogenous processes based on economic conditions like trade barriers, transport costs, intensification levels, marginal value of land etc • Agricultural production can increase through: expansion on non-agricultural land, increase in yields (i.e. yield-increasing technological progress), or trade between world regions • MAgPIE endogenously models agricultural yields and yield-enhancing technical change (see assumptions below) • Endogenous land use change (see assumptions below) • Initial potential yield levels for rainfed and irrigated crops are provided by the LPJmL crop model, and depend on soil fertility, climate conditions, terrain, water etc	• 'Coupled mode': MAgPIE can also be soft-linked and run iteratively with REMIND in coupled mode. Here, the soft link focuses on interactions of (1) bioenergy demand and supply; and (2) LUC emissions and GHG prices. Models are run iteratively, until an equilibrium is reached in the markets for bioenergy and land use emissions • Biodiversity costs associated with MAgPIE's BII calculation only indirectly affect output in REMIND through (1) the total agricultural costs channel; (2) possible constraints on land-based mitigation options from biodiversity protection scenarios • Modelers are currently discussing further developments to establish new channels to translate BII and other ecosystem losses (e.g. loss of pollinators, and soil erosion) into the general economic modelling (e.g., by subtracting directly from GDP)

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		REMIND	MAgPIE	REMIND-MAgPIE
GENERIC	**Description of model process**	**Energy system:** • Macroeconomic & energy modules are hard-linked by **final energy demand** (determined by economic activity) and **costs incurred by energy system** (negatively affecting the macroeconomic budget)	**Biophysical processes:** • **Carbon sequestration:** through afforestation and regrowing of natural vegetation. It can be processed exogenously though different carbon sequestration area targets, or endogenously though a premium awarding price on negative GHG emissions • **Water:** computes water availability and water demand. Main constraint requires water withdrawals to be smaller or equal to available water. Additional water constraints can be modelled by specifying that a certain quantity of water has to be retained in freshwater systems and not used for agricultural irrigation • **Biodiversity module:** computes the Biodiversity Intactness Index (BII) at the 0.5° grid cell level, weighted by a "scarcity layer" (see non-linearities below) • The default setting of the module computes separate BII values for each biome. This version allows target values for each BII to be input at the biome level (i.e., constraint on BII) • An alternative setting of the module computes an aggregate BII value which allows to estimate the economic costs associated with different conservation levels. These costs have been derived heuristically	
	Outputs	**Economic variables:** • Detailed representation of the energy system dynamics (e.g., primary, secondary and final demand, production, energy mix) per region • Final energy demand comprised of industry, buildings, and transport • Evolution of technical development per region • Detailed energy and technology mix and associated costs	**Economic variables:** • Costs of agricultural production on global, regional and spatial grid (0.5° x 0 .5°) level • Supply curves for commodities • Water demand associated with agriculture and non-agriculture sectors • Agricultural output quantities and prices • Agricultural GDP • Capital, labor costs and employment • Costs associated with biodiversity loss	As per REMIND and MAgPIE standalone

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		REMIND	MAgPIE	REMIND-MAgPIE
GENERIC	**Outputs**	• Changes in trade patterns over time (e.g., trade in emissions permits, exhaustible resources) • Global/regional costs associated with each mitigation policy and carbon price trajectory • GDP and welfare trajectories **Biophysical variables:** • Evolution of climate outcomes: atmospheric GHG concentration, radiative forcing, temperature impacts • Water withdrawal and water consumption associated with energy mix	**Biophysical variables:** • Estimations of different land-based GHGs: CO_2 from LUC and depletion of organic soil matter; N-related emissions from crops, pasture, livestock. CH_4 from livestock, rice • Specific land use patterns and agricultural yields for each spatial grid cell • Evolution of land use, land use maps • Biodiversity Intactness Index (BII): the intactness of local species assemblages (species richness) compared to a reference state (space-for-time approach) (between 0 and 1), depending on the type of land use change and on its location • Stock of biodiversity for each land cover, obtained by multiplying the BII with the area of associated land cover (in Mha) • Range-rarity weighted biodiversity stock: as above but with a 'scarcity layer' weighting towards areas that harbour high amount of rare species with a limited geographical range (from IUCN data) • Biodiversity Hotspots BII & Cropland Landscapes BII	As per REMIND and MAgPIE standalone
	Model access and useability	The model code is available open access and the model is designed on a flexible and modular basis. Model calibration requires various data inputs, some of which are paywalled	Version 4 is open access. Model is designed on a flexible and modular basis, to be adapted to different uses. 38 different modules within MAgPIE can either be switched on and off as needed, or run on a standalone basis. In this way, MAgPIE is a modelling framework rather than a fixed model, and can be adapted to answer different questions	The coupling code is part of the REMIND and MAgPIE releases

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		REMIND	MAgPIE	REMIND-MAgPIE
GENERIC	**References**	Developed by Potsdam Institut für Klimafolgenforschung (PIK) A model description paper on REMIND 2.1 has been published in Geoscientific Model Development (GMD): https://doi.org/10.5194/gmd-14-6571-2021 The model documentation for version 3.2.0 can be found at https://rse.pik-potsdam.de/doc/remind/3.2.0 **Latest release version:** https://github.com/remindmodel/remind/tree/master	Developed by Potsdam Institut für Klimafolgenforschung (PIK): https://rse.pik-potsdam.de/doc/magpie/4.3/index.htm Dietrich, J. P., Bodirsky, B. L., Humpenöder, F., et al. MAgPIE 4 – a modular open-source framework for modeling global land systems, Geosci. Model Dev., 12, 1299-1317, https://doi.org/10.5194/gmd-12-1299-2019, 2019 von Bloh, W. et al. Implementing the Nitrogen Cycle into the Dynamic Global Vegetation, Hydrology, and Crop Growth Model LPJmL (Version 5.0). *Geoscientific Model Development* **2018**, *11* (7), 2789-2812 https://doi.org/10.5194/gmd-11-2789-2018. Bonsch, M., Humpenöder, F., Popp, et al. (2016), Trade-offs between land and water requirements for large-scale bioenergy production. GCB Bioenergy, 8: 11-24 https://doi.org/10.1111/gcbb.12226 Dietrich et al., Forecasting Technological Change in Agriculture – An Endogenous Implementation in a Global Land Use Model. *Technological Forecasting and Social Change* **2014**, *81*, 236-249. https://doi.org/10.1016/j.techfore.2013.02.003 Mishra, A. et al. Land Use Change and Carbon Emissions of a Transformation to Timber Cities. *Nat Commun* **2022**, *13* (1), 4889. https://doi.org/10.1038/s41467-022-32244-w 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* **2023**, *14* (1), 2515. https://doi.org/10.1038/s41467-023-38043-1	Developed by PIK: coupled model documentation: https://www.iamcdocumentation.eu/index.php/Model_Documentation – REMIND-MAgPIE REMIND-MAgPIE has been used to translate SSPs into quantitative scenarios on land use and energy futures: Bauer et al., 2017. Shared Socio-Economic Pathways of the Energy Sector – Quantifying the Narratives, Global Environ. Chang., 42, 316–330, https://doi.org/10.1016/j.gloenvcha.2016.07.006 Kriegler et al., 2017. Fossil-fueled development (SSP5): An energy and resource intensive scenario for the 21st century, Global Environ. Chang., 42, 297-315. Popp et al., 2017. Land-use futures in the shared socio-economic pathways, Global Environ. Chang., 42, 331-345

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		REMIND	MAgPIE	REMIND-MAgPIE
SCENARIOS	**Scenarios that can be explored with the model**	**[Climate] Physical scenarios:** • Only climate, not biodiversity: Climate physical damages can be included (currently only RCP 2.6 only), and will directly affect output • This damage function can take a cost-benefit approach where climate damages are internalized through the social cost of carbon, which impacts the economy through relative price adjustments • Various other configurations and calibrations can be implemented such that different damage estimates based on literature can be provided, and optionally included in the optimization process of the model **[Climate] Transition scenarios:** • REMIND is designed to assess target-seeking climate scenarios • Analysis of different technology options, energy-economic transformation pathways, & climate mitigation proposals to achieve policy targets on GHG or temperature levels • The standalone version of REMIND can assess different regional policies including carbon taxes, cap-and-trade, budgets, allocation rules for distribution of emissions permits among regions	**[Climate] Physical scenarios:** • MAgPIE can assess the impact of temperature changes on yields, land use, agricultural production, water demand and biodiversity **[Climate] Transition scenarios:** • Land-based mitigation policies: limits on land use conversion, limits on CH_4 and N emissions, improved agri management, bioenergy with CCS, afforestation • MAgPIE can explore the impact of these mitigation policies on emissions associated with land use, land use areas, and biodiversity **Biodiversity/ Ecosystem Services Physical scenarios:** • It is possible to model the effects of water scarcity on agricultural yields (e.g. see Bonsch et al. 2016) • Currently the impacts of land degradation or other regulating ES – such as pollinators – on agri yields is being developed • The medium-term research agenda aims to refine the link between MAgPIE and the SEALS model as well as to link to INVEST ecosystem service models **Biodiversity Transition scenarios:** As used in Leclère et al. (2020), it is possible to assess: • Supply-side policies (sustainable crop yield increases & trade increases in agri goods) • Demand-side (reduced waste & dietary shifts)	**[Climate] Transition scenarios:** • As per REMIND and MAgPIE standalone **Biodiversity Physical and Transition scenarios:** • As per MAgPIE standalone • In coupled mode, the transmission mechanism from MAgPIE outputs to macroeconomic outcomes is limited to the effects on bioenergy demand, agricultural costs, and implied changes in abatement costs. These mechanisms are indirect and might underestimate true economic effects • Also worth noting that computational needs become more intensive the more modules are included in the intertemporal optimisation process. For this reason, there may be some inherent limits in the abilities to couple future research efforts (e.g., MAgPIE-INVEST) with the REMIND module

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		REMIND	MAgPIE	REMIND-MAgPIE
SCENARIOS	**Scenarios that can be explored with the model**		• Increased conservation efforts (protected areas, management, land restoration) • Also water constraints (Bonsch et al., 2016) • Not possible to implement different agricultural management approaches in spatially explicit way. Future work will link to LPJmL model to incorporate this into MAgPIE	
NATURE-ECONOMY ASPECTS	**Key economic and behavioural assumptions**	**GDP growth assumption:** • Exogenous population • CES parameters calibrated (by region) to reproduce OECD GDP reference scenarios • Labour productivity & energy efficiency progress calibrated to reproduce historic patterns • Capital and different energy carriers can change under different policy changes, causing an endogenous impact on GDP • Currently REMIND does not incorporate endogenous growth options related to human capital (some endogenous technical change, see below) **Production:** Represented with a nested CES including labour, capital and energy as factors (see Figure reproduced below table). Nested CES sectors are rather coarse and nested under energy as buildings, transport, industry where there is substitutability. It is possible to assign certain factors as perfectly complementary as one of the model setup choices. It is possible to assign putty-clay dynamics to some segments of the CES tree, which limits the extent to which energy demand can be reduced in response to higher energy prices	**Agricultural production:** Agricultural supply must equal demand globally, so there are no possibilities for food shortages in the model. Instead, food prices can become very high **Agricultural yields:** MAgPIE endogenously models agricultural yields based on the optimal production patterns, i.e. overall regional production costs structures, decisions on rainfed vs. irrigated production systems, investments in technology and land conversion, and location of production (intra- and inter-regionally). Yields are mainly dependent on water-related ecosystem services – the data for which comes from the LPJmL module. Currently effects of pollinators loss or soil erosion of crop yields is under development **Agricultural technical change:** modelled endogenously as a function of R&D investments in yield-increasing technical change, expressed by the multiplier-factor for yield increase (Dietrich et al. 2014). Region specific R&D costs based on level of agri development (agri land use intensity). Implementation is based on effectiveness of R&D on yield changes (investment-yield ratio) which is empirically derived from FAO, IFPRI and GTAP databases	See REMIND and MAgPIE standalone

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		REMIND	MAgPIE	REMIND-MAgPIE
NATURE-ECONOMY ASPECTS	**Key economic and behavioural assumptions**	**Energy:** is not part of the CES nest but is supplied to the CES-nested sectors from the linear energy system, where different final energy types are summed up. Note this means that bioenergy does not feature in the CES nests **Household consumption:** Single consumption good. Utilitarian utility function where social welfare is equal to the discounted intertemporal sum of utility, which itself is a function of per capita consumption **Trade:** single market for a general tradeable good (market clearing). Additionally, some other energy carriers are exchanged (coal, oil, gas). No detailed bilateral trade as no input-output tables. No armington elasticities **Technology:** • Fixed techno-evolution parameters for mature technologies such as coal fired power plants ("non-learning technologies") • Endogenous technical change with global learning curve for wind, solar PV, solar CSP, hybrid/electric/fuel cell vehicle technologies **Expectations formation:** perfect foresight, intertemporal optimization, taxes are budget neutral **Savings-Investment:** Endogenous interest rate from intertemporal optimisation based on Keynes-Ramsey rule	Investments induce higher yields but also increase the intensity of cropland use. This in turn raises the costs of further yield increases. Intensification cannotbe bounded but at a certain point it does imply extremely high costs. The model can also be run with an exogenous yield trajectories. Intensification is not linked to pesticide or fertiliser use in the model **Land use change:** • Endogenous. MAgPIE allocates optimal land uses for each grid cell by minimizing total cost of production so that supply equals demand • Potential production costs include type of production system (e.g., rainfed or irrigated), costs of technologies (intensification), costs of converting land, relocation of production/trade • MAgPIE is forced to use available cropland and rangeland first. Converting natural land only becomes relevant if land becomes scarce in region or if marginal benefits outweigh costs • Other costs could act as indirect constraints on land use change, e.g., transport costs related to converting very remote areas • Natural land can be excluded from conversion if designated as protected areas • Possible for mitigation policies to have perverse outcomes in terms of LUC. E.g., higher prices in one region might spark production relocation and LUC in another region if no protection policies are in place	

