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Summary

The Water, Energy, Food and Ecosystems (WEFE) nexus refers to the system of complex and highly non-linear interconnections between these four elements. It now represents the basic framework to assess and design policies characterized by an holistic environmental end economical perspective. In this work, we provide a systematic review of the macroeconomic models investigating its components as well as combinations of them and their interlinkages with the economic system. We focus on four different types of macroeconomic models: Computable General Equilibrium (CGE) models, Integrated Assessment Models (IAMs), Agent-based Models (ABMs), and Dynamic Stochastic General Equilibrium (DSGE) models. On the basis of our review, we find that the structure of IAMs is currently the most used to represent the nexus complexity, while DSGE models focus only on single components but appear to be better suited to account for the randomization of exogenous shocks. CGE models and ABMs could be more effective on the side of the policy perspective. Indeed, the former can account for interlinkages across sectors and countries, while the latter can define theoretical frameworks that better approximate reality.

Keywords: Agent-based, Computable general equilibrium, Dynamic stochastic general equilibrium, Integrated assessment, Macroeconomic models, Water-energy-food-ecosystems nexus

JEL Classification: Q18, Q25, Q43, Q54, Q57

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A review of macroeconomic models for the WEFE nexus assessment

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Abstract

The Water, Energy, Food and Ecosystems (WEFE) nexus refers to the system of complex and highly non-linear interconnections between these four elements. It now represents the basic framework to assess and design policies characterized by an holistic environmental end economical perspective. In this work, we provide a systematic review of the macroeconomic models investigating its components as well as combinations of them and their interlinkages with the economic system. We focus on four different types of macroeconomic models: Computable General Equilibrium (CGE) models, Integrated Assessment Models (IAMs), Agent-based Models (ABMs), and Dynamic Stochastic General Equilibrium (DSGE) models. On the basis of our review, we find that the structure of IAMs is currently the most used to represent the nexus complexity, while DSGE models focus only on single components but appear to be better suited to account for the randomization of exogenous shocks. CGE models and ABMs could be more effective on the side of the policy perspective. Indeed, the former can account for interlinkages across sectors and countries, while the latter can define theoretical frameworks that better approximate reality.

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Abbreviations

- ABMs: Agent Based Models
- AR: Autoregressive
- AIM: Asia Pacific Integrated Model
- CES: Constant elasticity of substitution
- CGE: Computable General Equilibrium
- CLEW: Climate, Land, Energy and Water
- CSA: Climate-Smart Agriculture
- CCS: Carbon capture and geological storage
- DICE: Dynamic Integrated model of Climate and the Economy
- E: Energy
- EC: Ecosystems
- EU: European Union
- F: Food
- FUND: Climate Framework for Uncertainty, Negotiation and Distribution
- FWLE: food, water, land and ecosystems
- GCAM: Global Change Analysis Model
- GDP: Gross Domestic Product
- GERD: Grand Ethiopian Renaissance Dam
- GTAP: Global Trade Analysis Project
- GE: General Equilibrium
- GHG: Greenhouse Gasses
- IAEA: International Atomic Energy Agency
- IGSM: Integrated Global System Model
- IPCC: Intergovernmental Panel for Climate Change
- IAM: Integrated Assessment Models
- IMAGE: Integrated Model to Assess the Global Environment
- MAgPIE: Model of Agricultural Production and its Impacts on the Environment
- MESSAGE: Model for Energy Supply Strategy Alternatives and their General Environmental Impact

- MFA: Material Flow Analysis
- REMIND: Regional Model of Investment and Development
- RICE: Regional Integrated model of Climate and the Economy
- SDG: Sustainable Development Goals
- TIMES: The Integrated MARKAL-EFOM System
- VWC: Virtual Water Content
- W: Water
- WEF: Water, Energy, Food
- WEFE: Water, Energy, Food, Ecosystems

1 Introduction

By its conceptualization at the Bonn conference in 2011, the Water, Energy, and Food (WEF, hereafter) nexus refers, as the name suggests, to the system of complex interconnections between these three elements (Simpson and Jewitt, 2019; Daher and Mohtar, 2021). It analyses the non-linear relationships between natural resources in the context of social needs and economic development. Consequently, in addition to its inherent complexity, it is also strongly characterized by feedback loops and externalities due to the adaptive behavior of agents to external social and ecological pressures and environmental changes (Heckbert et al., 2010; An, 2012).

