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Agriculture and Food Integrated Assessment Models Review

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Abstract

Integrated Assessment Models (IAMs) have become critical tools for analyzing the complex interactions within agriculture and food systems, offering valuable insights for evidence-based policymaking. This paper reviews twelve widely applied agriculture and food IAMs, categorizing them into four primary sub-groups: Food Security, Land Use, and Socio-economic Models; Hydrological and Water Resources Models; Land, Crop, and Food Production Models; and Food-Energy-Water Nexus Models.

The review highlights their respective capabilities, including cost minimization, depth of the food-energy-water nexus analysis, integration with other domains and tools, and spatial and temporal resolution. A comparative assessment underscores each model's unique strengths, such as resource intensity accounting in FABLE, climate-focused numerical analysis in MAgPIE and IMPACT, and resource balance optimization in GCAM and WEAP. Synergies between IAMs and their integration with other domains, including energy and economic systems, are also explored, demonstrating their potential for producing holistic scenarios addressing climate adaptation, resource constraints, and dietary transitions.

The findings emphasize the significant role IAMs play in advancing the EU's sustainability agenda, including the Green Deal and Common Agricultural Policy. By fostering tailored projections and capacity-building potential, IAMs enable interactive engagement with diverse stakeholders and provide a framework for aligning national and international policies. These integrated approaches are crucial for crafting strategies that enhance food system resilience, optimize resource use, and support climate goals, positioning IAMs as indispensable instruments for shaping sustainable and equitable food systems worldwide.

1. Introduction

Integrated Assessment Models (henceforth IAMs) have emerged as critical tools in the intersection of climate science and policy, evolving significantly since their inception around three decades ago. The origins of IAMs can be traced back to the need for comprehensive frameworks that integrate knowledge from various disciplines—such as economics, environmental science, and energy systems—to assess the multifaceted impacts of climate change and the effectiveness of potential policy responses. Early models primarily focused on the interactions between economic growth, resource use, and environmental degradation, providing a foundational understanding of how human activities affect climate systems and vice versa. One of the earliest examples of an IAM is the Climate Impact Assessment Program (CIAP),[1] initiated in the 1970s. This program focused on assessing the potential atmospheric impacts of supersonic transport aircraft, marking a significant early attempt to formalize integrated assessments through mathematical modeling. As IAMs evolved, they began to incorporate more complex interactions between energy systems and economic growth, with models like the RAINS model (Regional Acidification Information and Simulation) developed in the late 1980s playing a crucial role in addressing acid rain issues in Europe (Alcamo et al., 1987).

Integrated Assessment Models (IAMs) play a crucial role in the science-policy interface by bridging complex scientific data with actionable climate policy decisions. By synthesizing knowledge from multiple disciplines, IAMs enable policymakers to simulate various scenarios and assess the impacts of different strategies on greenhouse gas emissions, economic growth, and social equity. They help evaluate trade-offs between approaches, thereby guiding effective and equitable policy formulation. Additionally, IAMs illustrate the consequences of inaction and incorporate uncertainties related to technological and socio-economic changes, promoting resilient policy frameworks. Beyond scientific analysis, IAMs serve as educational tools that enhance public and policymakers understanding of climate issues, fostering informed dialogue and consensus-building. As global climate challenges escalate, IAMs are increasingly vital for developing informed, sustainable policies that address the complexities of climate governance.

Having said that, results based on IAMs should be approached with caution. Pindyck (2013), criticises IAMs on the basis that many inputs to these models are arbitrary, significantly influencing the resulting estimates of the social cost of carbon. Additionally, the models may rely on ad hoc descriptions of climate change impacts, lacking a solid theoretical or empirical foundation. Crucially, they fail to address the potential for catastrophic climate outcomes, which is a key driver of the social cost of carbon. As a result,

1 https://sedac.ciesin.columbia.edu/mva/iamcc.tg/TGsec2-1.html

analyses based on IAMs can create a misleading perception of knowledge and precision regarding climate policy, obscuring the inherent uncertainties and limitations of these models. Nonetheless, despite not being omnipotent, IAMs provide analytical tools in our science-based approach to tackle climate change. Climate change is arguably the greatest challenge of our time, and, to that end, all stakeholders need to mobilise as many resources as possible to address it. Keeping these criticisms in mind and not accepting the results of any potential IAM model at face value, we should be able to adapt to any potential misperceptions created during the study.

An initial reporting on existing IAMs has been carried out in 2023[2], compiling and evaluating widely used IAMs by examining their scope, output potential, accessibility, inputs, outputs, and potential for synergies. IAMs are characterized by their coverage of economic, energy, climate, and AFOLU-water-demographic trends. Their potential lies in the diversity and depth of their outputs, ranging from computationally intensive to specialized models, and their ability to interact with other models for enhanced insights. Accessibility varies from open-source programs to "black box" interfaces and customizable Excel formats. Inputs are drawn from diverse datasets, such as economic and agricultural metrics, while outputs span a range of fields, presented through tables, graphs, or maps. Synergies among IAMs are crucial for holistic sustainability analysis, achieved through cooperative, complementary, or independent integration of models. This approach highlights the importance of leveraging IAM strengths and interactions to address complex global challenges effectively.

IAMs focused on food systems and agriculture (henceforth food IAMs) integrate data and insights from various disciplines, including agronomy, economics, ecology, and climate science. They enable researchers and policymakers to explore how changes in factors like population growth, technological progress, and climate change might affect food security, agricultural land use, and environmental outcomes. By simulating different scenarios, food IAMs provide valuable insights to support decision-making and long-term planning in the food-agriculture domain. Food IAMs typically model the production, consumption, and trade of agricultural commodities, as well as the associated land use, greenhouse gas emissions, and impacts on biodiversity. They use advanced mathematical and computational techniques to simulate different scenarios and project long-term trends. By providing quantitative insights into the complex dynamics of the food system, food IAMs play a vital role in supporting decision-making and informing policies related to food security, sustainable agriculture, and environmental protection.

2 COP28, UN SDSN Global Climate Hub: Modelling Net Zero Pathways; Phoebe Koundouri, Dogan Keles, Yuen Yoong Leong, Rasmus Bramstoft, Maria Angeliki Chatzigiannakou, Konstantinos Dellis, Ioannis Kountouris, Conrad Landis, Theis Madsen, Georgios Papayiannis, Michael James Platts (1945-2022), Wing Thye Woo, Athanasios Yannakopoulos; Report 2023

This opinion paper aims to collate and assess the most widely used and effective IAMs related to agriculture and food systems and explore their potential role in informing science-policy interfaces and policy formulation. Section 2 meticulously describes the functioning and outputs of relative IAMs, highlighting the synergies with other models; Section 3 describes the evaluation methodology; Section 4 discusses the implications for EU policy formulation while the final section concludes.

2. Review of food IAMs

The 2023 COP report by the UN SDSN Global Climate Hub[3] categorizes IAMs based on their primary application domains, including agriculture, climate, economics, water, and demographics (population and migration). This section provides an overview of twelve agriculture-focused IAMs, classified by their specialization within the food systems domain. Additionally, 12 supplementary food IAMs are detailed in Appendix I. As illustrated in Figure 1, the classification of 24 food-related models includes categories such as Food Security, Land Use, and Socio-Economic Models; Hydrological and Water Resource Models Relevant to Agriculture; Land, Crop, and Food Production Models; and Food-Energy-Water Nexus Models.

Figure 1. Agri-food IAMs categorized according to their focus and specialization within the food category

3 COP28, UN SDSN Global Climate Hub: Modelling Net Zero Pathways; Phoebe Koundouri, Dogan Keles, Yuen Yoong Leong, Rasmus Bramstoft, Maria Angeliki Chatzigiannakou, Konstantinos Dellis, Ioannis Kountouris, Conrad Landis, Theis Madsen, Georgios Papayiannis, Michael James Platts (1945-2022), Wing Thye Woo, Athanasios Yannakopoulos; Report 2023

2.1 Agriculture IAMs description

2.1.1 Food Security, Land Use and Socio-economic Models

The FABLE Calculator[4] is an Excel accounting tool used to study the potential evolution of food and land-use systems over the period 2000-2050. It is the main modeling tool for the FABLE Consortium under the aegis of UN SDSN and IIASA. Its primary field is agriculture, while it includes land use, food systems, energy and biodiversity categories. Through a demand-based approach, it acknowledges agriculture as the main driver of land-use change and tests the impact of different policies and changes in the drivers of these systems through the combination of many scenarios. It includes data for 88 raw and processed agricultural products from the crop and livestock sectors and relies extensively on the FAOSTAT (2020) database for input data. The FABLE calculator combines scenarios for economic, environmental, energy and policy variables to compute pathways for the 2020-2050 horizon. Scenarios are the suite of possible actions that set a pathway on a certain trajectory and a Pathway represents the coherent development of a system along a certain trajectory. Assumptions are the conditions that a modeler establishes before the model is run to make predictions on, for example, causality chains and changes in specific parameters of the model according to the selected scenarios.

The Calculator computes the level of agricultural activity, land use change, food consumption, trade, GHG emissions, water use, and biodiversity conservation according to selected scenarios for every 5-year time step over the period 2000-2050, using agricultural products data from the FAOSTAT database (2020). Users can replace data from global databases with national or subnational data. The Calculator is linked to other models like GLOBIOM, BALMOREL, BayesPop, and MAGE in a synergistic way. It closely integrates with these complementary models, leveraging their specialized capabilities and data to enhance its own computations and analyses. This cross-model integration allows the Calculator to produce more robust, comprehensive, and accurate projections across a range of agricultural, land use, emissions, and environmental metrics.