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		REMIND	MAgPIE	REMIND-MAgPIE
NATURE-ECONOMY ASPECTS	**Key economic and behavioural assumptions**		**Biodiversity Intactness Index (BII)** calculation in each grid cell accounts for a 'scarcity layer' - weighting towards areas that harbour high amount of rare species with a limited geographical range (from IUCN data). This is to reflect the fact that biodiversity is heterogeneously distributed across space, and so in some areas small land use changes could have outsized impact	
	Key parameters	CES efficiency parameter assigned to each production factor, these are calibrated to improve to match exogenous scenario specifications (e.g. SSPs) Pure rate of time preference (impacting the intertemporal optimization) Learning curves for non-mature technologies	**Agricultural intensification vs extensification:** a very sensitive and flexible mechanism within MAgPIE which depends on various parameters governing which situation has the lowest marginal costs vs benefits • Parameters determining whether intensification takes place include level of trade openness, level of interest rates, size of yield differences • Parameters determining whether LUC takes place include land conversion costs (based on historical data one.g., clearing forests, establishing crops). These are fixed over time	See REMIND and MAgPIE standalone
	Sectors represented	Limited number of sectors (mostly energy-related). Utility maximisation is based on a homogenous final consumption good Energy system module of REMIND: >50 technologies represented in conversion of primary to secondary energy & distribution. Renewable & non-renewable (exhaustible) resources represented End-use energy sectors: electricity production, stationary non-electric, transport, buildings (all nested under energy)	MAgPIE only represents the agricultural sector: Agriculture: 20 cropping activities, 5 livestock (ruminant, pig, poultry, eggs, milk), forestry (timber). Primary products can be processed to secondary goods (sugar, oil, ethanol) Forestry: CO_2 emissions from land use, LUC in forestry. Reduced emissions from deforestation and forest degradation (REDD) represented as a mitigation option by marginal abatement cost curve	Running REMIND and MAgPIE in coupled mode balances supply and demand in the markets for bioenergy and emissions

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		REMIND	MAgPIE	REMIND-MAgPIE
NATURE-ECONOMY ASPECTS	**Sectors represented**	**Agriculture:** REMIND determines non-CO_2 and CO_2 emissions from various agricultural activities (including land use change) using MAgPIE emulators (in REMIND standalone mode only)	Other sectors exerting pressure on biodiversity that are **not** represented include: fisheries, chemicals, plastic, construction/urbanization, and mining. Demand for construction wood for the building sector can be exogenously defined (Mishra et al., 2022)	
	Financial aspects	Financial sector not represented	Financial actors not represented. Interest rates governing yield-enhancing technical change are exogenously given	
	Nature-economy interactions	Nature-related production factors (e.g., land) do not feature in the production function of REMIND. Output depends only on capital, labour, and energy. Hence no representation of limited substitutability assumptions Bioenergy demand, agricultural costs that enter budget through budget equation, and changes in abatement costs from land-based mitigation options are the only nature-related aspects impacting GDP (through the level of carbon prices needed to reach given targets, and by the costs of energy-generation technologies). Note that bioenergy does not feature in the CES nests but is supplied to CES-nested sectors via the linear energy substitution system These channels mean that effects on GDP from nature-related shocks are likely to be quite small because: (1) bioenergy is small component of final energy, (2) agricultural costs do not account for important feedback effects of land degradation on agri yields.	Land is a production factor in MAgPIE for agriculture, forestry, and pastures Land characteristics (from LPJmL) determine initial yields, but projected endogenous yields are currently only dependent on water availability and quality. Currently a feedback between land degradation / loss of other ES on yields under development There is no representation of feedback effects between different ecosystem services	REMIND-MAgPIE has not been used so far to assess biodiversity loss/policies on the economy. Possible feedback channels are as follows: **Land-use => economy:** MAgPIE emulators can affect REMIND macro module through changes in relative prices of bioenergy (MAgPIE supply curves determine bioenergy prices) and expenditures for abatement of landuse emissions (via marginal abatement cost curves). However, impact on GDP is likely limited **Other biodiversity / ecosystem services => economy:** • Changes in water supply can impact agricultural yields in MAgPIE, affecting output in REMIND through the agricultural and bioenergy costs channel (deducted from GDP) • Loss of soils and other ES do not affect yields currently in MAgPIE so no feedthrough to REMIND • Is it currently not possible to connect the costs of biodiversity loss computed in MAgPIE to output in REMIND …/…

NATURE-ECONOMY ASPECTS	**Interactions of nature with climate change**	None	**Impacts of CC on nature:** Accounts for climate impacts on cropland and pasture productivity, and terrestrial carbon (vegetation, litter, soil)	**Climate => biodiversity:** • Possible to model the biophysical interconnections between climate policies, water use, and land use. • Possible to assess how climate mitigation policies (REMIND) affect land use and biodiversity loss (MAgPIE)
			Impact of land-use on CC: Includes afforestation as a climate mitigation measure that is endogenously incentivised by carbon tax, or exogenously prescribed in area targets. Also large-scale bioenergy production includes near-term policies given by nationally determined contributions (NDCs) and land-based national targets for avoiding deforestation	**Biodiversity/land => climate:** • Carbon sequestration modeled in MAgPIE and land use GHG emissions feedback to the REMIND model and affect climate • Biodiversity protection policies (eg, protected areas) affect food prices, bioenergy prices, and emissions (in MAgPIE) And subsequently mitigation costs in REMIND.
COMPLEXITY FEATURES	**Non-linearities**	REMIND contains features such as non-linear production functions or adjustment costs	Non-linear optimization	See REMIND and MAgPIE standalone
	Treatment of network effects	Limited representation of intersectoral linkages beyond carbon pricing effects (no input-output table underlying the model). The link between sectors is only through carbon prices (lower mitigation by sector A increase the carbon price and hence affects sector B), but intermediary consumptions between sectors are not represented	No network effects between sectors No underlying input-output matrix	See REMIND standalone

3. AIM-Hub model evaluation

AIM-CGE			Land-use allocation model: AIM/PLUM
GENERIC	**Aims of model**	Can simulate energy supply and demand with the description of the whole economic transaction AIM/CGE is developed to analyse the climate mitigation and impact. The energy system is disaggregated to meet this objective in both of energy supply and demand sides. Agricultural sectors have also been disaggregated for the appropriate land use treatment. The model is designed to be flexible in its use for global analysis	Global land-use allocation model used to downscale regionally aggregated land-use projections into a spatially gridded land-use pattern for the interactive assessment of human activities and biophysical elements
	Time horizon	The base year of AIM/CGE is 2005. AIM/CGE can be run for the 2005-2100 period. For some applications, the model is run up to 2050. The time step of the model solution is one year	5 year time steps for the land allocation process
	Geographic scope	AIM/CGE can be run as a global module in which the geographical resolution is 17 socio-economic regions (e.g., Hasegawa et al. 2014): Japan, China, India, Southeast Asia, Rest of Asia, Oceania, EU25, Rest of Europe, Former Soviet Union, Turkey, Canada, United States, Brazil, Rest of South America, Middle East, North Africa, Rest of Africa Alternatively, it can be run at the national level only, where there are 110 different countries available (e.g., Thepkhun et al., 2013, doi:10.1016/j.enpol.2013.07.037.)	Global, 0.5 degree grid cells
	Environmental scope	**Type of biodiversity:** not explicitly modelled **Biodiversity pressures included:** climate change, land use and air pollutants – but as an energy-economy model, these are not explicitly linked to a nature/biodiversity module **Climate:** • Climate change is the main pressure modelled, GHGs include emissions from multiple sectors including agri, forestry & land use change	Land-use: The model disaggregates the various land-use obtained with AIM/CGE at the regional level, to obtain detailed land use maps (0.5 degree grid cells) The land use maps produced can then be combined with biodiversity models to obtain biodiversity metrics associated with land use maps (e.g. BII); cf. Leclère et al. (2020). Land-use maps can also be used for global environmental assessments of ecosystem services, food security, and climate policies

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GENERIC	**Environmental scope**	• AIM-CGE is soft linked to MAGICC6 to calculate atmospheric concentrations, radiative forcing, and annual mean temperature increases • AIM-CGE has no feedback from the climate module **Land-use:** • Some sectors (Agriculture, Forestry) use land to produce sectoral output • Models the allocation of land between different uses. 6 AEZs (Agro-Ecological Zones) by: Crop, pasture, forestry, Other forest, natural grassland and others. There is a land competition under multi-nominal logit selection • The aggregate land-use at the regional level can be disaggregated using AIM/PLUM (to obtain LU maps)	
	Type of macroeconomic model	Recursive dynamic computable general equilibrium model	Global land use allocation model
	Inputs	Population and labor force data taken from SSPs (typically SSP2) TFP is calibrated so as to reproduce a given GDP pathway (from SSP) Crop yield intensity and land productivity assumptions from IMPACT model, mapSPAM data and FAO statistics Initial Land use data for forest, grassland and primary land from RCP (Hurtt et al. 2011) and GTAP data	Land productivity, crop yields & water demand from LPJmL model Carbon stock density data from VISIT terrestrial vegetation model Spatially explicit grid maps on: • croplands and pastureland (Monfreda et al 2008) • protected areas (from UNEP-WCMC) • settlements, ice and water (from RCP scenarios) Land use areas & factor cost and prices from AIM-CGE
	Description of model process	**Macroeconomic core:** • The CGE model solves for an equilibrium in each 1yr time step, finding the prices where supply equals demand in each sector • Individual behavior functions describe the changes in supply, demand, investment or trade to changes in the prices of production factors, commodities, technology developments, consumer preferences and income • The model is dynamic: the main recursive dynamic mechanism is capital formation: every sector issues new capital each year which is carried over to the next year, accounting for some capital depreciation. Agents do not have perfect foresight: they react to individual market conditions in a given year	Regional aggregated land demand projected by AIM-CGE is fed into land use allocation model and downscaled into grid cells of 0.5 x 0.5 degrees, based on economic efficiency (profit maximization of land owner)

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GENERIC	**Outputs**	Economic results: GDP, sectoral value added Land-use results: projects aggregated land indicates the area dedicated to various types of land-use in each region Energy sector results: primary/final energy supply/consumption, energy balance tables, electricity/power plant production Climate results: GHG emissions, GHG emission prices, GHG emission trading, emissions per unit GDP Biodiversity impacts: impact of scenarios on potential habitat for 5 major taxonomic groups through link to species distribution model MAXENT	Spatial gridded land allocation patterns (0.5 degrees) CO_2 emissions from land use change
	Model access & useability	Open access, one Excel version and one GAMS version	
	References	S. Fujimori, T. Masui, Y. Matsuoka, AIM/CGE [basic] manual, 2012 IAM Documentation: Reference card – AIM-CGE, 2020 – AIM-Hub_12Mar2020.pdf (iamcdocumentation.eu) Fujimori, S., Hasegawa, T., Ito, A. et al. Gridded emissions and land-use data for 2005–2100 under diverse socioeconomic and climate mitigation scenarios. Sci Data 5, 180210 (2018). https://doi.org/10.1038/sdata.2018.210 Hasegawa, T., Sakurai, G., Fujimori, S. *et* al. Extreme climate events increase risk of global food insecurity and adaptation needs. *Nat Food 2*, 587–595 (2021). https://doi.org/10.1038/s43016-021-00335-4 Ohashi, H., Hasegawa, T., Hirata, A. *et* al. Biodiversity can benefit from climate stabilization despite adverse side effects of land-based mitigation. *Nat Commun* 10, 5240 (2019) https://doi.org/10.1038/s41467-019-13241-y	T. Hasegawa, S. Fujimori, A. Ito, K. Takahashi, T. Masui, "Global land-use allocation model linked to an integrated assessment model", Science of The Total Environment, Volume 580, 2017, Pages 787-796, https://doi.org/10.1016/j.scitotenv.2016.12.025 Fujimori, S., Hasegawa, T., Ito, A. et al. Gridded emissions and land-use data for 2005-2100 under diverse socioeconomic and climate mitigation scenarios. Sci Data 5, 180210 (2018). https://www.nature.com/articles/sdata2018210
SCENARIOS	**Scenarios that can be explored in model**	The model is designed to run **climate-related transition scenarios** including: • Climate mitigation (e.g. carbon tax and recycle, emissions trading) • Climate adaptation (e.g. food consumption aid or subsidy) • Energy policy (e.g. air pollution, energy taxes) • Land use and agriculture policy • Other policies (e.g. income tax change, subsidy change and so on)	The model is designed to run climate-related scenarios focusing on land use change. Including: • Land use change trajectories and associated emissions (baseline scenarios) • Land use based mitigation policies (carbon taxes, protected areas, bioenergy, afforestation)

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SCENARIOS	**Scenarios that can be explored in model**	Regarding **biodiversity-related transition scenarios**, Leclere et al. use AIM-CGE to explore: • Supply-side policies: Sustainable crop yield increases & Trade increases in agri goods • Demand-side policies Reduced waste in agri goods & Diet shift towards plant-based diets • Increased conservation efforts: increase in protected areas extent and management & increase in land restoration Allows to explore consequences of biodiversity/climate policies in terms of food security (as it models food prices)	
	Overview of results	Ohashi et al. (2019) – find that land-based mitigation policies can bring a net benefit to global biodiversity under a stringent GHG mitigation scenario, whereby habitat lost due to land use change is lower than baseline. Global biodiversity outcomes measured in terms of potential habitat for 5 major taxonomic groups (8428 species) using species distribution model MAXENT Hasegawa et al. (2021) – models food security implications of extreme climate scenarios, finding that additional 20-36% population may face hunger by 2050 in the event of a once-per-100yr extreme climate event. Did not model impacts on GDP. Climate impacts on crop yields were modeled by gridded crop model PRYSBI2	
NATURE-ECONOMY ASPECTS	**Key economic and behavioural assumptions**	**GDP growth assumption**: In the baseline scenario, GDP is assumed to be exogenous (based on SSPs), while TFP is endogenous (obtained so that GDP in output fits GDP from the scenario). In mitigation scenarios, TFP is then exogenous and taken from the TFP calculated in the baseline scenario **Production:** Each producer (represented by an activity) is assumed to maximize profits subject to a production technology represented by a nested CES function. Land is included as a factor of value-added production of crops, bioenergy and livestock products only **Land use change:** • Landowners allocate transform land to competing uses depending on land rents (rents dependent on land/crop productivity, commodity prices, bioenergy demand, shadow carbon prices). based on prices of goods produced on crop / pasture / forest land (the land "rent") • Land can be allocated to multiple use (which include natural land):primary forest, managed forest, primary grassland, grazing grassland (with various types of livestock), cultivated land (with various types of crops), fallow. There are 6 AEZs (Agro-Ecological Zones) • There is a land competition under multinomial logit selection • Multi-level nest based on multinomial logit function	Land allocations based on economic efficiency (profit maximisation). Landowners decide mix of land-use to obtain highest profit given biophysical land productivity in each land grid cell Revenue calculated as multiple of crop prices (from AIM-CGE) and yields (from LPJmL). Cost data taken from AIM-CGE For each land use sector, total land allocated always meets the area of land demanded Protected areas are not converted Afforestation is assumed in non-forest areas with a carbon stock density lower than 2kgC/m^2 Pasture land is allocated on a residual basis (i.e., to areas unprotected and not used for crops or afforestation)