In recent years, it gained increasing attention from researchers and decision-makers due to its central position in the current context of expected climate change and population growth.[1] Moreover, the acknowledgment of the ecosystem's role as an essential structure for the WEF components and the related nexus has led to the formalization of the Water, Energy, Food and Ecosystems (WEFE) nexus.

The entwined connections of the nexus components represent a challenge for the economists involved in the modelling activity since such complexity requires the combination of economic principles with physical models.[2] Different research skills, perspectives and dedicated tools must be structured coherently to provide a correct interpretation of the general WEFE framework while also delivering effective and scalable policy recommendations. In particular, integrating and optimizing the components of the WEFE nexus into an economic model with the final aim of implementing an empirical application is not simple. Indeed, economists need to develop modelling frameworks that can resemble as much as possible the dynamics of each WEFE element while also considering their nexus.

To achieve this goal, cooperation with other sciences is crucial at both the theoretical and empirical levels. In particular, physical disaggregated models are developed to describe the framework of each WEFE component in the most effective way while also providing key inputs for economy-wide models. At the same time, different spatial dimensions are investigated and then combined in a unique interconnected system to provide information on the geographical scope of the analysis. Geographical dependencies and interrelations must be considered in the design of the spatial dimensions to provide effective quantitative and qualitative outcomes.

The importance of such models to deliver results suitable from decision-makers must be acknowledged as well. To achieve this goal, researchers must have a deep knowledge of the technical tools and empirical awareness during the conceptualization of the research question. Moreover, the effective design of model coupling represents another key aspect for the development of complex policy exercises, able to provide comprehensive insights on the nexus as a whole and also detailing specific effects or implications related to its single components.

The main purpose of this work is to provide a structured analysis of the macroeconomic models developed in the field of the WEFE nexus developed in the latest years. We aim to understand the state of the art, criticalities, opportunities and potential improvements of this research topic. To this end, we focus our attention on four different types of macroeconomic models: the Computable General Equilibrium (CGE) models, the Integrated Assessment Models (IAMs), the Agent-Based Models (ABMs) and the Dynamic Stochastic General Equilibrium (DSGE) models.

We reviewed the scientific literature by searching specific target words in the principal online research repositories (such as Scopus, Science Direct and Google Scholar, among others). We

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[1] Among others, Godfray et al. (2010) discuss the importance of analysing the WEF nexus in light of external stressors (such as population) and drivers (e.g., climate change).

[2] On this side, Sherwood et al. (2020) review this topic focusing on modelling human and non-human systems' dynamic interactions and discussing the emergence of different sub-discipline in biophysical economics.

designed the identification of the studies based on a combination of different words characterizing the WEFE nexus, plus the expression *macroeconomic models*. The collected research articles were then sorted by macroeconomic modelling type. For each class of models, we summarized their main characteristics in terms of general structure and then focus on the components and combinations of the WEFE nexus. We did so by first following the original definition of the WEF nexus and then adding the fourth dimension (e.g., the Ecosystems). A short qualitative analysis of the evolution over time of the research articles in terms of modelling types and number of publications is performed, while also considering their distribution across WEFE components and the nexus.

With this work, we contribute to the literature by complementing the existing reviews on the state of the art in the field of economic modelling for the study of the WEFE nexus, providing a detailed analysis on the side of macroeconomics in recent years.