4 https://www.abstract-landscapes.com/fable-calculator

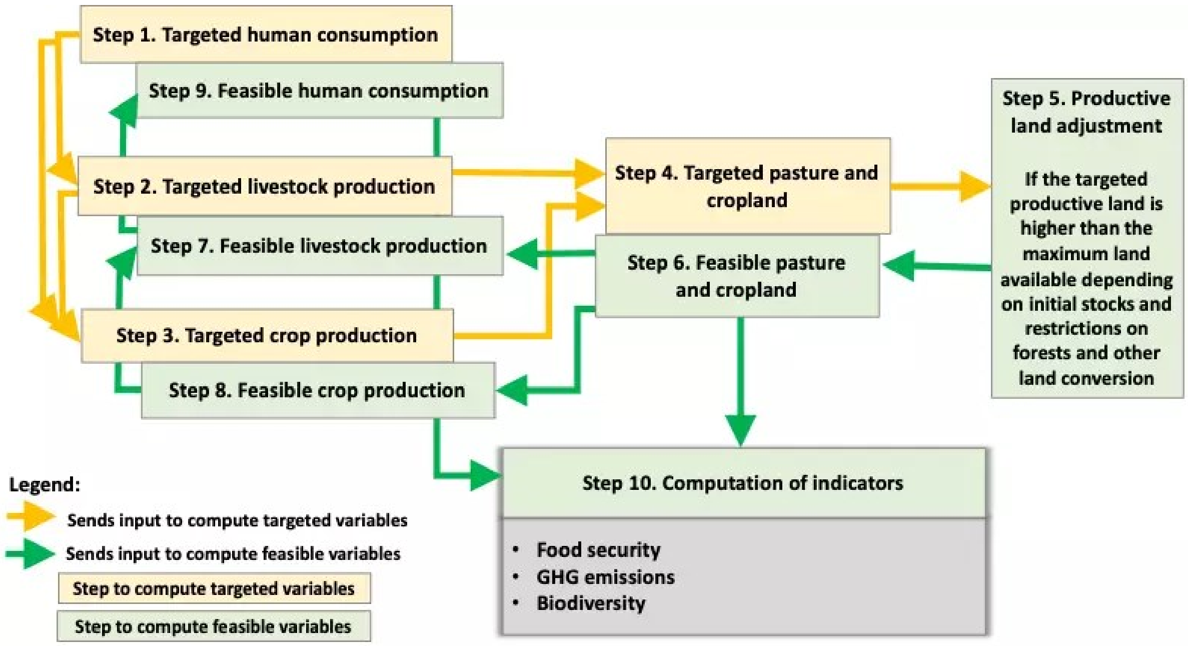


Figure 2. FABLE calculator methodology, Figure 6 in (Mosnier, et al., 2020)

MAgPIE[5] [6] (Model of Agricultural Production and its Impact on the Environment) is a global **land-use allocation model**, which is connected to the grid-based dynamic vegetation model LPJmL, with a spatial resolution of 0.5°x0.5°. Developed by the Potsdam Institute for Climate Impact Research, MAgPIE assesses land and water competition and sustainable development implications under scenarios of rising demands for food, energy, and materials, climate change impacts, GHG mitigation, and land-use policies. It uses regional economic data, including demand elasticity, technological advances, and production costs, alongside spatial data on crop yields and environmental constraints. The model aims to minimize production costs for meeting regional food and bioenergy demands, generating outputs on land-use patterns, yields, production costs, and land-based GHG flows. MAgPIE's results support analyses of climate change impacts on land-use and are further enriched through links with other models, such as **REMIND** and **MAGICC**, to provide a comprehensive understanding of global land and environmental systems. It belongs to the AFOLU and economy categorization.

5 https://www.iamcdocumentation.eu/index.php/Model_Documentation_-_REMIND-MAgPIE

6 https://rse.pik-potsdam.de/doc/magpie/4.3/

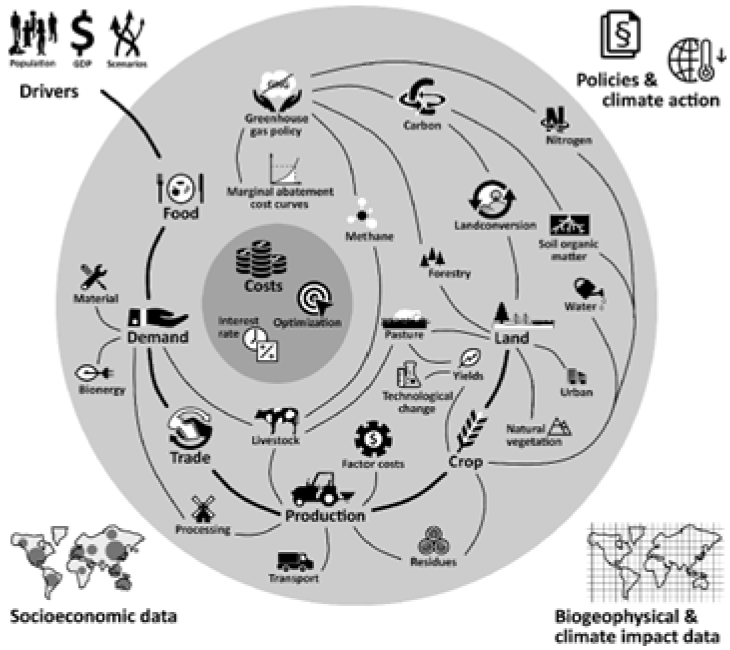


Figure 3. MAgPIE 4 framework, as presented in (Dietrich, et al., 2019)

The Global Forest Model (G4M)[7] is a climate model that evaluates the profitability of forests versus alternative land uses, such as agricultural crops or biofuels, helping to determine optimal land use based on potential income. It can be integrated with other models to enhance land-use insights and helps assess land management options by comparing afforestation, deforestation, and forest maintenance impacts. G4M computes optimal forest rotation times, biomass stocking, and harvesting rates, supporting efficient forest management decisions. Key inputs include forest characteristics, economic factors like wood demand and land rents, and environmental data. Outputs from G4M include afforestation and deforestation rates, forest biomass, CO_2 emissions, and forest management impacts under different climate policy scenarios, such as carbon taxes or incentives. This model is also closely linked with the GLOBIOM model, providing a comprehensive tool for evaluating land-use and climate strategies.

7 https://previous.iiasa.ac.at/web/home/research/researchPrograms/EcosystemsServicesandManagement/G4M.en.html

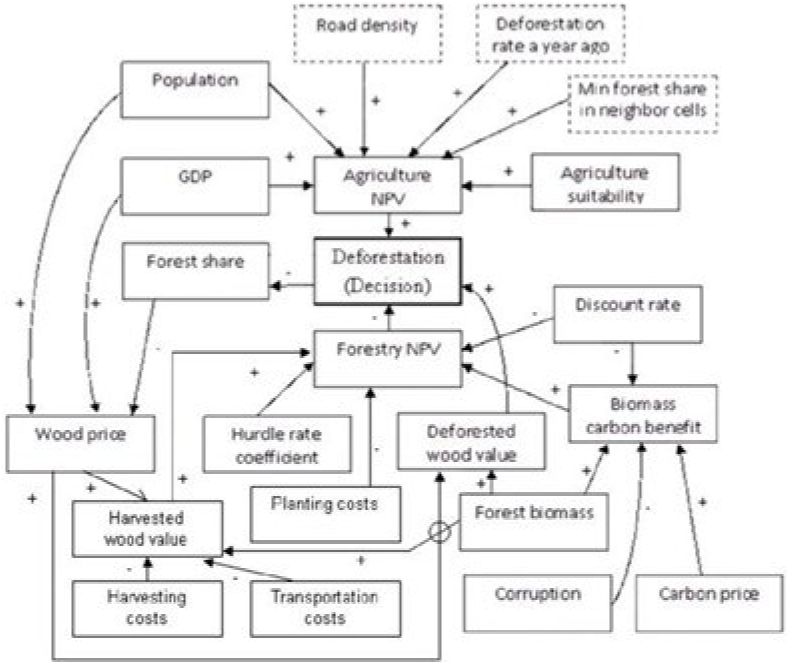


Figure 4. Casual diagram of the decision on deforestation in a grid cell. Source: Figure 3 in (Gusti, ESM, & IIASA, 2015)

GCAM[8] (Global Change Analysis Model) is a market equilibrium model with a global reach that projects trends from 1990 to 2100 in five-year increments. It examines how factors like population growth, income changes, and technology costs impact crop production, energy demand, and water use, while also assessing how shifts in one region's energy demand influence other regions. As a dynamic-recursive model, GCAM includes detailed representations of the economy, energy sector, land use, and water, and is connected to a climate model, making it useful for evaluating climate policies like carbon taxes, trading, regulations, and accelerated energy technology adoption. The model uses historical data on production, pricing, and emissions, along with projected technology and emissions data, to reach market equilibrium solutions. Its output span energy production and consumption, agricultural and forestry outcomes, greenhouse gas pricing, and land use projections. GCAM is also part of the Net Zero Worlds Initiative (NZWI), collaborating with models like TIMES, PLEXOS, and MESSAGE.