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NATURE-ECONOMY ASPECTS	**Key economic and behavioural assumptions**	• There are also implicit rents on non-productive land, much smaller than productive land to reflect the fact that it would be more costly to bring non-productive land into production, relative to already-cultivated land • There is no underlying data for non-productive land rents, so it is assumed such rent is 1/10th of productive land rents **Households consumption:** LES (linear expenditure system) function. Stone-Geary utility function, where a certain minimal level of essential goods has to be consumed regardless of its price or consumer income. **Trade:** the CES function is applied to the import of goods and the CET function is applied to the export of goods. Armington trade elasticities **Technology:** Crop yield coefficients (quantity produced per unit land used) are exogenously set (taken from IMPACT model) Energy demand is determined by calibration of Autonomous Energy Efficiency Improvements (AEEIs), which is set exogenously **Agricultural intensification vs extensification:** Exogenous technical change means that degree of intensification is also exogenously specified There is no sectoral linkage between intensification outcomes and increases in inputs from intermediate sectors (e.g., fertiliser or pesticides) **A goods-consumption-and-supply equilibrium** is achieved for each market **Savings-Investment balance:** savings rate endogenously determined to balance savings and investments, and capital formation for each good is determined by a fixed coefficient. They make putty-clay assumptions	
	Key parameters	Parameters for AIM-CGE are calibrated using a social accounting matrix (SAM) that tracks all flows on production and consumption of commodities, services, incomes, savings & investments, including transactions of agri goods in physical units **Elasticities of substitution:** these parameters are very small (less than 0.1). This is a deliberate choice by the modelers in order for the model outputs to not violate biophysical constraints. As a result, substitutability in the model is more or less inelastic	Crop yields and land rents are a key determinant of land use

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NATURE-ECONOMY ASPECTS	**Key parameters**	**Minimum consumption levels of essential goods:** (in Stone Geary utility function): the level of 'essential consumption' for each good is determined by the income elasticity for that good. E.g. luxury goods have higher income elasticities of demand, so falling incomes causes a much lower share in consumption basket relative to other goods like food. The income elasticity is derived from external data and used to calibrate parameters in the LES function, and these parameters are recalibrated for each year of the model run	
	Sectors represented	42 sectors, including 10 agricultural sectors including: rice, wheat, other grains, oil seed crops, sugar crops, other crops, ruminant livestock, raw milk, other livestock and fisheries, forestry. 13 other sectors including various types of mining, food processing, construction. 19 energy sectors (including biomass-power generation)	Hasegawa et al. 2017: 18 'sectors' for land use, including 11 crop sectors, plus bioenergy, afforestation, forest, settlement (settlement areas are exogenous, taken from RCP scenarios)
	Financial aspects	None	None
	Treatment of Nature economy interactions: physical shocks	**Nature loss feedback on the economy:** There is no feedback from loss of nature (e.g. loss of ecosystem services) on the economy. Crop yield coefficients (quantity produced per unit land used) are exogenously set (taken from IMPACT model) and there is no feedback effect from future climate damages (Fujimori et al., 2014) on yields. It is possible to proxy for some feedback effects by incorporating these shocks into scenario runs, as Hasegawa et al. 2021 did for climate effects on crop yields and food security **Climate feedback on the economy:** Overall, there is no feedback from climate change on the economy (no climate damage function)	
	Treatment of Nature economy interactions: transition policies	**Nature transition:** Leclere et al. use AIM/CGE to model the impact of protected areas, food policies (waste reduction, diet shifts) and supply policies (Sustainable crop yield increases & Trade increases in agri goods) on food prices only, with no general equilibrium effects **Climate transition:** Climate transition policies can be modelled, e.g. with a price of carbon (increase the relative cost of fossil-fuel energy)	Carbon prices considered as costs (i.e., affecting profits & land allocation decisions) in the mitigation scenarios

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NATURE-ECONOMY ASPECTS	**Interactions between nature and climate change**	No endogenous feedback loop from the climate component on the economy nor on nature. However, climate impacts on economic factors have been incorporated into scenario shocks – e.g., Hasegawa et al. 2021 (impact of climate events on crop yields) Biomass consumption included in emissions module – so it is possible to model bioenergy transition policies impacts on land use change
COMPLEXITY FEATURES	**Treatment of network effects**	Trade and supply chain linkages accounted for in the SAM No treatment of biodiversity-relevant sectoral linkages within agricultural sector – e.g., agricultural intensification (productivity improvements) is not linked to increased inputs from intermediate sectors (e.g., fertilisers, pesticides)

4. (a) IMAGE-MAGNET model evaluation

		IMAGE	MAGNET
GENERIC	**Aims of model**	Identifies socio-economic pathways, and projects the implications for energy, land, water, and other natural resources – subject to the constraints and limits posed by biophysical and technical processes	Flexible aims as modular structure allows tailored modelling approach depending on the research question. MAGNET has typically applied to analyse the environmental and economic implications of various land-based trade policies (see scenarios section below)
	Time horizon	Focused on long-term scenarios out to 2050 or 2100, annual or 5yr time steps	Typically used over the long run with multiple time steps. Can be set up to be comparative static or recursive dynamic (latter the same as GTAP-Dynamic)
	Geographic scope	Global Socio-economic processes treated at resolution of 26 aggregated world regions Land use and biophysical processes treated at grid resolution of 5 x 5 arcminutes (10x10km at the equator) Plant growth, carbon and water cycles modelled on 30x30 minutes resolution. The model is better suited to global analysis rather than local or regional: detailed, differentiated processes at local scale and national policies are represented as part of global region trends, without taking into account country-specific measures and processes	Global. MAGNET is flexible in its regional aggregation (160 regions and countries). In linking with IMAGE, MAGNET matches closely the regions in IMAGE, with some more detail in distinguishing the EU in two separate regions
	Environmental scope	**Type of biodiversity:** terrestrial and aquatic biodiversity intactness, measured by MSA, and also distribution and abundance of vertebrate species (calculated in external GLOBIO, and GLOBIO-Species model), **Biodiversity pressures included:** *Terrestrial:* Climate change, land use change, land-use intensity, fragmentation, infrastructure & encroachment, pollution flows, nitrogen[1] *Aquatic:* Flow deviation (e.g. through dams, nutrient flows (N&P), climate change[2]	**Type of biodiversity:** not explicitly modeled in MAGNET **Biodiversity pressures included:** land use change, climate change, direct exploitation of resources, pollution flows (including landfill, animal & crop waste) **Ecosystem services:** provisioning services include carbon sequestration & pollination (link to MAGNET under development), soil fertility, water availability and quality (see Scenarios box below for more detail on all these)

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1 See chapter and flow diagram: Ecosystem services – IMAGE (pbl.nl)

2 See chapter and flow diagram: Aquatic biodiversity – IMAGE (pbl.nl)

GENERIC	**Environmental scope**	**Ecosystem services:** provisioning services (crop, grass, livestock, timber, bio-energy, fibers, and also wild food) , water availability and quality, soil fertility, modification of erosion risk, pollination, natural pest control, food availabilitycarbon sequestration, flood protection, air quality, nutrient soil budgets (N&P), tourism, terrestrial and aquatic biodiversity[3]	
	Type of macroeconomic model	IMAGE is an integrated assessment model with a focus on biophysical process detail. It does not have a complete representation of the macroeconomy, instead relevant inputs are taken exogenously or via links to other macro models. IMAGE has modular structure allowing for deep dives in different areas as needed: **IMAGE 3.0 core model** comprises most processes in the Human system, the Earth system and their connections (land cover, land use and emissions) • IMAGE/Land&Climate which includes the LPJmL model (carbon, water, crop, and vegetation dynamics) – hard-linked • IMAGE/TIMER for the energy system – soft-linked and can be run independently **IMAGE 3.0 framework:** • Contains other models used to provide further detail on the human system (e.g., soft links to MAGNET or IMPACT (agro-economics) and FAIR (climate mitigation policies). The MAGNET model is the agro-economy model used in most recent scenario projects • Also contains other models that generate impacts (with no feedback back into IMAGE) – e.g., GLOBIO (biodiversity), GLOFRIS (flood risks), GISMO (human development) • These aspects are soft-linked (the models run independently with data exchange via data files)	Structural computable general equilibrium model, covering the whole global economy but with a special focus on agricultural sectors. Can be set up to perform comparative static or dynamic exercises. The standard GTAP model forms the core of the model. MAGNET has a modular setup that extends this GTAP core. Extensions include: • Differences in substitutability of land between sectors • Imperfect mobility of labor between agricultural and non-agricultural sectors • Output quotas for milk and sugar • Endogenous land supply • Biofuel sectors (1st and 2nd generation) and the biofuel directive • Modulation of the EU common agricultural policy from first to second pillar measures • Income elasticities dependent on GDP per capita • International capital mobility for dynamic analyses • Nutrition indicators and tracing nutrient flows • Household food security indicators (see scenarios below) • Circularity module: municipal solid waste flows and treatment options • Aquaculture and seaweed sectors • Endogenous natural resource stocks • Emission permit trading and mac curves, LULUC emissions • Climate damage assessment • Adaptations for investments, bilateral tariff rate quota, alternative consumption functions etc.
	Inputs	**Data/assumptions from scenarios:** • Population can be exogenous or derived from quantitative outputs of GISMO model, which captures feedback of air pollution and food insecurity on population • Economic variables (eg GDP, household consumption) are exogenous or taken from macroeconomic models quantifying scenario storylines	**From IMAGE core model:** • Technological change in agriculture (increase in productivity for crop and livestock production; can also be decrease in productivity for ad hoc shocks) • Land supply: available land for agriculture per grid or region depending on suitability and excluding protected areas and unsuitable areas

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3 See chapter and flow diagram: Ecosystem services – IMAGE (pbl.nl)

GENERIC	**Inputs**	• Technological and especially agricultural technical assumptions are exogenous depending on scenario narratives • Trade – also exogenous depending on scenario narratives. • A wide range of mitigation policies are exogenous or assumed depending on scenario narratives (see below) **Other relevant data inputs:** • Data on national crop/livestock production, agri yields, land resources from FAO • Energy data (fossil fuels, renewables & tech assumptions) from IEA and others	• Potential yields for crops and grasses, changing according to environmental impacts and location effects modelled in IMAGE **From external datasets:** • GDP per capita, population (usually taken from SSP database), capital supply, labour supply • Assumptions on income and price elasticities of demand, substitution elasticities and others (eg trade) – from GTAP database and others • GTAP8 database for sectoral input-output tables and bilateral trade (reference year 2007). Currently, MAGNET is based on Version 10 of the GTAP database (as of 2020)
	Description of model process	**Macroeconomic core:** • IMAGE does not have a complete representation of the macroeconomy • Instead, based on an exogenously given GDP path, various components of GDP (e.g. VA per sector, consumption expenditures) are estimated by more detailed models (models (e.g., OECD's ENV-Growth model, or agri model MAGNET) • These economic variables are then used as exogenous inputs into various modules of the IMAGE framework, to investigate how it drives environmental changes • Instead, IMAGE provides a relatively high level of detail on land-based processes (water, carbon and nutrient cycles) and can estimate indicators for biodiversity loss and flood risks in temporal and spatial resolution **Energy system:** • IMAGE/TIMER is a detailed energy system model that determines energy demand for a given population, income, lifestyle, and also describes the trajectories of fossil fuel vs alternative energy supply • TIMER soft-linked to IMAGE framework via calculated emissions and bioenergy demand (input to land use module) **Agriculture and land use:** • Agricultural supply and demand is determined through soft-link to MAGNET • IMAGE also calculates timber demand and forest management	**Macroeconomic core:** • Standard GTAP model plus MAGNET modules that can be activated as needed depending on the research question • GTAP is a static CGE that solves all equations simultaneously: prices adjust so that demand and supply in all markets for goods, labour, land, and capital are equal – equilibrium outcome • Supply side: regional representative household supplies factors (labour, land, capital, resources) to production sectors. Each sector combines factors with intermediate inputs to produce commodities • Demand side: household demand determined by factor income (from land, labour, capital, taxes). Representative household allocates consumption choices between domestic, foreign goods, and savings • Bilateral trade between all regions. Barriers accounted for by tariffs • Capital flows governed by a global bank that collects savings and uses them for international investments **Agricultural system:** • Household demand for agricultural products calculated in MAGNET based on changes in income, income/price/cross-price elasticities, preferences, and commodity prices • Supply of all commodities including agri modeled in MAGNET using input-output structure that accounts for intermediate consumption …/…