On the side of the novelty of work, there are several studies in this field and the majority address the topics of the WEF and WEFE nexus by examining the efforts made in the economic modelling activity as a whole. Among others, McCarl et al. (2017) review the models used in the field of the WEF nexus, focusing on the related challenges and discussing the importance of accounting uncertainty. One of the most relevant outcomes of their analysis is the recognition of a need for a new entire family of models, defined as "integrated WEF nexus modelling frameworks". The literature review of de Andrade Guerra et al. (2020) analyses scientific publications in the WEF field by focusing on sustainable development while also discussing how risk and uncertainty are approached. In a specific section, they organize reviewed articles summarizing case studies in continents to provide a regional perspective. In addition to that, their review collects definitions of the most relevant concepts in the WEF nexus context, sourced from the publications included in their analysis. Endo et al. (2020) review WEF nexus articles categorizing them into five groups: comprehensive review articles, targeted review articles, synthesis articles, articles that assessed the interlinkages, trade-offs and synergies, and nexus case studies. Torres et al. (2019) design a literature review to identify systematic procedures to assist in the development of management models based on nexus thinking, which in turn is constructed on the following four steps: understanding nexus thinking, identification of composing variables, evaluation (diagnosis and prognosis), and decision-making. Albrecht et al. (2018) review 245 journal articles. Among their findings, their analysis reveals that the assessments strongly favor quantitative approaches and that many nexus methods are confined to disciplinary silos.

The novelty of our work lies in our specific focus on the macroeconomic models in the field of the WEFE nexus. Our analysis identifies four specific modelling types, which are, in our opinion, among the most representative ones, and tries to organize recent scientific publications belonging to these categories under the structure of the WEFE nexus. Our analysis focuses on 58 scientific papers, among which 13 refer to ABMs, 19 to CGE models, 10 to DSGE models, and 16 to IAMs. The observed publishing time interval ranges from 2002 to 2021. IAMs have the highest number in the field of the WEF and WEFE nexus, followed by ABMs. Most of the CGE models address the combination of two components of the WEFE nexus, while DSGE models generally focus on just one of these elements.

The paper is organized as follows: Section 2 provides a summary of the state of the art through a qualitative analysis. Section 3 presents an exhaustive review of the selected papers, dividing them into different macroeconomic model types, providing a brief description of each of these research areas and discussing their linkage with the WEFE nexus. Section 4 concludes.

2 A summary on the state of the art

In this section, we provide a brief qualitative analysis of the selected works to understand the state of the art. In our review, we selected 58 papers. Table 1 provides the list and related classification on the side of the WEFE components. In detail, we found 13 ABMs, 19 CGE models, 10 DSGE models and 16 IAMs over twenty years between 2002 and 2021 (Figure 1). Figure 2 depicts the evolution of research over time and shows a concentration of new articles for all model types starting from 2015, confirming the growing interest in the WEFE nexus and its related facets. Figures 3 and 4 summarize the distribution of models across the WEFE components, WEFE combinations and the WEFE nexus. As regards the WEFE nexus single components, hence water (W), energy (E), food (F) and ecosystems (EC) considered each on their own, the DSGE models singularly address the first three. On the other hand, ABM and CGE models mainly tackle the element of ecosystems. The highest number of WEFE combinations are analyzed by CGE and IAM models, followed by ABMs. Moving to the WEF nexus, thus excluding ecosystems, it is studied mostly by IAMs, followed by ABMs. Finally, the WEFE nexus is approached in its entirety only by the IAMs. In general, the WEFE combination studied the most is the one at WEF nexus level, carried out firstly through IAMs, then by ABM models. On the other hand, DSGE models focused mostly on only one of the single components of the nexus.

Figure 1: Number of reviewed papers, organized by model type.

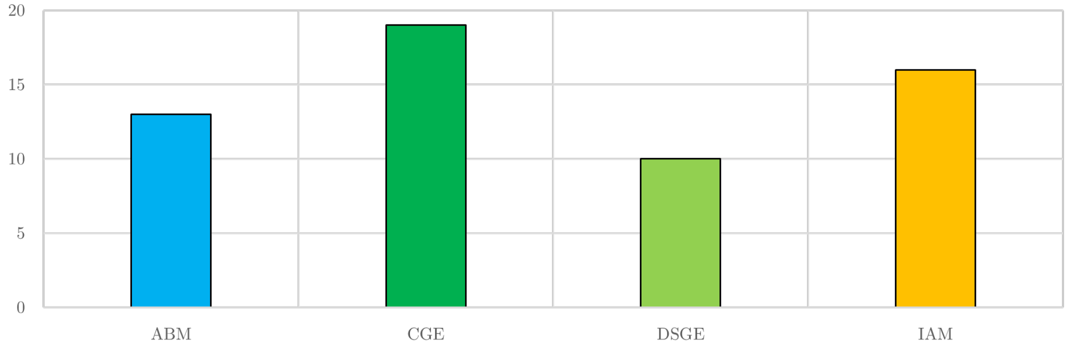


Figure 2: Overtime evolution of research articles by model type.