8 https://gcims.pnnl.gov/modeling/gcam-global-change-analysis-model

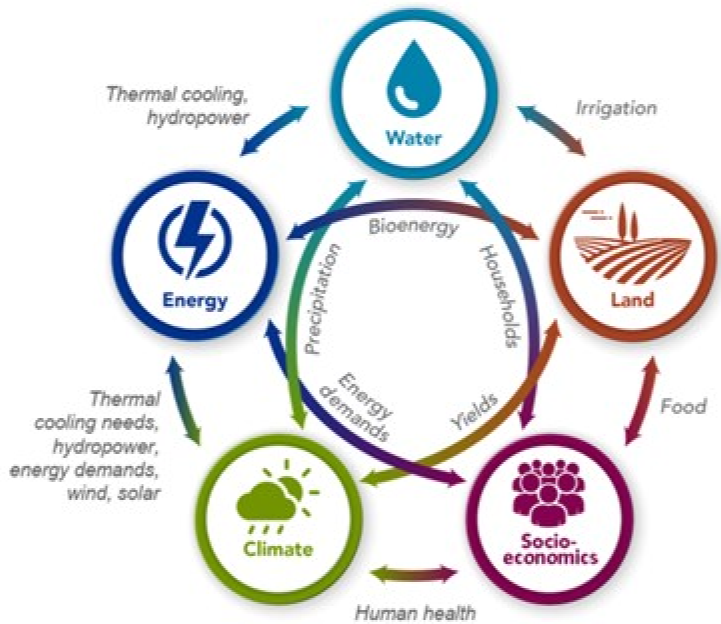


Figure 5. GCAM schematic[9]

GLOBIOM (Global Biosphere Management Model)[10] is a global recursive dynamic partial equilibrium model that integrates the agricultural, bioenergy, and forestry sectors to analyze land-use competition. It captures the interrelationships between population dynamics, socio-economic changes, technology, ecosystems, and climate, which affect land use and resource allocation. Initially developed to assess climate change mitigation policies in land-based sectors like biofuels, GLOBIOM is now used for agricultural and timber market projections, economic impacts of climate change, adaptation strategies, and various sustainable development goals. The model runs recursively and provides projections up to 2100, focusing on greenhouse gas emissions from the Agriculture, Forestry, and Other Land Use (AFOLU) sector, including N2O, CH4, and CO2. Input includes regional data on population, GDP, bioenergy, diets, trade, and land productivity, while outputs cover prices, demand, trade flows, land use, production, and emissions. GLOBIOM is also compatible with other models like WITCH, MAGICC, and G4M, GEM-E3, POLES, PRIMES, CAPRI, and GAINS, offering comprehensive insights into land-based systems.

9 Calvin, Katherine & Patel, Pralit & Clarke, Leon & Asrar, G. & Bond-Lamberty, Ben & Cui, Ryna & Di Vittorio, Alan & Dorheim, Kalyn & Edmonds, Jae & Hartin, Corinne & Hejazi, Mohamad & Horowitz, Russell & Iyer, Gokul & Kyle, Page & Kim, Son & Link, Robert & McJeon, Haewon & Smith, Steven J & Snyder, Abigail & Wise, Marshall. (2019). GCAM v5.1: representing the linkages between energy, water, land, climate, and economic systems. Geoscientific Model Development. 12. 677-698. 10.5194/gmd-12-677-2019.

10 https://iiasa.github.io/GLOBIOM/index.html

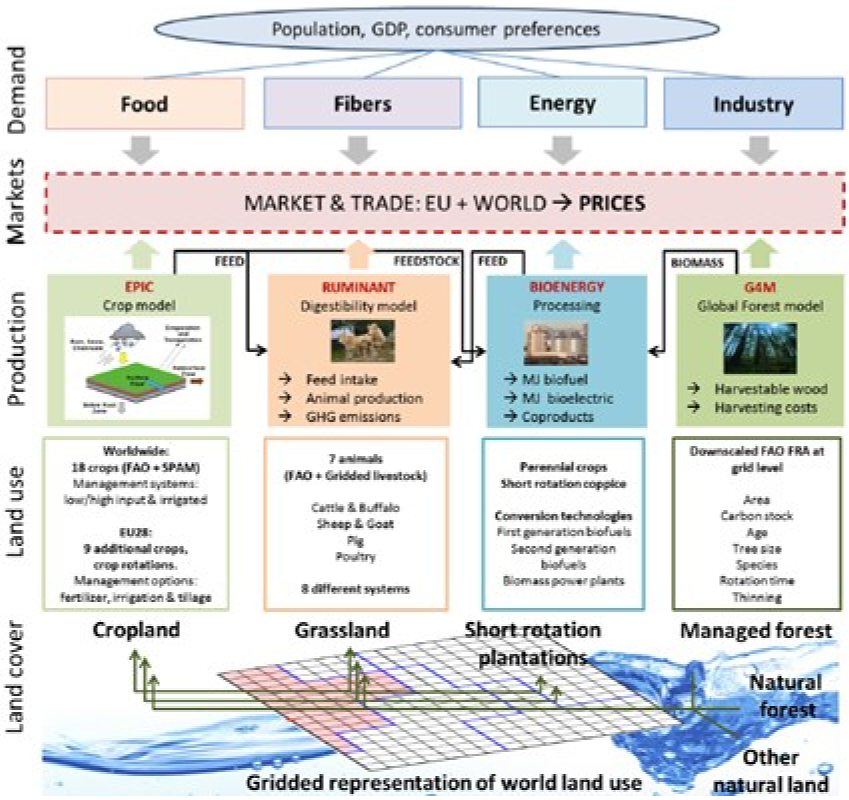


Figure 6. GLOBIOM schematic[11]

CAPRI[12] is an economic partial equilibrium model developed by European Commission research funds. It supports decision-making related to the EU Common Agricultural Policy (CAP) and environmental policy based on quantitative analysis. CAPRI has spatial coverage for all countries globally and a single-year, comparative static approach. The results are stored in GDX format, and a Java GUI allows model setup and scenario runs. CAPRI's input includes prices, agricultural land allocation, supply and use balances of agri-food commodities, productivity indicators, macroeconomic data, and policy information. Its consistent database combines global, national, and regional data from sources like EUROSTAT, FAOSTAT, and FADN. The model's outputs cover agricultural production, yields, trade, farmer income, prices, subsidies, greenhouse gas emissions, nutrient and carbon balances, and water use. CAPRI provides consistent agricultural activity projections for EU scenarios, with short-term, medium-term, and long-term analysis up to 2030 or 2050. CAPRI has synergies with other models like EDGAR,

11 Mant, Rebecca & Salvaterra, Tania & Miles, Lera & Kapos, Valerie. (2014). Assessing the biodiversity impacts of policies related to REDD+ Key considerations for mapping and land use change modeling, illustrative examples from Brazil. 10.13140/RG.2.2.32213.63204.

12 https://web.jrc.ec.europa.eu/policy-model-inventory/explore/models/model-capri/

IMPACT, GLOBIOM, and EBB, which provide inputs to complete its database. It is used for EU-focused agricultural and environmental policy analysis.

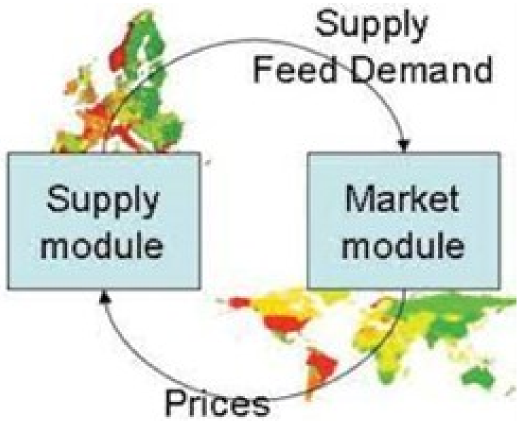


Figure 7. Concept of the CAPRI model[13]

TOA-MD (Tradeoff Analysis Model for Multi-dimensional Impact Assessment)[14] is a simulation tool developed by Oregon State University to analyze agricultural production systems and land use, focusing on economic and environmental outcomes. TOA-MD simulates the adoption and impacts of new technologies or changes in environmental conditions on a heterogeneous population of farms. It utilizes available data to approximate the results of a controlled experiment. The latest TOA-MD7.0 model can simulate economic, environmental, and social impacts of agricultural systems for diverse households with crops, livestock, and aquaculture. It calculates impact indicators like mean farm income, poverty, and threshold-based environmental/social outcomes for adopters, non-adopters, and the overall population. TOA-MD is used to assess the viability and impact of new agricultural technologies, evaluate farming system resilience to climate change, develop policies for sustainable agriculture and poverty reduction, and inform resource allocation decisions. Input includes crop/livestock yields, soil/climate data, farm characteristics, household demographics, input costs, output prices, technology adoption information, and risk/uncertainty parameters. Output covers socioeconomic and environmental outcomes, poverty/food security indicators, technology adoption assessments, and visualizations of trade-offs. TOA-MD has synergies with other models like GCAM, IMAGE, REMIND, MAGNET, IMPACT, DSSAT, MESSAGE-GLOBIOM, and EPPA.

13 Delince, Jacques. (2012). An integrated Modelling Platform for Agro-economic Commodity and Policy Analysis (iMAP) - a look back and the way forward.

14 https://tradeoffs.oregonstate.edu/tradeoffs/about-toa

IMPACT (International Model for Policy Analysis of Agricultural Commodities and Trade) [15] [16], developed by the International Food Policy Research Institute (IFPRI) in the early 1990s, is a dynamic model designed to address the long-term challenges of reducing hunger and poverty in a sustainable manner. Over the years, the model has evolved to tackle increasingly complex policy questions, expanding its focus to integrate food supply, demand, trade, and agricultural water use. IMPACT is a network of interconnected economic, water, and crop models, with a core partial equilibrium multi-market economic model that simulates both national and international agricultural markets. It incorporates environmental, biophysical, and socioeconomic trends, enabling detailed analysis of critical issues that affect food security and agricultural systems at national, regional, and global levels.