		IMAGE	MAGNET
GENERIC	**Description of model process**	• IMAGE/Land use module determines potential land uses on 5x5 minute grid based on suitability for expansion (population density, accessibility, topography, agri productivity) and regional preferences on production systems • Land use dynamics and agricultural technology determined through the IMAGE-MAGNET soft link, described in detail below (assumptions section) **Earth system:** • **Carbon cycle, natural vegetation, crop and grass production** modeled with LPJmL and linked iteratively with agri production modules • LPJmL determines productivity at grid level based on climate conditions, soil types and degradation, assumed tech / management capabilities • LPJmL uses land use and climate as inputs from other modules • **Water cycle** also modeled in LPJmL, full dynamically coupled to IMAGE. Water demand for irrigated agri modeled in IMAGE-LPJmL, other sectors based on population, growth & electricity production (from TIMER) • **Ecosystem services** variables are estimated in various ways using various IMAGE components, where ES supply is compared to the minimum quantity required by humans, in order to assess surpluses or deficiencies of a given ES. See Chapter 7.6 in documentation for more details	• Production factors (incl. land for crop prod) can substitute for each other, driven by changes in their relative prices according to price elasticity of substitution • MAGNET gives future management intensity levels per region, and also trade dynamics
	Outputs	The IMAGE 3.0 model outputs focus mostly on implications for the environment **Economy-related variables:** • Optimal GHG reduction pathways, based on cost-benefit analysis tool energy use, conversion and supply • Agricultural production, maps of land cover and land use, including fertiliser and water input, livestock densities, rain/irrigated crop proportions, bioenergy crops, forest management • As IMAGE does not represent a complete macroeconomy, its outputs are not suited to assessing impacts on GDP or other aggregate variables	**Economic variables:** • Crop production and prices, per region • Land use & prices • Changes in management intensity of crops • Livestock production and prices, per region • Changes in Management intensity of livestock • Food availability per capita • Demand per sector • Bilateral trade between regions per sector • Commodity price per sector

…/…

GENERIC	**Outputs**	**Biophysical variables:** • Nutrient cycles in natural and agricultural systems • Emissions to air and surface water • Carbon stocks in biomass pools, soils, atmosphere and oceans • Atmospheric emissions and concentration of greenhouse gases and air pollutants • Changes in temperature and precipitation • Sea level rise • Gridded land use (5 x 5 arc min) • Water use, discharge, water scarcity **Ecosystem services outputs (spatial data):** see GLOBIO-ES model ID card below **External impact indicators** (calculated by additional impact models that are not directly into the IMAGE core model) • **Biodiversity impact indicator:** Spatially Explicit Mean Species Abundance calculated in GLOBIO, that takes direct drivers from IMAGE and computes MSA for terrestrial & freshwater ecosystems • **Human health & development impacts:** burden of diseases, health impacts of air pollution and undernourishment – from GISMO model	
	Model access and useability	Developed by PBL Netherlands Environmental Assessment Agency Model documentation: Welcome to IMAGE 3.2 Documentation – IMAGE (pbl.nl). Open source availability of IMAGE model is under development Access to scenario data: Download – IMAGE (pbl.nl)	Developed by Wageningen Economic Research (WUR). Web-based documentation: https://www.magnet-model.org/model/
	References	***IMAGE model & scenarios*** • Stehfest, E., van Vuuren, D., Kram, T., Bouwman, L., Alkemade, R., Bakkenes, M., Biemans, H., Bouwman, A., den Elzen, M., Janse, J., Lucas, P., van Minnen, J., Müller, C., Prins, A. (2014), Integrated Assessment of Global Environmental Change with IMAGE 3.0. Model description and policy applications, The Hague: PBL Netherlands Environmental Assessment Agency • Van Vuuren, D. P., Stehfest, E., Gernaat, D. E. H. J., Van Den Berg, M., Bijl, D. L., De Boer, H. S., Daioglou, V., Doelman, J. C., Edelenbosch, O. Y., Harmsen, M., Hof, A. F. & Van Sluisveld, M. A. E. (2018) Alternative pathways to the 1.5 °c target reduce the need for negative emission technologies. Nature Climate Change 8, 391-397, doi:10.1038/s41558-018-0119-8	• Woltjer GB, Kuiper M, Kavallari A, van Meijl H, Powell J, Rutten M, Shutes L and Tabeau A (2014). The Magnet Model – Module description. LEI, part of Wageningen University and Research Centre, The Hague • Von Lampe M, Willenbockel D, Calvin K, Fujimori S, Hasegawa T, Havlik P, Kyle P, Lotze-Campen H, Mason d'Croz D, Nelson G, Sands R, Schmitz C, Tabeau A, Valin H, van der Mensbrugghe D and van Meijl H. (2014). Why do global long-term scenarios for agriculture differ? An overview of the AgMIP Global Economic Model Intercomparison. Agricultural Economics, Special Issue on Global Model Intercomparison (forthcoming) 45(1), pp. 1574–0862, DOI: 10.1111/agec.12086

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GENERIC	**References**	***IMAGE-GLOBIO biodiversity scenarios*** • PBL (2010) Rethinking Global Biodiversity Strategies: Exploring structural changes in production and consumption to reduce biodiversity loss. PBL Netherlands Environmental Assessment Agency. https://www.pbl.nl/en/publications/Rethinking_Global_Biodiversity_Strategies • Kok, M. T. J., Meijer, J. R., van Zeist, W. J., Hilbers, J. P., Immovilli, M., Janse, J. H., Stehfest, E., Bakkenes, M., Tabeau, A., Schipper, A. M. & Alkemade, R. (2023) Assessing ambitious nature conservation strategies in a below 2-degree and food-secure world. Biological Conservation 284, doi:10.1016/j.biocon.2023.110068	• Stehfest E, Berg M, Woltjer G, Msangi S and Westhoek H. (2013). Options to reduce the environmental effects of livestock production – Comparison of two economic models. Agricultural Systems 114, pp. 38-53
SCENARIOS	**Scenarios that can be explored with the model**	**Physical scenarios:** IMAGE can be used to assess impacts of economic trajectories on bio-physical environmental outcomes in the absence of new policies (baseline scenarios). It cannot estimate economic impacts in the absence of connection to MAGNET Baseline scenarios cover not only various future trends in economy and population, but also climate impacts, future soil degradation, technological development **Transition scenarios:** • ***Climate policies:*** - Global targets for temperature and/or carbon budgets, regional efforts, air pollution, energy access & security, bioenergy. Possible to ban certain technologies - Climate mitigation scenarios done by linking to FAIR model which addresses various views on burden sharing ***Land and biodiversity policies:*** • Possible strategies of biodiversity conservation (carried out e.g. to support IPBES process), and their implications for biodiversity, ES, and the agri-food system • Land-based climate mitigation: policies on REDD, afforestation and their effects on land use and food security • Food-system policies together with agro-economic model: trade, subsidies, taxes, yield improvements, organic farming • Implications of dietary preferences and transitions to sustainable diets (e.g. low-meat, artificial meat…)	**Physical scenarios:** • Pollination declines & carbon sequestration: possible to input ad hoc shock where biophysical impacts of pollinators/carbon seq on agri yields is modelled in IMAGE-GLOBIO and then input into MAGNET (through agri productivity channel) to model economic impacts. Modelling team now working to make this a dynamic soft-linkage • Climate impacts, soil degradation, water availability also feedback through to MAGNET through impacts on yields, either modelled through IMAGE or other external sources • Extreme physical shocks: MAGNET has been used to model e.g., Covid crisis, Ukraine, extreme climate shocks to yields, pollinator loss (latter with DNB and still unpublished). Adjusting the substitution elasticities allows to approximate short-run effects (see assumptions below) • Fish provision: MAGNET is able to separate fish into very detailed sectors (see sectors box below) but only models output in price terms at the moment, and is not linked to fish stocks modeled in IMAGE. So not possible to model shocks to fish stock quantities yet – although there are plans to improve this • Food security: MAGNET calculates food security indicators through the nutrition module (availability, access, utilization, and stability). Any food insecurity feeds back to aggregate demand indirectly: i.e., higher prices of food means lower demand for other sectors. Currently labour productivity is not affected by food security but this feedback loop could be easily added should convincing evidence of the link exist (e.g., they added impacts of climate-related heat stress on labour productivity) …/…

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SCENARIOS	**Scenarios that can be explored with the model**	***Water and Nutrients:*** • Policies to reduce imbalance nutrient cycles (N&P) and meeting the planetary boundaries for nutrient flows • Water: Several policies can be assessed with IMAGE-LPJmL, including improved rainwater management, improved irrigation efficiency, increasing storage capacity and land-use related interventions ***Resources and circular economy:*** • Policies to restrict resource availability (e.g., restricting deep sea oil and gas extraction) • Implications of a circular bio-economy on climate, pollution and resource consumption ***Sustainability transition, integrated scenarios:*** • Combining the policies and measures described above to integrated scenarios for achieving sustainability ambitions • Different governance systems can be tested by adjusting exogenous scenario parameters • Analysing synergies and trade-offs in the Land-Water-Land-Food-Climate-Energy Nexus	***Transition scenarios:*** • Protected area and REDD policies: by restricting land supply in both IMAGE and MAGNET, leading to lower elasticities, less land-use changes, and higher prices • Production quota module allows to model policies that set upper limits on output (e.g., European agri policies that set limits on milk and sugar output) • Land management: changes in crop and livestock production systems, such as more efficient production methods or organic farming) • Water: Several policies can be assessed with IMAGE-LPJmL, including improved rainwater management, improved irrigation efficiency, increasing storage capacity and land-use related interventions • Other: consumption changes, dietary preferences, biofuels, agricultural trade policies • According to the modelers, it is, in theory, possible to model some ad hoc transition shocks affecting other sectors (e.g., mining and fishing) subject to data availability on how these policies affect other sectors • Circular economy scenarios: e.g., reduced waste flows from sectors, and recycling into inputs to other sectors. The waste streams module calculates 5 consumer wastes (food, garden, glass, paper, and other). Treatment sectors then process waste into either compost, recycle, incinerate, or landfill. These choices feed back to economy through provision of intermediate inputs (recycling) or emissions-related damages (incinerate or landfill)
NATURE-ECONOMY ASPECTS	**Key economic and behavioural assumptions**	**GDP growth, household consumption, trade:** • These assumptions are exogenous and either taken as input data or from outputs of linked models quantifying scenario narratives **Production:** • The general global economy is represented through soft-linking with MAGNET-CGE	**GDP growth assumptions:** • Total factor productivity and labour productivity typically calibrated to reproduce SSP pathways • Labour productivity then adjusted to reflect differences between sectors • Possible to endogenise some technical change by including addition of R&D sectors

…/…

NATURE-ECONOMY ASPECTS	**Key economic and behavioural assumptions**	**Energy system (TIMER):** • TIMER is a simulation model that separately models energy demand, energy conversion, and energy supply • Aims to reduce relative costs of final energy mix based on tech development, resource depletion, preferences, trade, policies • Results are derived from previous system states based on single set of deterministic algorithms (comparable approach to GCAM) • Energy demand is determined for 5 sectors: industry, transport, residential, services, other sectors. Assumed that demand is always met • Energy supply determined based on the interplay between resource depletion and technology development • Accounts for dynamic relationships, e.g. inertia and learning-by-doing in capital stocks, depletion of resource base, trade between regions • Total amount of bioenergy is derived from spatially explicit bioenergy crop yields (0.5 x 0.5 degree grids) from IMAGE crop model • Potential bioenergy supply is restricted to production on abandoned agricultural land and natural grassland • Endogenous technology development in energy system based on learning by doing (costs decline as technology is used more)	**Household consumption:** • Representative agent with utility and cost optimizing behavior • Modeled by a constant difference of elasticity (CDE) function. This functional form doesn't inherently 'hard code' in a minimal consumption level for certain goods. However this can be achieved in various other ways, e.g., adjusting substitution behaviour between different food groups • MAGNET allows an option to vary income elasticities over time depending on income levels **Production:** • Option between the standard GTAP production structure or a fully flexible nested CES production function that allows production structure to vary among sectors depending on the research question • Modeler has full freedom to define each production structure, including number of nests, ordering of nests and inputs entering nests • Programme code facilitates computation of the substitution elasticities implied by the structure of the CES tree (using Keller equation). Cost share of inputs is an important component of this calculation. Since these vary by sector and region, the same CES structure can result in different implied elasticities across sectors and regions. Cost shares are updated with each run of the model, meaning implied elasticities also change with each run • Sluggish labour mobility between agricultural and non-agricultural sectors: this means that shocks to agriculture will have larger impacts on demand relative to other CGE models (e.g., GTAP) (i.e., farmers accept lower wage rates rather than switching to other sectors, and lower purchasing power feeds through to aggregate demand) • Land is a factor input for all crops, land-based livestock and forestry sectors. Coal, gas, oil and wild fish sectors have a natural resources factor input **Trade:** • Domestic and foreign products are not identical (imperfect substitutes) – i.e., Armington assumption …/…

NATURE-ECONOMY ASPECTS	**Key economic and behavioural assumptions**	**Agri land use dynamics: IMAGE-MAGNET soft-link:** → *Endogenous land supply and allocation of land uses* • IMAGE calculates total land potentially available for agriculture, based on soil and climate conditions, and where no restrictions exist (e.g. protected areas) • MAGNET relates this total available land area to land prices (rents) in imperfectly inelastic supply curves (asymptotic relationship). The price mechanism determines land use per sector and region in MAGNET • IMAGE takes crop & grassland production & changes in intensity levels from MAGNET, MAGNET takes total land supply & restrictions (protected areas) from IMAGE, as well as standard projections (per SSP) of crop productivity changes (optionally with climate change impacts) • Together, IMAGE-MAGNET allocate production to 5x5 minute grid cells in an iterative process until required regional production is met • Regions differ with regard to % land in use and changes in land prices in relation to changes in agri land use. E.g., regions with large reserve of suitable agri land (e.g. sub-Saharan Africa) have a larger price elasticity of land supply – i.e., land expansion occurs at smaller price changes. • A nested land use structure allows for differences in substitutability of land between different uses • Spatially explicit crop yields are computed in each timestep by combining potential yields (from IMAGE crop module) and regional management intensity (from MAGNET). This allows changes in crop yields over time to account for technological change, climate impacts, and land heterogeneity • IMAGE also accounts for urban land uses in a spatially explicit fashion: urban built-up area per grid cell, increasing over time as a function of urban population and a country- and scenario-specific urban density curve. However this is excluded from all biophysical modelling in IMAGE → *Land use change* • If demand exceeds (or is less than) supply (both calculated in MAGNET), agricultural area is expanded (or abandoned), with changing land prices determined by the imperfectly inelastic land supply curves in MAGNET. Land scarcity triggers large price increases and substitution effects (intensification) • Because of the asymptotic land supply curve, land prices will increase rapidly as available land with agricultural potential diminishes. This will trigger substitution effects in the production function, triggering agricultural intensification rather than further expansion • Expansion is not permitted in protected areas by default (although in a scenario like SSP3 this restriction can be loosened) • Which spatially explicit parcels of land that are converted is determined by either (1) simple linear regression analysis within IMAGE accounting for land suitability or by (2) dynamic link to the more detailed CLUMondo model **Intensification in agriculture: IMAGE-MAGNET soft-link:** • Technological development in agriculture is exogenous based on historical projections of agri productivity, water efficiency, fertIliser use, irrigation performance, and calculation of a Management Factor (see below) • Elaborations by the IMAGE team on FAO projections are used as exogenous technical development in MAGNET, and are adjusted to reflect the relative shortage of land, as part of MAGNET's calculation • Intensification can also take place due to substitution of production factors (i.e.., higher land prices triggering more use of capital) • Climate change may have some intensification effects, when impacts improve yields in some areas and under some conditions changes in agricultural area can also affect crop yields, i.e., moving to more or less suitable regions

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NATURE-ECONOMY ASPECTS

Key parameters

Table 2.2: Overview of key uncertainties in the IMAGE framework.