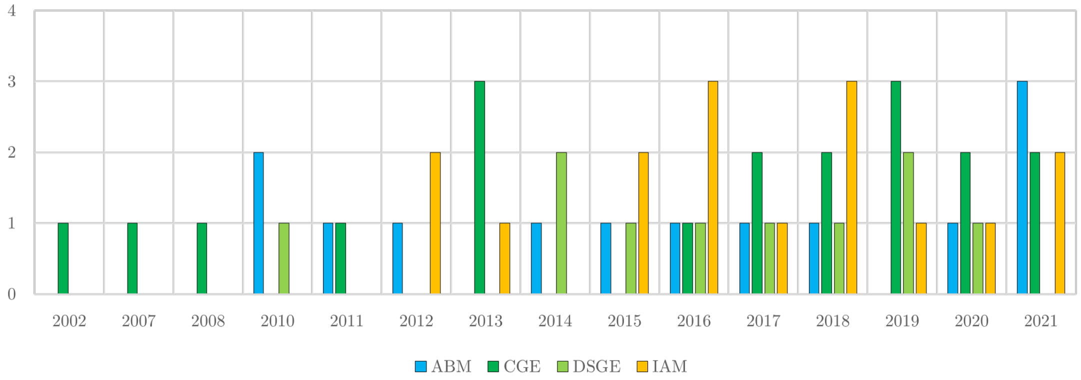


Table 1: Summary of reviewed scientific papers.

Model type	**Reference**	**W**	**E**	**F**	**EC**
ABMs	An (2012)				✓
	Balbi and Giupponi (2010)				✓
	Bazzana et al. (2021a)	✓		✓	
	Bazzana et al. (2021b)	✓	✓	✓	
	Dobbie et al. (2018)	✓		✓	
	Gebreyes et al. (2020)	✓	✓	✓	
	Heckbert et al. (2010)	✓	✓	✓	
	Li et al. (2017)	✓	✓	✓	
	Molajou et al. (2021)	✓	✓	✓	
	Schouten et al. (2014)	✓		✓	
	Smajgl et al. (2011)				✓
	Smajgl et al. (2015)				✓
	Smajgl et al. (2016)	✓		✓	
CGE models	Basheer et al. (2021)	✓	✓		
	Berrittella et al. (2007)	✓		✓	
	Birur et al. (2008)		✓	✓	
	Burniaux and Truong (2002)		✓		
	Calzadilla et al. (2011)	✓		✓	
	Dudu et al. (2018)	✓		✓	
	Kahsay et al. (2017)				✓
	Khan et al. (2020)				✓
	Nechifor and Winning (2017)	✓		✓	
	Osman et al. (2019)				✓
	Sartori et al. (2019)				✓
	Su et al. (2019)	✓	✓		
	Sun et al. (2021)	✓	✓		
	Taheripour et al. (2013a)		✓	✓	
	Taheripour et al. (2013b)	✓	✓	✓	
	Teotónio et al. (2020)	✓	✓		
	Tyner and Taheripour (2013)		✓	✓	
	Vatankhah et al. (2020)				✓
	Zhou et al. (2016)	✓	✓		
DSGE models	Blazquez et al. (2019)		✓		
	Bonsch et al. (2016)	✓	✓	✓	
	Bukowski and Kowal (2010)		✓		
	Colla-De-Robertis et al. (2019)			✓	
	Devarajan et al. (2017)		✓		
	Golosov et al. (2014)		✓		
	Li and Swain (2016)	✓			
	Permeh et al. (2017)		✓	✓	
	Punzi (2019)		✓		
	Tavakoli et al. (2020)		✓		
IAMs	Blanc et al. (2017)	✓		✓	
	Bouckaert et al. (2011)	✓	✓		
	Bonsch et al. (2016)	✓	✓	✓	
	Davies et al. (2013)	✓	✓		
	de Vos et al. (2021)	✓	✓	✓	
	Hermann et al. (2012)	✓	✓	✓	
	Kebede et al. (2021)	✓	✓	✓	✓
	Liu et al. (2015)	✓	✓		
	Miralles-Wilhelm and Muñoz-Castillo (2018)	✓	✓	✓	
	Schlör et al. (2018)	✓	✓	✓	
	Kim et al. (2016)	✓	✓	✓	
	van Vuuren et al. (2015)	✓	✓	✓	
	Veerkamp et al. (2020)	✓	✓	✓	✓
	Yang et al. (2016a)	✓	✓	✓	
	Zhang et al. (2019)	✓	✓		
	Zhou et al. (2018)	✓	✓		