The model utilizes a wide range of inputs, including climate change scenarios, crop yield data, renewable water resources, agricultural costs, and historical data on crop production. It also considers population growth, income levels, urbanization, technology adoption, and policy interventions such as subsidies and taxes. The output includes projections of agricultural production, prices, trade, food consumption patterns, and water demand, alongside estimates of food insecurity and malnutrition risks. IMPACT helps policymakers assess the long-term effects of various scenarios, such as technological advancements, climate change, and policy changes, on food systems, water resources, and nutrition outcomes. The model's results support decision-making by providing insights into trade-offs and policy

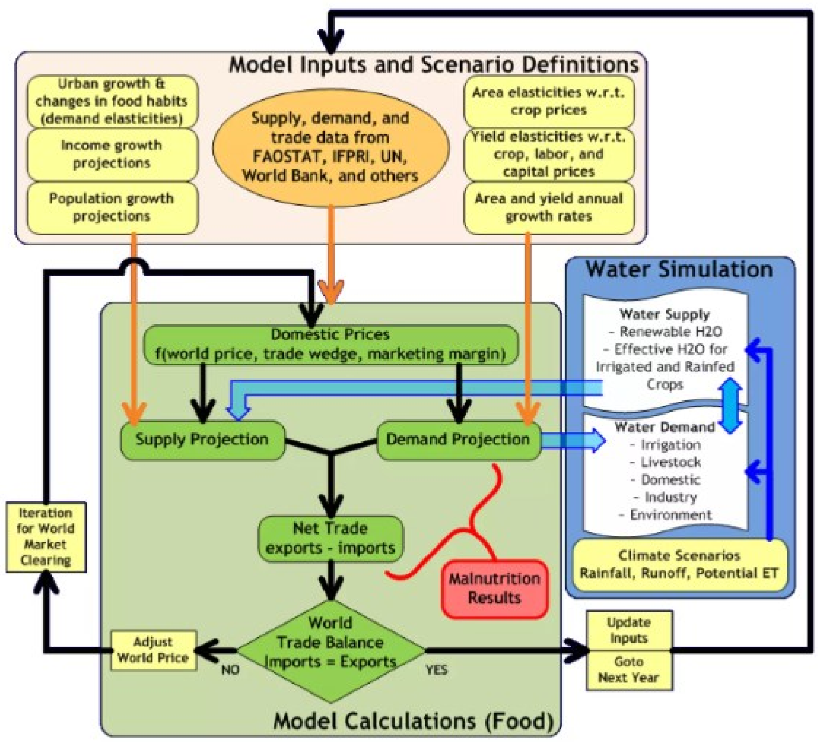
15 https://www.ifpri.org/project/ifpri-impact-model/

16 https://www.researchgate.net/publication/285446531_The_International_Model_for_Policy_Analysis_of_Agricultural_Commodities_and_Trade_IMPACT_Model_description_for_version_3

impacts and is synergistically linked with other models such as GCAM, IMAGE, GLOBIOM, MESSAGE-GLOBIOM, WaterGAP, REMIND, EPPA, MUSE, AIM, and AIM/CGE.

Figure 8. Schematic of the IMPACT model[17]

MAGNET (Modular Applied General Equilibrium Tool)[18 19] is a global general equilibrium model designed with a modular structure, allowing it to be tailored to specific research questions, regions, and sectors of interest. It analyzes the impacts of agricultural, trade, land, and bioenergy policies on the global economy, particularly focusing on land use, agricultural prices, nutrition, and household food



security. Covering 141 regions and 113 sectors, including agriculture, manufacturing, and services, MAGNET provides detailed insights into the socio-economic impacts of policies, such as GDP, welfare, production, consumption, and food security indicators. The model also generates projections on macroeconomic variables, production factors, and environmental impacts like greenhouse gas emissions.

17 https://www.slideshare.net/slideshow/robinson-bishkekapr2014/33760730#6

18 https://www.magnet-model.eu/#about

19 https://web.jrc.ec.europa.eu/policy-model-inventory/explore/models/model-magnet/#model-typology

MAGNET utilizes data from sources like the GTAP database, EU agricultural outlooks, and FAOSTAT, and is synergistic with the models GCAM, GLOBIOM, IMAGE, MESSAGE-GLOBIOM, WaterGAP, AIM, EPPA, DSSAT, AIM/CGE, and IMPACT for comprehensive assessments across various sectors.

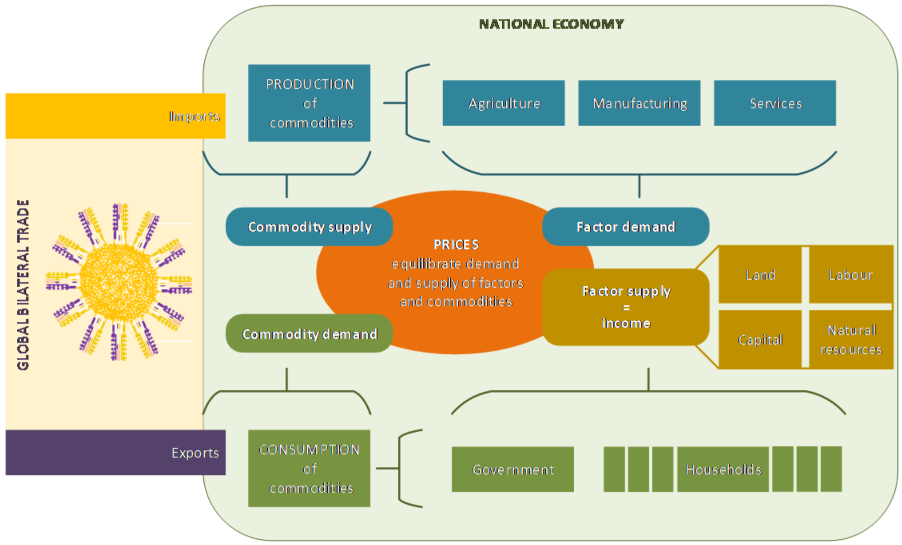


Figure 9. Graphic representation of the MAGNET model. In this specific version two household types in Ghana are distinguished, and a nutritional module is added as post analysis.[20]

2.1.2 Hydrological and Water Resources Models Relevant to Agriculture

WEAP (Water Evaluation and Planning), is a software tool developed by the Stockholm Environment Institute's U.S. Center, designed to support integrated water resources planning. It considers water supply, demand, quality, and ecological factors to allocate water across agricultural, municipal, and environmental uses. The tool features a water balance database, scenario generation tools, and policy analysis functions to evaluate various water management options and their implications on water sufficiency, costs, environmental targets, and uncertainties. WEAP models water demand, supply, runoff, stream flows, pollution, and treatment under different policy, climate, and cost scenarios. Its user-friendly interface presents results through maps, charts, and tables, and it integrates with other models such as QUAL2K, MODFLOW, MODPATH, PEST, Excel, and GAMS for comprehensive analysis.

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20 https://www.researchgate.net/publication/343889929_The_distribution_of_food_security_impacts_of_biofuels_a_Ghana_case_study

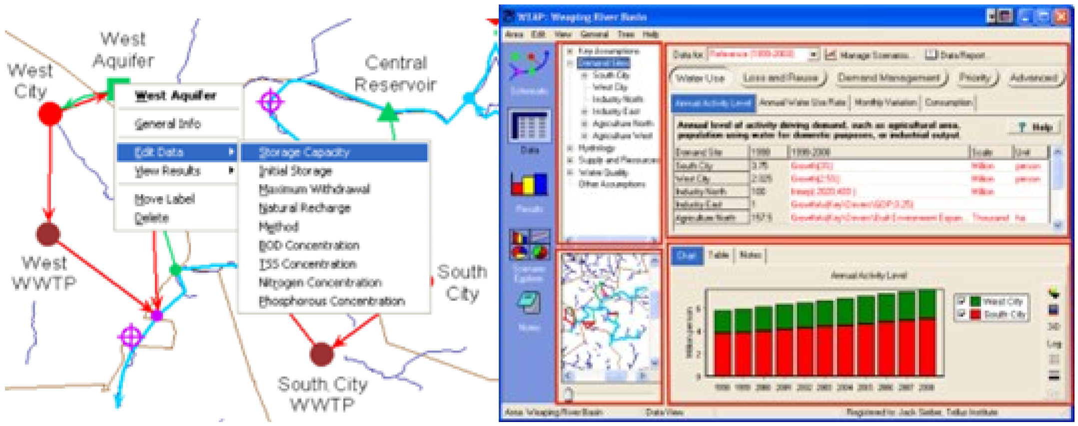

Figure 10. WEAP schematic view (left side) and WEAP data view (right side)[21]

2. 1. 3 Land, Crop, and Food Production

IMAGE (Integrated Model to Assess the Global Environment), [22] [23] [24] [25] developed by PBL Netherlands Environmental Assessment Agency and launched in 1990, is a comprehensive tool designed to assess the interactions between human activities and natural systems globally, with a focus on long-term sustainability. The model evaluates how socio-economic pathways—such as population growth, economic development, and technological advancements—affect critical resources like energy, land, water, and biodiversity. IMAGE is particularly focused on addressing global challenges such as climate change, resource depletion, and ecosystem service sustainability, projecting future scenarios up to 2100. By integrating a broad range of socio-economic and environmental factors, IMAGE provides insights into energy use, agricultural production, land use changes, emissions, and carbon stocks. It also projects climate impacts, including greenhouse gas emissions, temperature and precipitation changes, and sea level rise. The model's output helps stakeholders assess resource limitations, climate impacts, and sustainability challenges, providing a solid foundation for policy development and adaptive strategies. IMAGE can also be combined with the models MESSAGE, REMIND, WITCH, GCAM, TIAM, and AIM, enabling holistic analyses of the food-water-energy nexus and contributing to informed decision-making in global sustainability.