Model component	Uncertainty
Drivers	Overall population size, economic growth
Agricultural systems	Yield improvements, meat consumption, total consumption rates
Energy systems	Preferences, energy policies, technology development, resources
Emissions	Emission factors, in particular those in energy system
Land cover / carbon cycle	Intensification versus expansion, effect of climate change on soil respiration, CO_2 fertilization effect
N-cycle	Nutrient use efficiencies
Water cycle	Groundwater use, patterns of climate change
Climate system	Climate sensitivity, patterns of climate change
Biodiversity	Biodiversity effect values, effect of infrastructure and fragmentation

Essential coefficients: 'The model also uses a large number of essential coefficients, such as Armington trade elasticities, consumption function parameters, substitution elasticities for all production nests, CET elasticities for land-use transformations, and elasticities in the land-supply curve. Some parameters are based on econometric research or economic literature, while others are no more than 'best guesses' (Woltjer et al., 2011). The autonomous technological yield change is often based on FAO projections in both MAGNET and IMAGE.' – p.118 IMAGE documentation

- Elasticities of substitution can be adjusted to a degree (e.g., to approximate short term shocks) but cannot be reduced to zero as the model does not solve (i.e., disequilibrium outcome)

Land supply: 'A recent model comparison within AgMIP included ten global agro-economic models using harmonised scenario drivers (Nelson et al., 2014; Von Lampe et al., 2014). Results indicate that MAGNET is in the upper range of other models, in terms of future land-use expansion. This is probably due to the relatively large land supply in MAGNET, which allows further expansion of agricultural land, particularly in North and South America, and Africa.' – p118

Management Factor as determinant of land use change: technological development in agriculture is also affected by Management Factor (MF) – a key exogenous parameter representing actual yield per crop group & region as a % of maximum potential yield. Initial MF is calibrated using FAO stats on actual crop yields. Future MF is calculated from FAO future projections combined with MAGNET projections of production volumes and land availability. Documentation notes that "Because the MF is such a decisive factor in future net agricultural land area, careful consideration of uncertainties is warranted." p.59. Note that this factor does not consider different land management options in terms of, e.g., organic vs non-organic farming. These are instead input as policy options during scenario runs (see transition scenarios above)

Other uncertainties: autonomous technical change, relative contribution of intensification or expansion to total production growth, long term dietary preferences. From the IMAGE documentation: 'the empirical basis for many of these parameters in MAGNET and all other agro-economic models needs to be improved' – p.119

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NATURE-ECONOMY ASPECTS	**Sectors represented**	Energy system: demand determined for industry, transport, residential, services, other sectors (not specified) Food and agriculture: see MAGNET >>	MAGNET covers 113 sectors: 65 of which are from GTAP, and 49 are MAGNET extensions (in **bold** below) that provide additional details on sectors related in particular to the bioeconomy or circular economy. These include: • **Crops:** paddy rice, wheat, cereal grains, veg/fruit/nuts, oil seeds, sugar cane & beet, plant-based fibres, crops nec, **animal feed** • **Biofuels: biogasoline, biodiesel, biofuel feedstock grains, biofuel feedstock sugar, biofuel feedstock molasses, biofuel feedstock oils, second generation biofuels** • **Livestock: cattle, other cattle (sheep & goats etc), pigs and other live animals, poultry and eggs,** raw milk, wool, pork **and other animal products nec**, poultry meat, other cattle meat, beef meat • **Fishery: diadromis fish, freshwater fish, crustaceans, marine fish, moluscs, seaweed** • **Forestry:** forestry, **plantation, pellet**, wood products • **Circular economy: compositing, recycling, landfilling, incineration, waste collection glass paper** • **Plastics and chemicals: bioplastic, fertilizer nutrient n, fertilizer nutrient p, fertilizer nutrient k** • There are also numerous secondary industries: paper products, dairy products, food products nec, etc. One extension from GTAP is the inclusion of 13 by-product sectors, most of which are residues from agricultural activities (e.g., molasses as by-product of sugar)
	Financial aspects	N/A	N/A
	Nature-economy interactions	**Land use, other biodiversity / ecosystem services → economy:** • As IMAGE does not represent a complete macroeconomy, it cannot include feedback effects on GDP, sector value added or other aggregate variables • Documentation notes that IMAGE is better adapted for long-term trends than for short-term issues, and is not suitable to assess detailed economic impacts, such as sector level impacts (see p.52)	**Land use, other biodiversity / ecosystem services → economy:** • There is no explicit 'damages' module relating environmental impacts to 'costs' on output. Instead the transmission channels are two-fold: • On the supply side: negative shocks hit sector productivity levels (e.g., pollinator loss lowering crop yields), this then leads to lower output and higher prices, increasing factor and input costs across the macroeconomy …/…

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NATURE-ECONOMY ASPECTS	**Nature-economy interactions**	• However, through adapting the modular configuration, it is possible to model the implications of physical scenarios on selected relevant variables such as agricultural productivity and food security **Economy → biodiversity and ecosystem services:** • Via various modules, IMAGE can assess the implications of baseline economic trajectories and policy scenarios on biodiversity (MSA), ecosystem services, nutrient cycles, carbon cycles and natural vegetation, forest cover, water availability, atmospheric composition and temperature increases	• On the demand side: for some sectors that must be consumed (e.g., food), higher prices will lower demand for other sectors, impacting aggregate demand • MAGNET also has sluggish labour mobility between agri and non-agri sectors, meaning shocks to agricultural sectors reduce incomes and hence purchasing power of farmers relatively more, especially in lower income countries **Economy → biodiversity and ecosystem services:** Change drivers calculated from IMAGE-MAGNET linkage, can be inputted into GLOBIO to calculate impacts on terrestrial, freshwater biodiversity (in MSA) and ecosystem services (see model ID cards below)
	Interactions with climate change	**Climate → biodiversity/land:** impact of temperature and rainfall changes on vegetation including crop productivity. IMAGE model outputs linked to GLOBIO to estimate biodiversity impacts in MSA/km (see tables below) **Biodiversity/land → climate:** GLOBIO outputs do not factor in IMAGE modelling (one-way link only)	**Climate → biodiversity/land:** as per IMAGE, impact of temperature and rainfall affect agricultural yields, and outputs can be linked to GLOBIO to estimate biodiversity impacts
COMPLEXITY FEATURES	**Non-linearities**	N/A	N/A
	Feedback effects	The IMAGE framework can account for some biophysical-socioeconomic feedbacks endogenously, e.g., temperature & rainfall changes on agri productivity & water availability Importantly, impacts on biodiversity are not endogenised into the IMAGE framework – as they are calculated separately in the GLOBIO model, using IMAGE inputs	Agricultural yields are the main feedback effect mechanism. At the moment, through the coupling with IMAGE, these can be impacted by: • climate impacts (temperature, rainfall) • water availability • soil degradation • technical change (exogenous) • land use change (expansions into less suitable areas) Modelling team is currently developing a more dynamic feedback between pollinator loss, carbon sequestration and agricultural yields (currently can only run ad hoc scenarios)
	Treatment of network effects	N/A	Intersectoral and trade linkages are modelled at the equilibrium outcome (underlying GTAP model approach)

4. (b) GLOBIO model evaluation (part of IMAGE framework)[4]

		GLOBIO	GLOBIO-Aquatic
GENERIC	**Aims of model**	Calculates the impact of environmental drivers and potential policy options on terrestrial biodiversity	Calculates the impact of environmental drivers and potential policy options on freshwater biodiversity
	Time horizon	Focused on long-term scenarios out to 2050 or beyond, depending on input data	
	Geographic scope	Global scale, 9 regions considered in aggregate (North America, Latin America, North Africa, Sub-Saharan Africa, Europe, Russia and North Asia, West Asia, Asia, Ocean (inc New Zealand and Japan). Spatial resolution possible is 10 arc seconds	
	Environmental scope	**Type of biodiversity:** • Local terrestrial biodiversity intactness, measured by Mean Species Abundance (MSA) – an indicator of the degree to which an ecosystem is intact (similar to the BII) • 2 major taxonomic groups: warm-blooded vertebrates (mammals and birds) and vascular plants (for the current version, GLOBIO v4) **Biodiversity pressures included:** land-use change, land-use intensity, climate change, atmospheric nitrogen deposition, infrastructure disturbance, encroachment (hunting) and fragmentation **Other ecosystem services:** the GLOBIO-ES module calculates provisioning, regulating, and cultural ecosystem services, and ecosystem service effect values (see outputs below)	**Type of biodiversity:** • Local freshwater biodiversity intactness, measured by Mean Species Abundance (MSA), in rivers and streams, deep and shallow lakes, and wetlands **Biodiversity pressures included:** land-use and nutrient loss within catchments, water flow deviations (e.g. from dams), climate change **Other ecosystem services:** Prevalence of algae blooms (indicator of water quality)
	Type of macroeconomic model	N/A	N/A
	Inputs	**From IMAGE model:** → *Spatial data* • Protected area maps (also taken from World Database of Protected Areas) • High resolution land cover maps downscaled from IMAGE • Nitrogen deposition • Inorganic nitrogen fertilizer application • Land use	**From IMAGE model:** → *Spatial data* • Land cover and land use maps • N and P discharge to surface water • River discharge (from the PCR-GLOBWB model)

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4 Note there is also a model component for biodiversity at the species level (GLOBIO-Species). See https://www.globio.info/resources for more information.

	External datasets: → *Spatial data* • Biomes (maps by Dinerstein et al. 2017) • Infrastructure (from GRIP database ; Meijer et al. 2018) • Land suitability layers • Settlements in tropical regions	**External datasets:** • Digital water network maps (from DDM30) describing drainage directions of surface water (from PCR-GLOBWB model) • Database of empirical relationships between environmental pressures and reduction in MSA for aquatic ecosystems (Janse et al. 2015) • GLWD – global lakes and wetlands maps database • Lake depths database • Water temperature (from PCR-GLOBWB model)
Description of model process	Overall, GLOBIO combines pressure input data with cause-and-effect relationships per pressure to derive a spatially explicit MSA estimate. Description of model calculations per pressure: **Land use and land-use intensity:** • Changes in land use and intensity are taken from IMAGE or from the PREDICTS database (2016 release) and allocated to starting maps • GLOBIO includes a module to downscale land use data to a finer resolution of 10 arc seconds • All regional cropland, forests & grazing areas are geographically distributed per intensity class by adjusting proportions per grid cell, avoiding protected areas • Relationships between environmental pressures and reductions in MSA values are applied to the land use maps, with proportions of each intensity class, to yield the MSA land use map for each year considered (see Schipper et al. 2020 for full process description) **Climate:** • Pressure-impact relationships for climate change estimated using the database published by Nunez et al., (2019), using data on fraction of remaining species (FRS) **Nitrogen:** • Impacts of atmospheric nitrogen deposition are calculated based on the database published by Midolo et al., (2019) **Infrastructure and encroachment:** • Infrastructure maps from GRIP database. Direct impacts (from infrastructure) occur in 1km zone both sides of roads and MSA value derived from meta-analysis on disturbance effects (Benitez-Lopez et al. 2010)	Similar to its terrestrial counterpart, the driver-impact relationships for aquatic biodiversity are based on meta-analyses of empirical data from the literature. GLOBIO aquatic calculates: **(1) The effect of land use change in the catchment areas of the aquatic ecosystems in scope** • Streams, rivers, wetlands: relationship between biodiversity (expressed in MSA) and land use type and intensity fitted by linear regression • Lakes: relationship between biodiversity and P & N concentrations fitted by logistic regression for deep and shallow lakes (effects correlate well with type and intensity of land use) • River network and GWLD maps combined to estimate nutrient loadings to water bodies **(2) The effect of human interventions (dams, climate change) on the hydrology of rivers and floodplain wetlands** • Monthly river discharges (in pristine, present or future scenarios – e.g. affected by climate or dams) are derived from LPJ hydrology model or PCR-GLOBWB model • Used to calculate deviation between affected and natural seasonal pattern – combined and compared to literature on biodiversity in rivers under different management, expressed as MSA **(3) The probability of dominant harmful algal blooms in lakes** • Calculated based on P concentration, N:P ratio, and water temperature. • Expressed as % lakes with cyanobacteria biomass above the WHO standard **Aggregation of results:** calculated by multiplying the values for relevant drivers. Final value is the area-weighted average of MSA values for rivers, lakes and wetlands …/…

	• Indirect impacts (from encroachment) defined from the 20km impact zones around croplands • MSA map obtained by combining direct and indirect effects **Ecosystem fragmentation:** • Based on data on min area requirements of species from PREDICTS, a pressure-impact relationship is constructed between patch size and relative no. of species compared to a non-fragmented situation, known as the minimum area requirement (MAR) curve (Verboom et al. forthcoming) • The relative number of species in a certain patch according to this MAR curve is used as a proxy for mean species abundance (MSA) **Impacts of hunting:** • Quantified based on the distance to small settlements within tropical biomes, using data from Benítez-Lopez et al. 2019) • Only studies that assessed impact of hunting on wildlife abundance with reference to a control unhunted site included within this database **Aggregation:** Total MSA values per area unit calculated by multiplying individual MSA values related to separate drivers of change	
Outputs	GLOBIO outputs spatially explicit indicators: **Mean species abundance (MSA):** • Indicator of the degree of intactness of local biodiversity on a scale from 1 (fully intact) to 0 (all original species extirpated) • Calculated for each pressure and year, using empirical relationships between pressure and change in MSA (from Schipper et al., 2020) • MSA values aggregated across the pressures to obtain one total value **Land use and land-use intensity maps:** • High resolution maps based on ESA-CCI landcover data **Wilderness area maps:** • Non-agricultural areas close to their natural state, with MSA values above 0.8	GLOBIO-Aquatic outputs spatially explicit indicators: **Mean species abundance (MSA):** • MSA in lakes, rivers, and wetlands **Probability of harmful algal blooms in lakes:** • Caused by cyanobacteria