[21] www.weap21.org
[22] https://ndcpartnership.org/knowledge-portal/climate-toolbox/integrated-model-access-global-environment-image
[23] https://www.pbl.nl/en/image/about
[24] https://models.pbl.nl/image/Framework_overview
[25] https://www.iamconsortium.org/resources/model-resources/image/

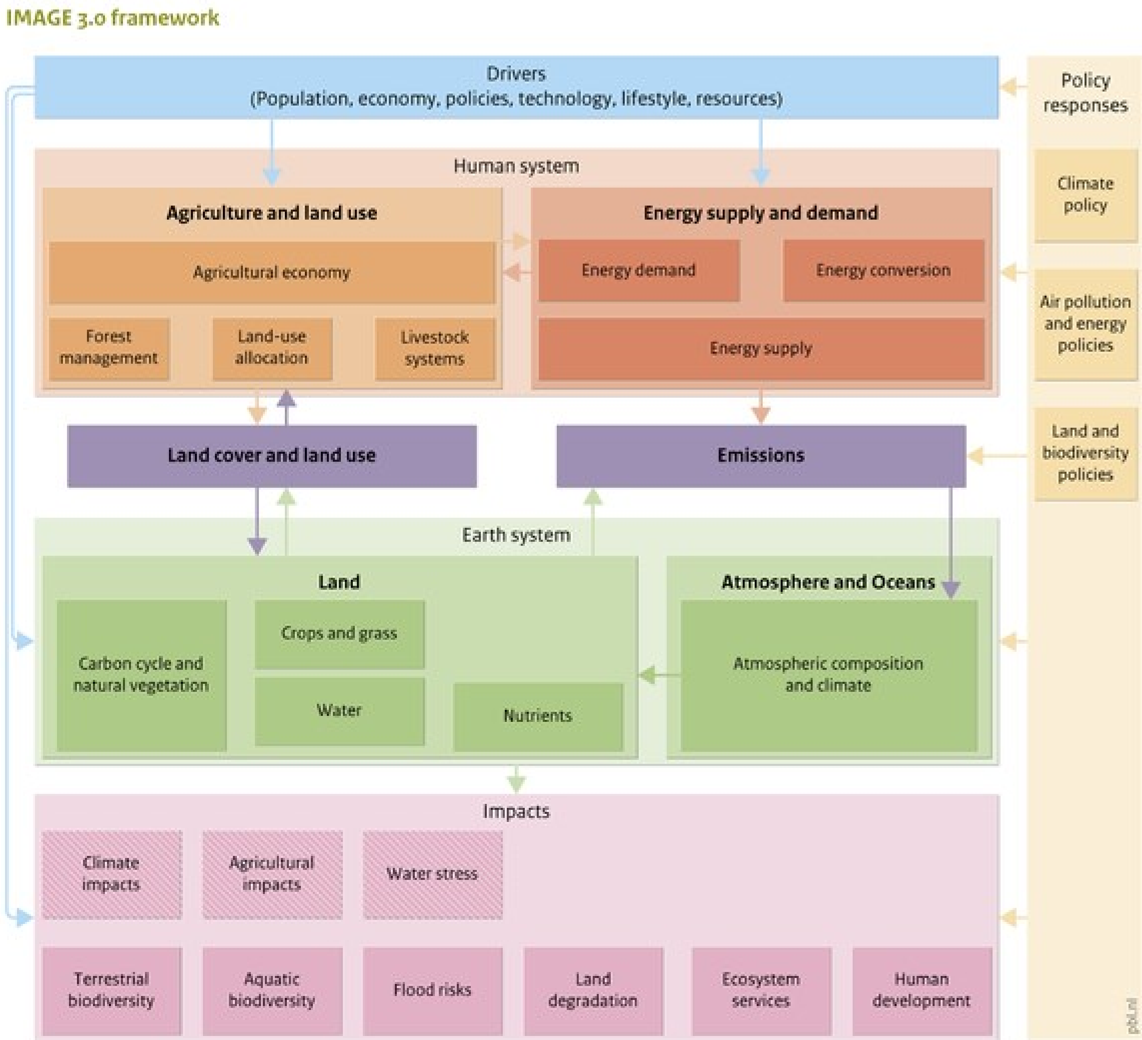

Figure 11. Framework of IMAGE 3.0 version

2.1.4 . Food-Energy-Water Nexus Models

SIM4NEXUS[26] [27] Primarily focused on European systems, this model examines the interdependencies of water, energy, food, and land, emphasizing policy interventions and climate adaptation. SIM4NEXUS aims to foster a transition to a resource-efficient, low-carbon economy by

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[26] https://sim4nexus.eu/Startseite

[27] https://www.pik-potsdam.de/en/output/projects/all/496

developing innovative methodologies and policy-design tools to close knowledge gaps related to the water-land-food-energy-climate Nexus, especially under climate change. It predicts the societal impacts of resource use and relevant policies on agriculture, biodiversity, and ecosystem services using model-based analyses. Central to SIM4NEXUS is a cloud-based "serious game," which allows users to simulate and evaluate policy decisions across scales from regional to global and over various time horizons. This game, validated through ten regional and national case studies as well as European and global scenarios, aims to support decision-making and explore potential applications, with a business plan ensuring the long-term viability of the project's insights and tools.

2.2 Agri-Food Models in Modelling Suites

At this point, it is essential to emphasize the pivotal role of agriculture-focused IAMs in comprehensive modeling frameworks, where cross-disciplinary synergies—spanning economics, energy, and climate—yield robust insights for sustainable policy design. These models IAMs link agricultural practices with emissions trajectories, guiding policymakers on achieving climate targets, as for example in the case of the EU Green Deal. Embedding agri-food IAMs in modelling suites including economic, climate, and energy models (among others) enhances their credibility and solidifies their output as it decreases the level of arbitrariness in the choice of climate scenarios, trajectories of variables measuring economic activity (e.g. GDP growth and trade balance) and land availability considering geological developments. Furthermore, linking agriculture-specific models with economic and energy models increases policy coherence across different sectors and fosters the development of holistic socioeconomic pathways.

The European Commission[28] employs model-based scenario quantification to support impact assessments and the evaluation of policy options. Scenario modeling generates updated greenhouse gas (GHG) emission reference scenarios for the EU and its Member States, reflecting current trends and policies and developed in consultation with Member State experts. The outcomes of policy scenarios provide critical analytical insights for assessing environmental, economic, and social impacts, including cost-effectiveness and other multifaceted analyses addressing multiple objectives. The current suite of models, illustrated in Figure 12, has contributed to key initiatives such as the EU Reference Scenario 2020, policy scenarios for Delivering the European Green Deal, the impact assessment for the EU Climate Target Plan, and the in-depth analysis of the EU Long-Term Strategy. This modeling framework spans the period from 1990 to 2050 in five-year intervals, encompassing all EU Member States and relevant neighboring countries. The

[28] https://climate.ec.europa.eu/eu-action/climate-strategies-targets/economic-analysis/modelling-tools-eu-analysis_en

calculated impacts extend across various sectors, including energy, transport, industry, agriculture, forestry, land use, atmospheric dispersion, health, ecosystems (acidification and eutrophication), macroeconomics (multi-sectoral), employment, and social welfare.

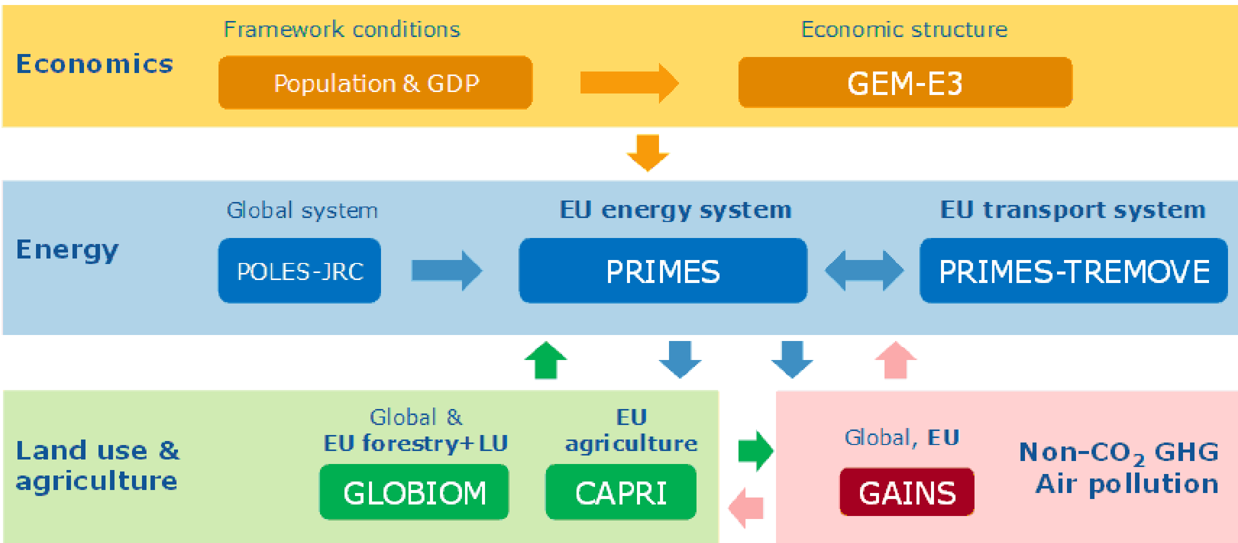

Figure 12 . The Modelling tools for EU analysis, as presented in the European commission webpage[29]

Key agri-food IAMs, such as GLOBIOM and CAPRI, are integral to the European Commission Modelling tools for EU analysis (Figure 12). These models (GLOBIOM managing agriculture and land use sector for both global and EU forestry and land use, and CAPRI manages EU agriculture) interface with others, including GEM-E3 (economics), POLES-JRC and PRIMES (energy), and GAINS (non-CO_2 emissions), to address sectors like agriculture, land use, and transport. For greenhouse gas (GHG) emissions, CO_2 is managed by PRIMES (energy) and GLOBIOM/G4M (land use), while GAINS covers non-CO_2 gases (CH_4, N_2O, fluorinated gases, and air pollutants). As presented in Figure 12, the modeling suite leverages developments across many aspects. Furthermore, the coupling of REMIND (energy-economy) with MAgPIE (land use-agriculture) further enables analysis of food security, water demands, and land use under climate scenarios.

[29] https://climate.ec.europa.eu/eu-action/climate-strategies-targets/economic-analysis/modelling-tools-eu-analysis_en

3. Evaluation Criteria and policy maker's options

We established five key criteria for evaluating the twelve models focused on food security, land use, and socioeconomic systems and water management: (i) cost minimization, (ii) addressing nexus (the interdependence of water, food, energy, land use, and climate), (iii) integration with other models, (iv) coverage of diverse economic sectors, and (v) spatial and temporal resolution. The assessment procedure consisted of thoroughly evaluating each model's description to extract important information, analyzing how each model addressed each criterion, and assigning a strength level - high, medium or low—strong, moderate, normal, or weak—to each characteristic. Assessing the score for these qualities in terms of strength enabled us to determine each model's respective strengths and limitations, resulting in a clear comparison study. A traffic-light scoring system was used to assign a score of high, medium or low performance in these five criteria, and the results are summarized in Table 1.

The distinct characteristics of each model provide specific capacities for addressing distinct research needs. This differentiation allows researchers to select models based on the features most relevant to their objectives.

For example, FABLE excels in addressing the nexus between resources such as water, energy, and seeds, and the products derived from them. This capability is particularly valuable for understanding how the intensity of resource use changes over time while tracking transformations in products—both in terms of innovations and the processes involved. For instance, plant-based meat can satisfy human dietary calorie needs differently compared to conventional lamb meat. As these two products vary in price and nutritional efficiency, the value added (calculated as price multiplied by quantity) between them changes, especially if conventional meat demand is replaced by plant-based alternatives. FABLE also features an internal loop that supplements the basic accounting function of balancing supply and demand, adding further analytical depth.

	Model Features				
Models	**Cost Minimization**	**Addressing Nexus**	**Integration with Other Models**	**Sectoral Coverage**	**Spatial & Temporal Resolution**
FABLE	☒ (Low)	☒ (Medium)	☒ (Medium)	☒ (High)	☒ (Medium)
MAgPIE	☒ (High)	☒ (High)	☒ (Medium)	☒ (High)	☒ (High)
G4M	☒ (High)	☒ (Medium)	☒ (Medium)	☒ (Medium)	☒ (High)
GCAM	☒ (Low)	☒ (High)	☒ (High)	☒ (High)	☒ (High)
GLOBIOM	☒ (High)	☒ (High)	☒ (High)	☒ (Low)	☒ (High)
CAPRI	☒ (High)	☒ (High)	☒ (High)	☒ (Low)	☒ (High)
TOA-MD	☒ (Medium)	☒ (Medium)	☒ (High)	☒ (Medium)	☒ (Medium)
IMPACT	☒ (Medium)	☒ (High)	☒ (High)	☒ (High)	☒ (High)
MAGNET	☒ (Medium)	☒ (High)	☒ (High)	☒ (High)	☒ (High)
WEAP	☒ (Medium)	☒ (High)	☒ (High)	☒ (Medium)	☒ (Medium)
IMAGE	☒ (Medium)	☒ (High)	☒ (High)	☒ (High)	☒ (Medium)
SIM4NEXUS	☒ (Low)	☒ (High)	☒ (Low)	☒ (High)	☒ (High)

☒: High, ☒: Medium, ☒: Low

Table 1: IAM Scoreboard

By contrast, MAgPIE benefits from spatial resolution and the integration of spatially explicit data through satellite imaging, which provides valuable insights into potential crop yields and land and water constraints. This spatial capability offers advantages over FABLE (which lacks spatial resolution), G4M (which lacks an explicit cost optimization function), and WEAP (which, while capable of modeling water balances, cannot capture or retrieve spatial data). MAgPIE's ability to minimize production costs through land-use modeling also stands out, making it highly effective for analyzing food-water nexus interactions.

G4M, on the other hand, assesses the profitability of different land uses, including forestry, agriculture, and bioenergy. This model provides valuable feasibility analyses for various land use practices and supports enhanced forest management through its carbon pricing mechanisms. The built-in consideration of harvesting and transportation costs also facilitates cost minimization strategies. When combined with GLOBIOM, G4M's outputs on afforestation and deforestation rates under different climate policy scenarios offer a powerful tool for evaluating land use strategies and climate policies. Additionally, GLOBIOM, which is integrated with the EPIC model for crop feedstock data, highlights forestry's role as an important feedstock resource for industry.

GCAM is a global framework for analyzing the interactions between climate conditions, land use, energy, water, and demographics. This model enables evaluation of how global changes affect resource availability, while representing 235 global water basins and deploying supply curves to highlight alternative options, including hydropower reservoir storage, groundwater, and desalination. However, GCAM lacks the ability to capture satellite data or incorporate real-time data transfers. Despite this, GCAM remains a strong tool for understanding land, energy, water, and socio-economic interactions, providing robust support for policy analysis.

Although CAPRI's integration with other models is an important feature, it does not provide as extensive a toolkit as some of the other models in this evaluation.

The IMPACT 3 and TOA-MD models bring together advantages found in FABLE, while also benefiting from MAgPIE's spatial data capabilities. IMPACT 3 uses spatial data from maps to simulate climate processes accurately, providing predictive analytics on climate change impacts. TOA-MD also offers flexibility by supporting both explicit and implicit spatial analysis. However, MAGNET lacks the spatial data integration that other models provide.

WEAP is particularly strong in accounting for water resources but lacks an explicit cost optimization function. While it includes scenario, economic, and sensitivity analyses that can indirectly inform cost-related decisions, it does not incorporate a direct optimization algorithm. WEAP also lacks the complexity needed to model multidisciplinary interactions involving multiple stakeholders. Its simulation results often require expert interpretation to develop actionable water resource management plans.

In summary, models like FABLE effectively describe projections related to resource intensity variability, while models such as MAgPIE, IMPACT 3, and TOA-MD leverage satellite data to enhance their numerical analysis of climate and environmental interactions. GCAM and WEAP excel in representing water balance conditions at a regional level, with GCAM providing a more comprehensive exploration of the energy-water-land-socioeconomic nexus.

4. Discussion

Integrated Assessment Models (IAMs) in the context of food systems are uniquely valuable tools for understanding the complex interactions between agricultural production, land use, water resources, energy demands, and climate impacts. Food-focused IAMs should be seen as complementary, not competitive, as each model provides insights into distinct aspects of food system dynamics. By combining various IAMs, each with sectoral expertise, can achieve more precise and nuanced predictions relevant to agriculture, forestry, and land use (AFOLU) as well as their interactions with energy, emissions, and water resources models by combining Earth systems models with a variety of IAMs to uncover land use effects at a downscaled spatial resolution (Hasegawa et. al. 2017). Leveraging these synergies allows IAMs to address multifaceted food security and sustainability challenges, such as climate adaptation, resource constraints, and dietary changes, through integrated scenarios.

A key strategy for increasing the relevance of food IAMs is the ability to downscale their applications to local contexts or specific agricultural sectors. For instance, downscaling an IAM to analyze a country's agricultural and food sector could provide insights into climate impacts on regional crop yields, irrigation requirements, and land use shifts, as demonstrated on crop yields in Norway (Mohammadi et. al. 2023). Additionally, IAMs focused on agriculture should integrate economic, energy, AFOLU, and climate data and outputs, with a preference for indices that span multiple sectors, like the Water-Energy-Food Index, ensuring that food system interactions with energy and environmental variables are accurately captured (Simpson et. al. 2022).

To maximize the effectiveness of food IAMs, it is crucial to establish a structured approach for their use and integration. This involves defining the specific tools, data requirements, and monitoring systems necessary for accurate assessments. Such integration would benefit from a certain degree of flexibility, allowing for cross-checks on common input parameters, alignment of calculation methods, and consistency in calibration processes to ensure accuracy across models. A shared query tool that gathers unique data sets, including population trends, food demand, agricultural land prices, and energy spot prices, could further enhance food IAMs by adding critical inputs not readily available across all models. This would allow for the integration of data that go beyond macroeconomic indicators, capturing real-time trends in food markets and welfare impacts on agricultural stakeholders. The Agricultural Model Intercomparison and Improvement Project (AgMIP) has provided a unified framework for improved representation in IAMs using a multi-model approach and data standardization for downscaling or upscaling climate impacts on agriculture (Ruane et. al. 2017).