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	The GLOBIO-ES module can also separately calculate impacts upon ecosystem services: • Ecosystem services effect values: database on relationships between environmental factors and ES • Provisioning: food availability (including fish, food from agro-ecosystems, wild food), wood, distance to water, and water availability • Regulating: carbon sequestration, reduced erosion risk, flood protection, natural pollination, presence of natural pest control • Cultural: suitability for nature-based tourism
Model access and useability	All GLOBIO documentation and code is available open access at the following links: • https://github.com/GLOBIO4/GlobioModelPublic/wiki • https://www.globio.info/resources
References	Benítez-López A, Santini L, Schipper AM, Busana M, Huijbregts MAJ (2019) Intact but empty forests? Patterns of hunting-induced mammal defaunation in the tropics. Plos Biology, 17, e3000247-e3000247 Kok, M.T.J., Meijer, J.R., van Zeist, W.-J., *et* al. 2023. Assessing ambitious nature conservation strategies in a below 2-degree and food-secure world. *Biological Conservation*. **284**, p.110068 Midolo G, Alkemade R, Schipper AM, Benítez-López A, Perring MP, De Vries W (2019) Impacts of nitrogen addition on plant species richness and abundance: A global meta-analysis. Global Ecology and Biogeography, 28, 398-413 Nunez S, Arets E, Alkemade R, Verwer C, Leemans R (2019) Assessing the impacts of climate change on biodiversity: Is below 2°C enough? Climatic Change, 154, 351-365 Schipper, AM, Hilbers, JP, Meijer, JR, et al. Projecting terrestrial biodiversity intactness with GLOBIO 4. *Glob Change* Biol. 2020; 26: 760–771. https://doi.org/10.1111/gcb.14848 Van Toor, J., Piljic, D. and Schellekens, G. 2020. *Indebted to nature Exploring biodiversity risks for the Dutch financial sector* [Online]. De Nederlandsche Bank. Available from: https://www.dnb.nl/media/4c3fqawd/indebted-to-nature.pdf Alkemade R, Janse JH, Van Rooij W and Trisurat Y. (2011b). Applying GLOBIO at different geographical levels. In: Y. Trisurat, R. P. Shrestha and R. Alkemade (eds.), Land Use, Climate change and biodiversity modeling: perspectives and applications. IGI Global, Hershey (PA), pp. 150-170 Janse JH, Kuiper JJ, Weijters MJ, Westerbeek EP, Jeuken MHJL, Alkemade R, Mooij WM and Verhoeven JTA. (2015). GLOBIO-aquatic, a global model of human impact on the biodiversity of inland aquatic ecosystems

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SCENARIOS	**Scenarios that can be explored with the model**	**Physical scenarios** • GLOBIO is regularly used to calculate the biodiversity impacts of alternative socio-economic development pathways or broad-scale environmental policy measures. Effects of these pathways or measures are estimated based on changes in pressures • It is possible to adjust selected pressure inputs in ad hoc scenarios to assess particular physical shocks: e.g., nitrogen exceedance in certain locations • However, such scenarios should be designed with caution as GLOBIO relies on simple and generic cause-effect relationships between pressures and MSA. The model is not suitable to assess specific impacts in specific locations nor can it investigate non-linearities and ecosystem collapse scenarios • Note that the effects of changes in biodiversity calculated by GLOBIO do not feedback into the IMAGE model – it is not currently possible to calculate economic consequences resulting from modeled biodiversity loss (although this is under development in conjunction with the MAGNET modelling team) **Transition scenarios** • GLOBIO has used in conjunction with IMAGE model suite to analyse policies on biodiversity (e.g., van Toor et al., 2020), including - Expanding protected areas - Reducing deforestation - Closing yield gaps - Improved efficiency of nutrient use - Reducing post-harvest losses - Changing diets (healthy, and 'no meat') - Improving forest management – high ambition - Mitigating climate change – with & without bioenergy • As above, GLOBIO has so far only been used to assess impacts on biodiversity, not the impact of biodiversity policies on economic indicators	**Physical scenarios** GLOBIO aquatic is regularly used to calculate the biodiversity impacts alternative socio-economic development pathways or broad-scale environmental policy measures. Effects of these pathways or measures are estimated based on changes in pressures **Transition scenarios** GLOBIO aquatic can analysis the freshwater biodiversity impacts of biodiversity-related policies including: • Expanding protected areas • Reducing agricultural area • Consumption changes • Reduced food losses • Increases in agricultural productivity • Improved efficiency of nutrient use …/…

NATURE-ECONOMY ASPECTS	**Key assumptions**	Cause-effect relationships between pressures and changes in biodiversity are fixed over time and linear, hence not able to account for tipping point dynamics By definition, MSA does not account for natural differences in species richness between different ecosystems. So a given loss of MSA in a desert is considered equivalent to the same loss of MSA in a biodiversity hotspot in the tropics (there is no straight-forward method to weight ecosystems differently). However, results can be presented per biome	Cause-effect relationships between driver and change in biodiversity are fixed over time. Hence not able to account for non-linear changes that might occur from tipping point dynamics Several pressures not yet accounted for: exploitation (fisheries, aquaculture), invasive species, toxic stress Possible interaction between drivers has not yet been included
	Key parameters	Uncertainties arise from the cause-effect relationship parameters Input data also have uncertainties and potential biases. E.g., may contain biases towards well-studied species groups (eg birds) and biomes (tropical forests)	Uncertainties and potential biases: • Large variations in input data, with effects depending on characteristics of study sites, taxonomic groups, and other factors • Geographical bias towards well-studied regions, and those where both disturbed and comparable reference ecosystems still exist (e.g. North America, Australia)
	Sectors represented	Sectors represented by GLOBIO results will be dependent on the economic models connected to IMAGE which is used to estimate changes in pressures	As per GLOBIO
	Financial aspects	N/A	N/A
	Nature-economy interactions	GLOBIO takes direct drivers of biodiversity loss as inputs from IMAGE. Changes in these drivers can reflect economic dynamics if IMAGE is itself linked to economic models (e.g., MAGNET) GLOBIO outcomes do not feedback into the IMAGE framework, hence the link cannot be used to estimate economic consequences of biodiversity loss	As per GLOBIO
	Interactions with climate change	It is possible to model impacts from climate on biodiversity: • Impact of global mean average temperature increases • Impact of land-based climate mitigation policies	As per GLOBIO

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COMPLEXITY FEATURES	**Non-linearities**	See key assumptions	See key assumptions
	Feedback effects	Various research papers applying IMAGE-GLOBIO investigate the interactions and trade-offs between different pressures. For instance, Kok et al. (2023) explores the interaction between conservation policies, climate mitigation, and food security – amongst other interactions	
	Treatment of network effects	N/A	N/A

5. MESSAGEix-GLOBIOM model evaluation

		MESSAGEix	GLOBIOM	MESSAGE-GLOBIOM coupling
GENERIC	**Aims of model**	MESSAGEix helps to evaluate the impact of climate regulations on energy system development, it optimizes the energy system so that it can satisfy specified energy demand at the lowest cost MACRO, a single sector macro-economic model, which provides estimates of the macro-economic demand response that results from energy system and services costs computed by MESSAGEix	GLOBIOM aims to model land-use dynamics, through a representation of the competition between different land-use based activities (Food, fibers, energy, industry)	The coupling of MESSAGEix and GLOBIOM allows to assess the implications of utilizing bioenergy of different types and to integrate the GHG emissions from energy and land use
	Time horizon	MESSAGEix models the time horizon from 2010 to 2110, generally in 10-year periods (2020, 2030, 2040, 2050, 2060, 2070, 2080, 2090, 2100, 2110), using 2010 as the base year	GLOBIOM models the time horizon 2000 to 2100 in 10 year time steps, with the year 2000 being the base year of the model	Time horizon of 2010 to 2110 is generally subdivided into 5 or 10-year periods, using 2010 or 2015 as the base year
	Geographic scope	Global coverage, divides the world into 11 regions (North America, Western Europe, Pacific OECD, Central and Eastern Europe, Former Soviet Union, Centrally planned Asia and China, South Asia, Other Pacific Asia, Middle East and North Africa, Latin America and the Carribean, Sub-Saharan Africa)	Global coverage, 30 regions, reduced to 11 when linked with MESSAGE. (Canada, USA, EU_MidWest, EU_North, EU_South, ROWE, Turkey, ANZ, Japan, Pacific_Islands, EU_Baltic, EU_CentEast, RCEU, Former_USSR, China, RSEA_PAC, India, RSAS, South Korea, RSEA_OPA, MidEastNAfr, Brazil, Mexico, RCAM, RSAM, Congo_Basin, EasternAf, SouthAf, RoSAfr, WestCentrAfr) Geographically explicit representation of land-based activities at a 0.5° × 0.5° grid cell resolution	Global coverage, divides the world into 11 regions

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GENERIC	**Environmental scope**	Climate change: GHG emissions from energy (MESSAGE – CO_2, CH_4, N_2O, F-gases, other radiatively active gases, such as NOx, volatile organic compounds, CO, SO_2, and BC/OC) and land-use (GLOBIOM), and resulting climate change (MAGICC) Water demand associated to energy production (but water supply is not modelled)	Land use, detailed representation of the agricultural, forestry and bio-energy sectors GHG emissions associated to land-use change and agriculture	• Climate change: GHG emissions from energy (MESSAGE – CO_2, CH_4, N_2O, F-gases, other radiatively active gases, such as NOx, volatile organic compounds, CO, SO_2, and BC/OC) and land-use (GLOBIOM), and resulting climate change (MAGICC) • Land-use (from GLOBIOM) • Air pollution (GAINS model) • Water demand associated to energy production (but water supply is not modeled)
	Type of economic model	MESSAGEix itself is a partial equilibrium model. It is an energy systems optimization model, and it is recursive dynamic Through its linkage to MACRO, general equilibrium effects are taken into account. MACRO is a stylized computable general equilibrium model that is solving through intertemporal optimization	GLOBIOM is a partial-equilibrium model representing land-use based activities. It is recursive-dynamic (i.e., it is solved for each period individually and then passes on results to the subsequent periods)	
	Inputs	**Economy:** Historical GDP (PPP) – World Bank (World Development Indicators, 2012) Projected GDP (PPP) – Dellink et al. (2015), also see Shared Socio-Economic Pathways database (SSP scenarios) **Population:** Historical Population – UN Population Division (World Population Projection, 2010) Projected Population – KC and Lutz (2014), also see Shared Socio-Economic Pathways database (SSP scenarios) **Energy:** Historical Final Energy – International Energy Agency Energy Balances (IEA, 2012)	Population and GDP The average yield level for each crop in each country is taken from FAOSTAT (2007). Management related yield coefficients according to fertilizer and irrigation rates are explicitly simulated with the EPIC model	

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GENERIC	**Description of model process**	MESSAGEix's main task is to optimize the energy system so that it can satisfy specified energy demands at the lowest costs. It is a linear programming (LP) energy engineering model with global coverage. It represents an energy system with all its inter-dependencies from resource extraction, imports and exports, conversion, transport, and distribution, to the provision of energy end-use services. Policies are implemented via constraints or cost coefficients (negative and positive) in the optimization problem MESSAGE carries out this optimization in an iterative setup with MACRO, a single sector macro-economic model, which provides estimates of the macro-economic demand response that results from energy system and services costs computed by MESSAGEix. For the six commercial end-use demand categories depicted in MESSAGE, based on demand prices MACRO will adjust useful energy demands, until the two models have reached equilibrium	GLOBIOM is built following a bottom-up setting based on detailed gridcell information, providing the biophysical and technical cost information The demand for food is computed at the level of 30 economic regions, while the production is modeled at a much finer level ("simulation units") based on local biophysical characteristics of land. Production adjusts to meet demand, and market equilibrium is determined through mathematical optimization which allocates land and other resources to maximize the sum of consumer and producer surplus. Prices are endogenous Exogenous scenario assumptions (GDP, population, preferences, technology) also determine the use of land and the product mix. The model is solved in a recursive dynamic manner for 10y time steps For forests: For spatially explicit projections of the change in afforestation, deforestation, forest management, and their related CO_2 emissions, GLOBIOM is coupled with the G4M (Global FORest Model) model (Kindermann et al., 2006; Kindermann et al., 2008; Gusti, 2010). The spatially explicit G4M model compares the income of managed forest (difference of wood price and harvesting costs, income by storing carbon in forests) with income by alternative land use on the same place, and decides on afforestation, deforestation or alternative management options	When coupled to MESSAGE, GLOBIOM assesses the implications of utilizing bioenergy of different types and to integrate the GHG emissions from energy and land use To reduce computational costs, MESSAGE iteratively queries a GLOBIOM emulator which provides an approximation of land-use outcomes during the optimization process instead of requiring the GLOBIOM model to be rerun iteratively. Only once the iteration between MESSAGEix and MACRO has converged, the resulting bioenergy demands along with corresponding carbon prices are used for a concluding analysis with the full-fledged GLOBIOM model. This ensures full consistency of the results from MESSAGE and GLOBIOM, and also allows producing a more extensive set of land-use related indicators, including spatially explicit information on land use The climate constraints are thus taken up in the coupled MESSAGEix-GLOBIOM optimization, and the resulting carbon price is fed back to the full-fledged GLOBIOM model for full consistency. Finally, the combined results for land use, energy, and industrial emissions from MESSAGEix and GLOBIOM are merged and fed into MAGICC a global carbon-cycle and climate model, which then provides estimates of the climate implications in terms of atmospheric concentrations, radiative forcing, and global-mean temperature increase