In addition, food IAMs can be adapted for project-oriented applications, allowing for analysis of smaller, localized agricultural systems or facilities. For instance, models could be downscaled to study complex farm operations, multi-purpose energy platforms integrating renewable and hydrogen sources for food production, or multi-agent agricultural facilities. IAMs adapted for such specific projects could provide granular insights using remote sensing data, assessing how individual farms or regional agricultural zones are affected by water scarcity, changing climate conditions, or shifts in local energy markets. Another valuable adaptation could be the use of input-support tools for regression analysis as used in The Integrated Future Estimator for Emissions and Diets (iFEED), identifying how factors like rainfall, fertilizer use, or crop selection correlate with yield or carbon sequestration, which would enhance model calibration and accuracy for food system (Pasquel et. al. 2023).

Tracking academic and research outputs produced using food IAMs would offer insights into their impact in the scientific community. Creating a library of publications derived from food-focused IAMs could help showcase their role in advancing knowledge, facilitating new research topics, and supporting policy decisions around food security and agricultural resilience. An archive of these studies would also enable stakeholders to review practical applications in areas such as emissions mitigation, sustainable land use, and climate adaptation, promoting the collaborative development of food IAMs across different research domains.

Scientific knowledge derived from agri-food IAMs) significantly influences policy formulation on agriculture and food systems by providing evidence-based insights and a comprehensive framework for assessing trade-offs, synergies, and long-term implications of policies. Through evidence-based mathematical and computational methods they provide decision makers with assessments of the environmental and socioeconomic impacts of national and regional policy measures, such as subsidies, greening requirements, promotion of agricultural technologies, trade agreements or rural development programs. Barreiro-Hurle et al. (2021) illustrate how the European Commission utilized the capacities of the CAPRI model to assess key policies underpinning its Common Agricultural Policy (CAP) (Barriero-Hurle et. al. 2021). Encompassing data and inputs across sectors and through the integration with economic, energy and climate models, agri-food IAMs directly map agricultural practices and food system attributes to variables that constitute policy targets for all national authorities, such as GHG emissions, energy demand, health outcomes and economic growth. Finally, since the interplay between agriculture, energy, industry, biodiversity, and water systems is at the epicentre of agri-food IAMs, they can highlight synergies and trade-offs for policymakers catering to a portfolio of targets across economic and societal sectors.

5. Conclusions

The research community has made significant advancements in developing and optimizing Integrated Assessment Models (IAMs) related to agriculture and food systems, enhancing their efficiency, and relevance for policymaking in the field of sustainable food systems. IAMs serve as indispensable tools for analyzing the intricate dynamics of agricultural production, land- and water use, biodiversity, energy demand, and climate interactions. Their potential to inform evidence-based policymaking in the realm of sustainable food systems is particularly vital as the European Union and other global stakeholders seek innovative solutions to balance food security, climate action, and resource sustainability.

IAMs focused on food systems are not standalone solutions but complementary tools, each offering unique insights into specific facets of agricultural dynamics. By leveraging synergies across models—integrating expertise from AFOLU, energy, and water domain researchers can deliver more precise and nuanced projections. In addition, integrating food IAMs in intricate modelling suites as the ones described in this opinion paper, reduces the degree of arbitrariness in assumptions and provides a holistic framework for scientific projections and policymaking. These integrated approaches enable the development of scenarios that address critical challenges, such as climate adaptation, resource constraints, and shifting dietary patterns, fostering comprehensive strategies for food system resilience.

In Section 2, we provide an overview of twelve widely applied agriculture and food IAMs, categorized based on their primary focus and specialization within the food system domain. This classification consists of four sub-groups: The Food Security, Land Use and Socio-economic Models group encompasses nine IAMs — FABLE, MAgPIE, G4M, GCAM, GLOBIOM, CAPRI, TOA-MD, IMPACT, and MAGNET) and the Hydrological and Water Resources Models Relevant to Agriculture set is illustrated with the presentation of WEAP model. The Land, Crop, and Food Production set is represented by IMAGE and the group of Food-Energy-Water Nexus Models are exemplified by SIM4NEXUS. For each model, we provide a concise description of its primary functions, computational features, required inputs, outputs, and potential synergies with other IAMs. Where available, schematic representations are included to enhance understanding of the conceptual framework of each model. Additionally, we briefly discuss the integration of food system models with IAMs from other domains, such as energy and economic systems, supported by relevant examples.

We contribute to policy formulation and the functioning of the science-policy interface by primarily assessing the 12 IAMS with respect to their attributes related to cost minimization, addressing the water, food, energy and climate nexus, their integration with other models, the breadth of coverage of economic sectors, and their degree of spatial and temporal resolution. The approach of model assessment enabled a comparative analysis of the most influential model's capabilities and limits. FABLE demonstrates a great efficiency in the description of the resource intensity capability while the product changes itself (it is differentiated with an innovative form along with a new process), as long as its Value Added (VA) and its capacity to cover a specific need change also. Other models such as MAgPIE, IMPACT 3, and TOA-MDl deploy data retrieval from maps, offering numerical analysis options with regards to climate and environmental conditions. Another important category is the models which are efficient in resource accounting, like water management and the balance between physical availability and consumption and this is a powerful feature for GCAM and WEAP and GCAM. Especially for the last one, an additional significant feature is the way to look through the nexus between energy-land use, water resources and socioeconomics key assumptions.

The models that were described and explored under thorough screening enable researchers to produce deliverables capable of achieving a bigger impact on policy making. These deliverables can be adopted by the national, international or multinational entities (i.e EU, UN) institutions and foundations. These models enable researchers to have interactive action with communities and society since they offer a capacity building potential in research methodologies and policy deliverables per sector, use and population target group, while they present the availability for downscaling policies in EU Member States.

The implications for EU agricultural and food policy are profound. With tailored IAM projections, policymakers can craft informed strategies that align with the Green Deal's sustainability goals, optimize land and resource use, and support climate-resilient food systems. Scientific evidence that build alternative trajectories for food systems in the EU and beyond are material in informing the EU Common Agricultural Policy (CAP) and the national commitments enshrined in climate mitigation and adaptation plans. By prioritizing IAM development and collaboration, the EU can lead global efforts to transition toward sustainable and equitable food systems, addressing the interconnected challenges of food security, climate change, and environmental stewardship.

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Appendix I

Additional Food IAMs short description

SWIM (Soil and Water Integrated Model)[30] [31] is an eco-hydrological, process-based, semi-distributed model developed by the Potsdam Institute for Climate Impact Research. It simulates hydrology, water management, and agriculture, often applied to river basins in Europe. SWIM has a 3-level structure (basin, subbasins, and hydrotopes) and GIS support, offering balanced complexity by integrating hydrological, vegetation, and nutrient processes more effectively than simpler models. Inputs include daily weather data, vegetation cover, crop types, land management practices, soil properties, elevation and slope information, hydrological data, and agricultural management details. Outputs include river discharge, crop yield, and nutrient levels, presented as time series and maps. SWIM has synergies with models like MAgPIE, GCAM, LPJmL, REMIND, IMAGE, and AIM.

WaterGAP[32], initially developed as a water resources model, has evolved to include agricultural demand modules, allowing it to project irrigation water use and assess its impacts on food security. In its latest version, WaterGAP v2.2d integrates data on water availability, demand, and usage across sectors such as agriculture, domestic, and industry, at both global and regional levels. It calculates annual water withdrawals for livestock, households, and small businesses, while also estimating water needs for irrigated crops, considering factors like climate, soil moisture, crop types, and irrigation efficiency. The model helps assess water stress in agricultural regions, highlighting how water shortages may affect crop yields and food security. It also evaluates the impact of agricultural water withdrawals on river flows, groundwater, and ecosystem health, distinguishing between blue water (surface and groundwater) and green water (rainwater stored in soil), which helps understand the reliance on different water sources in agriculture.

H08[33] [34] is a global hydrological model designed to simulate the relationship between food production, water requirements, and water availability, making it a valuable tool for understanding the food-water nexus. The model incorporates six sub-models, including land surface hydrology, crop growth, river routing, reservoir operation, environmental flow, and water abstraction. Recent improvements, such as

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[30] https://www.pik-potsdam.de/en/institute/departments/climate-resilience/models/swim
[31] https://www.pik-potsdam.de/~wortmann/swim/
[32] https://gmd.copernicus.org/articles/14/1037/2021/
[33] https://www.isimip.org/impactmodels/details/52/
[34] https://gmd.copernicus.org/articles/16/3275/2023/

country-specific calibration and enhanced algorithms, allow H08 to more accurately simulate crop yields for key crops like maize, rice, and soybean, though it still has limitations in capturing interannual yield variability. It provides crucial insights into the role of irrigation in global food production, helping to assess how climate change and water scarcity may impact agricultural outputs.

H08 integrates diverse input data, including climate variables, atmospheric datasets, land use data, and river routing information, to simulate water loss, soil moisture, irrigation needs, and crop yields. The model produces valuable outputs that inform water management strategies by analyzing water availability, demand, and the impact of agricultural water use on crop yields and ecosystem health. H08's ability to integrate with the models REMIND, LPJmL, MAgPIE, GCAM, DICE, IMAGE, and AIM enhances its capacity for comprehensive assessments of the food-water-energy nexus, aiding policymakers in addressing challenges related to food security, water management, and climate change.