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GENERIC	**Outputs**	Energy supply and demand for a range of energy technologies, energy prices, GHG emissions, and macroeconomic consequences of energy and climate-related transition policies (GDP impacts, etc.) Can give the carbon price that allows to reach a given climate target at the lower cost	Land-use maps, food production, food prices, availability and cost of bio-energy, and the availability and cost of emission mitigation in the AFOLU (Agriculture, Forestry and Land Use) sector	
	Model access & useability	The scientific software underlying the global MESSAGE-GLOBIOM model (called the MESSAGEix framework) is open-source		
	References	V. Krey, P. Havlik, P. N. Kishimoto, et al. MESSAGEix-GLOBIOM Documentation – 2020 release. Technical Report, International Institute for Applied Systems Analysis (IIASA), Laxenburg, Austria, 2020. URL: https://pure.iiasa.ac.at/id/eprint/17115 , doi:10.22022/iacc/03-2021.17115		
		(Huppmann et al., 2019 [[31]]) https://docs.messageix.org/en/latest/model/MACRO/macro_core.html	Chang, J., Havlík, P., Leclère, D., et al. 2021. Reconciling regional nitrogen boundaries with global food security. *Nature Food*. **2**(9), pp.700-711 Frank, S., Gusti, M., Havlík, P., et al.. 2021. Land-based climate change mitigation potentials within the agenda for sustainable development. *Environmental Research Letters*. **16**(2), p.024006 Petr Havlík, Uwe A Schneider, Erwin Schmid, et al. (2011). Global land-use implications of first and second generation biofuel targets. *Energy Policy*, *39 (10)*, 5690-5702 Petr Havlík, Hugo Valin, Mario Herrero, et al. (2014). Climate change mitigation through livestock system transitions. *Proceedings of the National Academy of Sciences*, *111 (10)*, 3709-3714	O. Fricko, P. Havlik, J. Rogelj, et al. The marker quantification of the Shared Socioeconomic Pathway 2: A middle-of-the-road scenario for the 21st century. Global Environmental Change, 42:251-267, 2017. doi:10.1016/j.gloenvcha.2016.06.004 Janssens, C., Havlík, P., Krisztin, T., et al. 2020. Global hunger and climate change adaptation through international trade. *Nature Climate Change*. **10**(9), pp.829-835 Hasegawa, T., Havlík, P., Frank, S., et al. 2019. Tackling food consumption inequality to fight hunger without pressuring the environment. *Nature Sustainability*. **2**(9)

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SCENARIOS	**Scenarios that can be explored in model**	**(Climate) transition scenarios:** Energy and climate-related transition policies: • GHG emission pricing • GHG emission caps and trading emission allowances • Renewable energy portfolio standards • Renewable energy and other technology capacity targets • Energy import tariffs • Fuel subsidies and micro-financing for achieving universal access to modern energy services in developing • countries • Air pollution legislation packages	GLOBIOM has been used to assess: • the effect of biodiversity policies on land use, biodiversity and food prices (Leclère et al. 2020) • the implications of energy and climate policy development (eg biofuel targets) on land-use • the implication of land-use and agriculture developments (e.g. livestock transitions) on climate change • the consequences of nitrogen mitigation policies on food production and security (Chang et al. 2021) • the implications of achieving key SDGs (including water and biodiversity) on land-based climate mitigation potential (Frank et al. 2021). Biodiversity policies explored include increasing share of protected areas, avoiding conversion of biodiversity hotspots, and respecting water flow requirements for freshwater ecosystem protection	The coupling of MESSAGE and GLOBIOM have been used e.g. to assess: • the food security implications of climate mitigation scenarios (Fujimori et al. 2019)
	Key economic and behavioural assumptions	**Energy model:** The primary drivers of future energy demand in MESSAGEix are projections of total population and GDP (PPP) The optimization can be made with perfect, foresight, limited foresight, or myopically The choice of the individual mitigation options across gases and sectors is driven by the relative economics of the abatement measures	**Demand:** Food demand is determined by exogenous scenario drivers (population, GDP growth, dietary preferences, trade policies) and endogenous responses based on behavioural elasticities (price and income) **Supply:** is a function of technological change (exogenous from scenario assumptions) and endogenous components: including supply-side elasticities and agri yields (themselves depending on biophysical variables, see below). Yields can change through the choice of land use allocation and choice of management system.	

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SCENARIOS	**Key economic and behavioural assumptions**	Non-monetary factors influencing costs of end-use technology (mostly for transportation, residential and commercial sectors): • Inconvenience factors (for end-use technologies). The cost entry of the technology is calculated as the monetary costs, multiplied by the inconvenience factor. The inconvenience factors for a given world region increase with the level of affluence (GDP per capita) in this region • Implicit discount rates which change perceived upfront investment costs by consumers Technological change for energy: Technological change in MESSAGEix is generally treated exogenously. The current cost and performance parameters are generally derived from the relevant engineering literature. The quantitative assumptions about technology cost development are derived from the overarching qualitative SSP narratives. In SSP1, for instance, whose "green-growth" storyline is more consistent with a sustainable development paradigm, higher rates of technological progress and learning are assumed for renewable energy technologies and other advanced technologies that may replace fossil fuels Baseline energy service demands are provided exogenously to MESSAGEix, though they can be adjusted endogenously based on energy prices using the MESSAGEix-MACRO link	For each crop, spatially explicit leontief production functions for 4 different management systems are parameterized using biophysical models (see below), to compute the economic costs for each production/management option in each grid cell. There are 4 possible management systems (irrigated, high input – rainfed, low input – rainfed and subsistence) **Yields, costs, and production info:** crop yields are generated at the grid cell level on the basis of soil, slope, altitude and climate info from IIASA's EPIC crop model. Grassland productivity comes from EPIC and CENTURY models. Livestock production info taken from various scientific studies and the RUMINANT model. Forestry costs and yields are sourced from the G4M global forestry model **Land use allocation:** GLOBIOM allocates land between crop, livestock and forestry activities, subject to land availability constraints, such that the sum of producer and consumer surpluses is maximised (i.e., intersection of supply and demand curves for each commodity) **Land use change:** Land conversion over the simulation period is endogenously determined for each Supply Unit within the available land resources based on the economic costs of converting land vs using a more intensive management system. The land transition matrix gives the land conversion possibilities and associated conversion costs – which are non-linear and increase with the area of land converted – that is taken into account in the producer optimization behavior

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SCENARIOS	**Key economic and behavioural assumptions**	**Macroeconomic model:** • MESSAGE is soft-linked to a aggregated, single-sector macroeconomic model (MACRO) • **Demand:** MACRO maximizes the intertemporal utility function of a single representative producer-consumer in each world region • **Supply:** Production function is a nested CES using capital, energy and labour. • Optimization result is a sequence of optimal savings, investment, and consumption decisions Market clearing	Land conversion possibilities are further restricted through biophysical land suitability and production potentials, and through a matrix of potential land cover transitions Trade: International trade representation is based on the spatial equilibrium modelling approach, where individual regions trade with each other based purely on cost competitiveness because goods are assumed to be homogenous	
NATURE-ECONOMY ASPECTS	**Key parameters**	Elasticity of substitution in CES production function Cost share of bioenergy in CES nests	The endogenous behavioral response to prices/costs depend on various elasticity parameters. E.g., food demand will depend on the price elasticity ε, the latter calculated from USDA. Because food demand in developed countries is more inelastic than in developing ones, the value of this elasticity is assumed to decrease with the level of GDP per capita	
	Sectors represented	Energy sector, and three energy end-use sectors, i.e. transport, residential/commercial (also referred to as the buildings sector) and industry	GLOBIOM covers the agriculture, forestry and bioenergy sectors 31 Crops: • 17 with four management systems (irrigated, high input – rainfed, low input – rainfed and subsistence): barley, dry beans, cassava, chickpea, corn, cotton, ground nuts, millet, potatoes, rapeseed, rice, soybeans, sorghum, sugarcane, sunflower, sweet potatoes, and wheat • 14 with two management systems (irrigated and rainfed): bananas, other dry beans, coconuts, coffee, lentils, mustard seed, olives, oil palm, plantains, peas, other pulses, sesame seed, sugar beet, and yams	MESSAGEix covers all greenhouse gas (GHG)-emitting sectors, including energy, industrial processes as well as agriculture and forestry through its linkage to GLOBIOM

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NATURE-ECONOMY ASPECTS	**Sectors represented**		Livestock: GLOBIOM differentiates 4 species aggregates: cattle/buffaloes (bovines), sheep/goats (small ruminants), pigs, & poultry • 8 production systems 8 for ruminants: grazing systems in arid (LGA), humid (LGH) and temperate/highland areas (LGT); mixed systems in arid (MXA), humid (MXH) and temperate/highland areas (MXT); urban systems (URB); and other systems (OTH) 2 production systems for monogastrics: smallholders (SMH) & industrial systems (IND)	
	Financial aspects	None	None	None
	Treatment of Nature economy interactions: physical shocks	None	It is possible to represent physical shocks in GLOBIOM through ad hoc shocks to biophysical variables determining agricultural yields (e.g., water variables modelled in CWAT model, or biophysical variables determining crop yields in the EPIC model). These kind of ad hoc scenarios could be run to assess the impact on prices of food, bioenergy and land-based emissions mitigation	Land not in the production function, so any physical shocks modelled in GLOBIOM will only have an indirect linkage to macroeconomy through energy and carbon prices (see below)
	Treatment of Nature economy interactions: transition policies	Climate and energy policies only	GLOBIOM can be used (standalone) to assess the impact of land-based policies on food production and prices, as well as knock on effects on indicators of food security. E.g., Chang et al. 2021 assess the impacts of nitrogen mitigation policies on food security	As per above, indirect linkage to macroeconomy through effect of transition shock on (1) energy prices, and (2) carbon price effects
	Interactions with climate change	Impact of climate policies on land use and land-use CO_2 emissions		The MESSAGE-GLOBIOM coupling can assess the impact of climate policies on land use and land-based GHG emissions, and effects of climate impacts on agricultural production/prices (e.g., see Janssens et al. 2020)
	Non-linearities	None		

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COMPLEXITY FEATURES	**Feedback effects**	Energy is the main channel that shocks feed back through to the macroeconomy		Energy is the main channel through which shocks feed back to the macroeconomy. Via the GLOBIOM emulator, the main links are (1) carbon price and (2) price of bioenergy. The emulator can also be adjusted to include other parameter constraints related to water, food security, etc. This has been in done for the SDGs in Hasegawa et al (2019)
	Treatment of network effects	None	Interactions between agricultural sectors (e.g. feed is an input to livestock production)	
	Main advantages of model	Very detailed energy sector and energy policies that can be implemented in the model, multiple technology options	Quite detailed cops and livestock sector, with multiple types of agricultural management (including e.g. low input and high input)	
SUMMARY	**Main limitations of the model**	The macroeconomic model only includes energy (in production function) – other nature considerations are only very indirect when the model is coupled with GLOBIOM, and GLOBIOM results feedback to the macroeconomy through only one tiny channel (bioenergy production). No sectorial granularity		

6. GCAM version 7 – model evaluation

		GCAM Core + Energy	GCAM-LAND
GENERIC	**Aims of model**	Explore and quantify implications of possible future scenarios in an integrated, multi-sector model that represents interactions between five systems: energy, water, agriculture and land use, the economy, and the climate	
	Time horizon	Typically applied to long time horizons (1990-2100), with 5-year time steps (with flexibility to adjust temporal resolution, e.g., to annual time steps)	
	Geographic scope	Global model, with different levels of resolution between each sub-system: • Macroeconomy: 32 geopolitical regions • Energy system: 32 geopolitical regions • Land system: 384 subregions • Water systems: 235 hydrological basins • Physical Earth system (climate): global There are detailed regional versions of the model for the USA and China Gridded spatial resolution of land is 5 arc minutes	
	Environmental scope	**Type of biodiversity:** Not explicitly modelled, but land subregions are characterized to reflect the native biome **Biodiversity pressures included:** Climate change, land use change, direct exploitation (of water only – withdrawals for energy & agriculture and consumption modelled, water supply modelled as a physical relationship between precipitation, evapotranspiration, recharge and runoff with river-routing) **Ecosystem services:** Not explicitly modelled	
	Type of economic model	Dynamic recursive computable general equilibrium model, focusing on energy, agricultural, and water markets	Dynamic recursive partial equilibrium model
	Inputs	**Economic and demographic inputs to scenarios:** • Population (from SSPs) • GDP projections (SSPs, taken from Dellink et al. (2017) using the OECD-Env model) • Labour productivity (calibrated to meet SSP pathways)	**Land and agriculture inputs:** • Historical land use, land cover, harvest area, cropland cover (from FAO & others) • Terrestrial carbon (Houghton 1999) • Value of unmanaged land (from Moirai Land Data System) …/…

GENERIC	**Inputs**	**Other economic and demographic data inputs:** • Historical GDP for runs prior to 2015 (from USDA, World Bank datasets) • Near-term growth rate projections (from IMF) • National accounts data (from Penn World Table and GTAP v10) **Energy-related inputs:** • Historical demand for energy and other technology characteristics (IEA) • Energy intensities (Liu et al. 2016) **Water-related inputs (consumption and withdrawal coefficients):** • Agriculture, livestock water coefficients (from Mekonnen and Hoekstra 2011) • Industrial and electricity coefficients (From Vassolo & Döll 2005 and others) • Primary energy water coefficients (from Maheu 2009) • Municipal water withdrawals and use efficiency (FAO Aquastat and others)	• Historical demand for crops, livestock, forest commodities (from FAO and Moirai) – used to derive historical yields • Agricultural productivity growth (from FAO) used to derive future yields • Elasticity parameters to calculate food demand based on changing prices and incomes (calculated separately in ambrosia model and input into GCAM)
	Description of model process	**GCAM core:** GCAM takes in a set of assumptions and then processes those assumptions to create a full scenario of prices, energy and other transformations, and commodity and other flows across regions and into the future. GCAM represents five different interacting and interconnected systems. The interactions between these different systems all take place within the GCAM core; that is, they are not modelled as independent modules, but as one integrated whole. The five systems in the GCAM Core are as follows: macroeconomy, energy, water, physical earth system, land use and agriculture **Macroeconomy:** • Sets the scale of economic activity in GCAM. Takes population and labour productivity as exogenous input assumptions, and outputs regional GDP and regional populations as inputs to other modules. • There is one final good which requires capital, labor and energy services as inputs • Representative agents for each regional sector use prices and other information to make decisions about allocation of resources and indicate their supply/demand for goods and services in each market	**Agriculture and land use:** • Computes land use allocation, land cover, land use change (detailed below) • Models the production of bioenergy, food, fibre, and forest products resulting from land use allocation for 15 different agriculture & forestry commodities (see sectors below) • Demand driven by population, income levels, and commodity prices • Provides information about carbon stocks and net GHG emissions and various aerosol gases • Demand for bioenergy is a derived demand by the energy sector. Agriculture and land systems demand water from water systems

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GENERIC	**Description of model process**	• GCAM solves for a set of market prices that balance supply and demand in all markets across the model. Iterative solution process until equilibrium is reached • Markets include: supply and demand for labor, supply and demand for saving, supply and demand of energy commodities; supply and demand of agricultural commodities; supply of all water types and demand for water withdrawals and consumption **Energy system:** • Detailed representation of the sources of energy supply, modes of energy transformation, and energy service demands such as transport, industrial energy use across subsectors, and residential and commercial energy service demands • The module reports demands for and supplies of energy forms as well as emissions of greenhouse gases, aerosols and other short-lived species. Energy systems demand bioenergy from agriculture and land systems and water from water systems • Non-renewable resources: oil, gas, coal, and uranium • Renewable sources: onshore wind, offshore wind, solar (including rooftop, thermal towers, field arrays), geothermal, hydropower, and biomass • Energy transformation sectors: electricity, refining, gas processing, hydrogen production, district services **Water systems:** • Provides information about water withdrawals and water consumption for energy, agriculture, municipal and other uses **Physical Earth System:** • Modelled using Hector. Hector includes carbon cycle, and simple atmospheric composition modules and a emulator that provides information about the composition of the atmosphere based on emissions provided by the other modules, ocean acidity, and climate

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GENERIC	**Outputs**	**Economic variables:** • Energy supply and demand • Agricultural production and consumption • Water availability and use • Prices for all markets • Changes in GDP, consumption from shocks (from MACRO module) • 'Deadweight loss' resulting from shocks (bottom-up approach considering costs of technology switches, i.e., area under MAC curves) **Biophysical variables:** • Emissions • Atmospheric concentrations and temperature	**Biophysical variables:** • Land based emissions • Land uses and land use change **Economic variables:** • Quantity of commodities produced and prices
	Model access and useability	GCAM is available open access and has extensive model user guides (http://jgcri.github.io/gcam-doc/user-guide.html) including YouTube video guides (https://www.youtube.com/@GCIMS/videos)	
	References	Documentation for v7: http://jgcri.github.io/gcam-doc/index.html Arango-Aramburo, Santiago, Sean WD Turner, Kathryn Daenzer, Juan Pablo Ríos-Ocampo, Mohamad I. Hejazi, Tom Kober, Andrés C. Álvarez-Espinosa, Germán D. Romero-Otalora, and Bob van der Zwaan. "Climate impacts on hydropower in Colombia: A multi-model assessment of power sector adaptation pathways." *Energy Policy* 128 (2019): 179-188 Calvin, K., Wise, M., Clarke, L., Edmonds, J., Kyle, P., Luckow, P., & Thomson, A. (2013). Implications of simultaneously mitigating and adapting to climate change: initial experiments using GCAM. *Climatic Change*, *117*(3), 545-560 Sinha, E., Calvin, K.V., Kyle, P.G., Hejazi, M.I., Waldhoff, S.T., Huang, M., Vishwakarma, S. and Zhang, X. 2022. Implication of imposing fertilizer limitations on energy, agriculture, and land systems. *Journal of Environmental Management*. **305**, p.114391 Snyder, A., Calvin, K., Clarke, L., Edmonds, J., Kyle, P., Narayan, K., ... & Patel, P. (2020). The domestic and international implications of future climate for US agriculture in GCAM. *PloS one*, *15*(8), e0237918 Waldhoff, Stephanie T, Ian Sue Wing, James Edmonds, Guoyong Leng, and Xuesong Zhang. "Future Climate Impacts on Global Agricultural Yields over the 21st Century." *Environmental Research Letters* 15, no. 11 (October 21, 2020): 114010 https://doi.org/10.1088/1748-9326/abadcb Zhao, X., Calvin, K.V., Wise, M.A., Patel, P.L., Snyder, A.C., Waldhoff, S.T., Hejazi, M.I. and Edmonds, J.A. 2021. Global agricultural responses to interannual climate and biophysical variability. *Environmental Research Letters*. **16**(10), p.104037	

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SCENARIOS	**Nature-related scenarios that can be explored with the model**	**Physical scenarios:** • It is possible to represent ad hoc physical shocks in GCAM through adjustments to selected variables determining agricultural yields (e.g., water variables). See for example, Arango-Aramburo, et al (2020), Waldhoff, et al. (2020), Snyder, et al. (2020), and Calvin, et al. (2013) • Zhao et al. (2021) show a strong transmission of interannual variability in climate-induced biophysical yield shocks to agriculture markets, further magnified by endogenous market fluctuations resulting from modelling adaptive expectations **Transition scenarios:** • Energy policies: production constraints (e.g., constraints on bioenergy), incentives, energy intensity standards • Water supply policies: price-based policies (e.g., subsidies) • Land policies: - protected lands (7 different options depending on suitability for economic activity, intactness of ecosystem & high or low levels of protection) - Shadow carbon price of land - Bioenergy constraints (e.g., negative emissions budget, externality cost) - Regionally-specific land constraints - Agricultural management systems (irrigated vs rainfed, high versus low fertiliser use), although no explicit organic or agroforestry option • Food policies: adjusting preference elasticities to influence demand for certain food types (e.g., less meat consumption) • GCAM v5 has been used to explore the impact of reducing global fertiliser usage on land use change, agricultural commodity price and production, energy production and GHGs (Sinha et al. 2022) • Finds that *"constraining fertiliser usage results in higher price for food, minimal impact on food consumption… due to the assumed low price elasticity of food demand in GCAM"*	
NATURE-ECONOMY ASPECTS	**Key economic and behavioural assumptions**	**GDP growth assumptions:** • Total factor productivity (TFP) can be calibrated to achieve SSP pathways based on GDP and population inputs • In GCAM v7 it is also possible to fully endogenise GDP responses through a two-way coupling between GDP and the energy module such that GDP reflects the cost of delivering energy services within a given scenario • Also in v7, estimates of future labor supply and assumptions of total factor/labor/capital/energy productivity improvements can be used directly to determine future GDP	**Agricultural markets:** • Food demand is modelled through evolution of historical demand according to changes in incomes, prices, and exogenous parameters from SSPs – using approach documented in Edmonds et al. (2017). Feed demand based on logit sharing approach • Forestry demand is determined by price, income and population size • Agricultural supply for each commodity is a function of potential yields, availability of water for irrigation, prices, and land allocation • Market equilibrium approach solves for prices such that supplies match demands in all markets • Different sectors and fuels are linked (increase in cost of one may alter demand for another, e.g., fertiliser prices and cost of gas)

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NATURE-ECONOMY ASPECTS	**Key economic and behavioural assumptions**	**Agent behaviours:** • As a dynamic recursive model, decision-makers do not know the future when making a decision in each time period • Agents are assumed to maximise own self-interest, but these can be sub-optimal from an overall social perspective (because model is not optimizing for the whole economy) **Production:** • Single final goods sector (called Materials) which produces all new final goods and services other than net energy exports, which are determined in the Energy system. The Materials sector uses as inputs, Labor, Capital and Energy Services suppled by the Energy system • Production function for final good X is a nested CES function with capital, labour, energy services as factors. The function displays constant returns to scale (homogenous of degree 1) • There is currently no land in the production function, and land is not included as a fixed or variable cost in the production of agricultural commodities (because profit rates of commodities determine land use allocation). This means that land has a very indirect mechanism to impacting the macroeconomy, namely through relative price effects of bioenergy-related commodities. Integration of Agriculture-Land-Use into the macroeconomy is under development **Savings & investment:** • Global capital market distributes savings and capital investment flows between the Energy and Materials sectors. In the broader macroeconomy • Energy module uses putty-clay capital representation (i.e., once investment is made, capital stock remains productive through lifetime as long as operating costs covered) • The Materials sector uses a simple exponential capital stock decay model **Trade:** • Armington approach used to model commodity trade, for example, coal, gas, oil, bioenergy, wheat, corn, forest products	**Land allocation in the GCAM *Agriculture-Land-Use* module:** • Logit model of land sharing: each competing land use has a distribution of profit within a region (rather than single value) • Nested structure of land uses: where assumed to be easier to switch between nodes than across nodes ('logit exponents' = transformation elasticities) • Land allocated based on *probability* that economic use has the highest profit relative to competing uses – means that uses allocated up until the point at which the marginal profit rates are equal to each other, and so marginal land values also equal • "Because the logit sharing approach reflects non-linear representations of crop profits and market share, it results in diminishing returns to scale as land uses expand further from historical values [on any of the 384 land-use regions]. In contrast to a linear model with constant returns to scale, the GCAM approach does not require explicit constraints on land use to govern behaviour" • Within each land use subregion in GCAM, economic uses of land are allocated based on that subregion's own relative profit rate distributions, not what its yields or its profit rates are compared with the rest of the globe. This means that land use allocations are based on comparative advantage rather than absolute advantage • Land nesting strategy and choice of logit exponents based on modeller judgement • Zero exponents only used for limited situations – it is not possible to switch from agricultural land uses to urban/desert/tundra **Land intensification:** • Multiple management options exist for each crop within each subregion: rainfed vs irrigated, high vs low fertiliser, capital vs labor intensity • Each crop technology is assigned future yield improvement rates based on FAO projections by country, crop, and irrigation level • These management options form part of land nesting approach, meaning that intensification is price-induced based on the relative profitability of each practice. That is, as profits of a higher yielding management option increase, more land will be allocated to that option, increasing overall average yields (i.e., intensification) …/…

NATURE-ECONOMY ASPECTS	**Key economic and behavioural assumptions**	• Due to this mechanism, the documentation notes that *"GCAM captures changes in yield due to increases in fertilizer use or irrigation endogenously."* Otherwise, agricultural yields are calculated by applying agricultural productivity growth projections (FAO) to historical yield data (various sources including FAO), weighted by the fraction of the land unit deploying that crop-technology combination • GCAM is not linked to a separate crop or vegetation model. But it is possible to connect yield variables to external models using yield emulators • In general, GCAM will intensify when there is a lot of land competition (like when carbon in land is valued) • It is also possible for average yields in a region to decline if commodity prices fall or if the price of fertiliser and water increases **Land use change:** • Expansion of land uses to natural areas effectively takes place as the alternative to intensification (above) based on relative profitability, suitability & protection policy assumption constraints • The logit model effectively depicts a supply curve for non-commercial land with land supply elasticity determined implicitly by the logit exponent and assumed profit rates (implicit cost of land use change) • Profits for each commercial land use are determined by price, cost, yield and subsidy. Non-commercial land profits are based on the value of the land and serves as a numeraire against which to compare expected profitability in commercial appplications • Available land for expansion is then based on levels of suitability and protection constraints. There are 7 mutually exclusive types of land based on these suitability and protection constraints. They are: 1. Unsuitable and Unprotected 2. Suitable and Unprotected 3. Suitable with a high level of protection that is intact 4. Suitable with a high level of protection that is deforested 5. Suitable with a low level of protection 6. Unsuitable with a high value of protection 7. Unsuitable with a low value of protection …/…

NATURE-ECONOMY ASPECTS	**Key economic and behavioural assumptions**		• By default land that is classified as Suitable and Unprotected (No 2 from the above) will be made available for expansion. The user can make other types of land available and can define a custom area of land for protection
	Key parameters		• Parameters for land logit model are calibrated from historical data, where underlying economic values of various land types are implied from real world shares of each land • Larger logit exponents will result in a stronger transition to a land type whose profit increases than would occur with lower logit exponents (Zhao et al. 2020)
	Sectors represented	One final goods sector Energy: • 5 depletable resources oil, unconventional oil, gas, coal, uranium) • 6 renewables (onshore/offshore wind, solar, geothermal, hydropower, biomass). And in some regions a 'traditional biomass' resource (for buildings sector only) • 5 broad energy transformation sectors (electricity, refining, gas processing, hydrogen production, district services) – each with further subsections within • Multiple energy services, e.g. passenger km of transportation services, process heating services, and space cooling services. • Energy trade for coal, gas, oil, and biomass using Armington approach	Agriculture: • 8 agricultural commodities: wheat, rice, other coarse grains, oilseeds, sugar crops, ruminant meat, non-ruminant meat and eggs, dairy products
	Financial aspects	None	
	Nature-economy interactions	**Land use, other biodiversity / ecosystem services → economy:** • As of version 7, land is not in the production function, so any physical or transition shocks affecting land modelled in GCAM will only have an indirect linkage to macroeconomy through relative changes in bioenergy and carbon prices • It is possible to represent ad hoc physical shocks in GCAM through adjustments to selected variables determining agricultural yields (e.g., water variables). This kind of analysis has not yet been done however in the context of nature-related shocks • *Note: the GCAM team are working to releasing version 7.1, where the agricultural sector will be connected to the macroeconomy. Here, agricultural commodities will become an input into final goods, and labour and capital will allocate between general economy, energy, and agricultural sectors. This future version will make the link between any shocks to agriculture and the macroeconomy more direct* **Economy → biodiversity and ecosystem services:** • Not modelled	

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NATURE-ECONOMY ASPECTS	**Interactions with climate change**	**Climate → biodiversity/land:** • Currently no feedbacks from climate impacts onto agricultural sector (e.g., no impacts of temperature or precipitation changes on agricultural yields) – • However, GCAM has been used to model agricultural climate impacts, e.g. Snyder et al. (2020), Waldhoff, et al. (2020) using scenarios • Future work (currently under review) seeks to endogenise these feedbacks between climate impacts and agricultural production to be coupled in code **Biodiversity/land → climate:** • Not modelled
COMPLEXITY FEATURES	**Feedback effects**	See above
	Treatment of network effects	None

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