WBM (Water Balance Model) [35] developed by the University of New Hampshire, is a global hydrologic model, used in various global assessments, simulating the land surface components of the global water cycle and including water extraction for use in agriculture and domestic sectors. The new version WBM v.1.0.0, introduces water source tracking modules that analyze flow-path histories in water supply. What is more, the model can partition sources for each stock or flux. It includes three tracking categories: a. primary water inputs to the terrestrial hydrologic cycle (liquid precipitation, snowmelt, glacier melt, and unsustainable groundwater); b. extracted water for human use that is returned to the hydrologic system; and c. runoff from user-defined land units. This tracking enhances transparency, allowing users to understand the mechanisms behind simulated behaviors. WBM v.1.0.0 effectively simulates global river discharge and irrigation withdrawals, demonstrating how these fluxes are generated using the new tracking functions. Datasets of river networks, daily precipitation, daily average temperature, dams and reservoirs, soil available water capacity, root depth, glacier runoff, volume and area, crop maps and calendars, SW:GW ratio, irrigation efficiency, rice paddy percolation rate are used. Outputs include daily river discharge, monthly river discharge, annual discharge comparison,irrigation water withdrawals, levels of moisture content in the soil, total water loss from soil and plants, detailed accounts of water inputs and outputs for specific regions, insights on how precipitation translates to runoff. This model links to SWIM, GCAM, REMIND, LPJmL, IMAGE, AIM, MAgPIE.

[35] https://gmd.copernicus.org/articles/15/7287/2022/

SWAT (Soil and Water Assessment Tool) [36] [37] [38] [39] is a comprehensive modeling tool designed to evaluate the impacts of land use and water management on both water quality and quantity, particularly in agricultural settings. It is highly effective for assessing issues like agricultural runoff, soil erosion, and crop yields at watershed scales. SWAT operates across a wide range of spatial scales, from small watersheds to large river basins, making it ideal for evaluating soil erosion control, managing nonpoint source pollution, and supporting watershed management efforts. The model simulates daily water flow cycles, nutrient loading, crop growth, and agricultural practices such as irrigation and fertilizer use. SWAT divides watersheds into subbasins and Hydrologic Response Units (HRUs), which allows for detailed, spatially explicit assessments of water resources. To function, SWAT requires a variety of input data, including weather variables (precipitation, temperature, solar radiation), land use, soil properties, and digital elevation data (DEM) to define watershed boundaries and slopes. Agricultural practices, like crop rotation, irrigation, and fertilization, further enhance the model's accuracy in simulating land management effects on water and soil. Outputs from SWAT include estimates of surface runoff, groundwater recharge, soil erosion, nutrient concentrations in water bodies, and crop yield predictions. It also provides data on water quality indicators such as dissolved oxygen and suspended solids. SWAT is compatible with other tools, enhancing its functionality and ease of use. For instance, it integrates with ArcSWAT, QSWAT, and MWSWAT, which enable users to visualize model inputs and outputs within geographic information systems (GIS). These synergies facilitate the practical application of SWAT for environmental management practices and policy evaluations, making it a valuable resource for stakeholders involved in land and water resource planning.

LPJmL (Lund-Potsdam-Jena managed Land) [40] [41] is a dynamic global model that integrates vegetation, hydrology, and crop growth to assess the interactions between water, agriculture, and carbon under changing climatic conditions. Developed by the RD1 and RD2 working groups at PIK, it simulates carbon and water cycles for both natural and agricultural ecosystems, incorporating processes like photosynthesis, plant growth, soil moisture, and hydrology. LPJmL is unique for its detailed representation of carbon, nitrogen, and water flows, including bioenergy production and land use dynamics. The model uses spatially explicit data on climate, land use, soil, and river flow, providing simulations at a global scale, from daily to annual outputs for both natural and managed landscapes. Its results include carbon storage,

[36] https://swat.tamu.edu/
[37] https://www.fao.org/land-water/land/land-governance/land-resources-planning-toolbox/category/details/en/c/1111246/
[38] https://www.climatehubs.usda.gov/hubs/international/tools/soil-and-water-assessment-tool
[39] https://swatviewer.com/
[40] https://www.pik-potsdam.de/en/institute/departments/activities/biosphere-water-modelling/lpjml
[41] https://emf.creaf.cat/external_models/lpjml/

carbon exchange, soil moisture, evapotranspiration, runoff, river flow, and crop yields, offering insights into how land use and climate change impact both ecosystems and agriculture. Additionally, LPJmL is linked to other models such as MAgPIE and IMAGE, and is integral to the POEM and PIAM frameworks.

CLM (Community Land Model) [42] [43] [44] is the land part of the CESM (Community Earth System Model) and the Community Atmosphere Model (CAM), used in both global and regional modeling systems to simulate the interactions between land, climate, and ecosystems. CLM integrates key processes such as hydrology, biogeochemistry, dynamic vegetation, and human influences, focusing on how ecosystems—both natural and managed—affect climate through energy, water, and gas cycles. It models processes like vegetation structure, photosynthesis, carbon-nitrogen cycling, land cover changes, and hydrological dynamics, providing insights into how ecosystems influence climate and respond to climate change. With recent updates improving accuracy, CLM now offers better representation of hydrological and ecological processes, including a more detailed depiction of land management practices. The model is rigorously evaluated and linked to other models like MESSAGE, IMAGE, GCAM, AIM, LandSHIFT, and COMET-AB, making it an essential tool for understanding land-atmosphere interactions and climate dynamics. Its inputs include climate data (temperature, precipitation, solar radiation, wind speed), vegetation type, soil properties, agricultural practices, and land management. Outputs include carbon storage, emissions, water fluxes (evapotranspiration, runoff, soil moisture), plant growth, energy balance, and nutrient cycling.

EPIC (Environmental Policy Integrated Climate) [45] [46] [47], developed by the USDA, is a model used to assess the environmental and economic impacts of agricultural practices on soil, water, and nutrient management. It simulates around 80 crops and evaluates their effects on soil erosion, water quality, and crop yields, integrating field-scale agricultural activities such as crop rotation, irrigation, and nutrient application. EPIC is particularly valuable for monitoring greenhouse gas fluxes, hydrology, erosion, and nutrient cycling, providing insights into sustainable land management and the impacts of climate change

[42] https://www.cesm.ucar.edu/models/clm
[43] https://agupubs.onlinelibrary.wiley.com/doi/full/10.1029/2018MS001583
[44] https://www2.cgd.ucar.edu/tss/clm/
[45] https://ndcpartnership.org/knowledge-portal/climate-toolbox/environmental-policy-integrated-climate-model-epic
[46] https://web.jrc.ec.europa.eu/policy-model-inventory/explore/models/model-epic/#model-inputs
[47] [https://www.climatehubs.usda.gov/hubs/southeast/tools/environmental-policy-integrated-climate-epic-model

on agriculture. The model's accuracy in simulating historical agricultural conditions makes it a reliable tool for forecasting future global agricultural trends. EPIC is used worldwide by institutions like IIASA and offers a user-friendly interface (WinEPIC) for practical application. The model utilizes inputs such as daily meteorological data, soil profiles, land use, and agricultural practices, and produces outputs related to biomass production, nutrient losses, crop yields, and hydrology. It tracks issues like nitrogen leaching, sediment transport, greenhouse gas emissions, and soil carbon sequestration. EPIC can be integrated with other models, including IMAGE, MAGNET, MAgPIE, GLOBIOM, and GCAM, to support comprehensive assessments of agriculture, water, and emissions, enhancing its ability to inform policy and environmental decision-making.

Other models, such as **DSSAT (Decision Support System for Agrotechnology Transfer)** and **AgMIP (Agricultural Model Intercomparison and Improvement Project)**, provide valuable tools for assessing agricultural systems under changing conditions. DSSAT models crop growth, water, and nutrient requirements for various crops, incorporating different climate, soil, and management scenarios to predict crop yields. AgMIP serves as a collaborative platform that integrates various crop models, including DSSAT and APSIM, to generate projections on climate impacts, crop yields, and water use, helping improve the accuracy and consistency of agricultural projections across diverse regions. These models are critical for understanding the agricultural dimensions of climate change and supporting informed decision-making in agricultural management.

CLEWs (Climate, Land, Energy, and Water strategies)[48] [49] [50] framework is designed to analyze interlinkages among resource systems to understand how food, energy, and water production and land use contribute to climate change, as well as how climate change, in turn, impacts these systems. The framework assesses pressure points and explores ways to reduce trade-offs while enhancing synergies, involving a robust quantification process. This approach requires the development of sector-specific models (water, energy, and land-use) that consider varying climate futures, with applications across geographical scales—from global to regional, national, and urban levels. CLEWs models offer flexibility in analytical complexity: they can use simple accounting frameworks, develop sectoral models that are soft-linked iteratively, or integrate interactions within a single modeling tool to explore key nexus questions. At the urban level, the CLEWs framework has been applied successfully in New York City to investigate water and energy interventions and examine cross-sectoral impacts of resource management. The tool is

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[48] https://sdgintegration.undp.org/climate-land-use-energy-and-water-systems-clews-models#:~:text=The%20Climate%2C%20Land%2Duse%2C,change%20may%20affect%20resource%20systems.

[49] http://www.osimosys.org/

[50] https://www.iaea.org/topics/economics/energy-economic-and-environmental-analysis/climate-land-energy-water-strategies

continually enhanced through collaboration with the United Nations Department of Economic and Social Affairs (UNDESA) and the United Nations Development Programme (UNDP), forming an essential part of the Global OpTIMUS (Open Tools, Integrated Modelling, and Upskilling for Sustainable Development) community of practice.