Note: summary of the scientific papers reviewed, organized for macro modelling type and classified for each WEFE nexus component: water (W), energy (E), food (F) and ecosystems (EC).

Table 2: Number of selected papers organized by model type and WEFE component.

Model type	**WEFE component**				**WEFE combination**			**WEFE nexus**		
	W	E	F	EC	W+E	E+F	W+F	W+E+F	W+E+F+EC	**Total**
ABM				4			4	5		**13**
CGE		1		5	5	3	4	1		**19**
DSGE	1	7	1			1				**10**
IAM					5		1	8	2	**16**
Total	**1**	**8**	**1**	**9**	**10**	**4**	**9**	**14**	**2**	**58**

Figure 3: Number of reviewed papers by WEFE component, WEFE combination and model type.

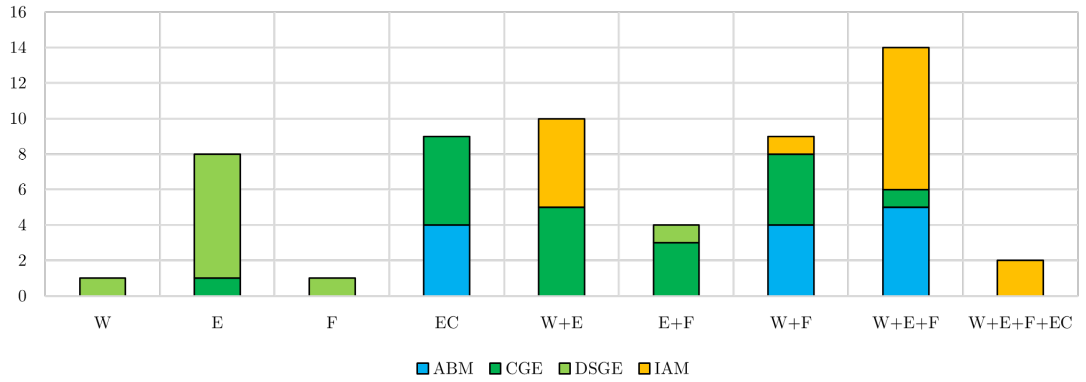
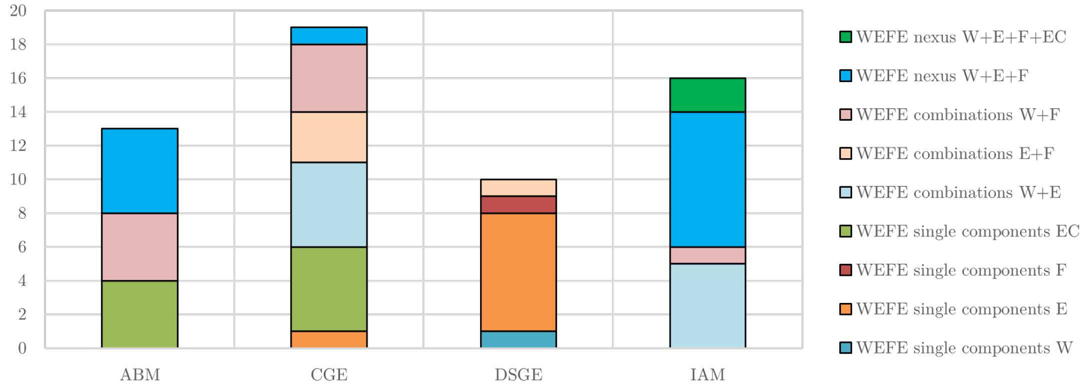


Figure 4: Number of reviewed papers by model type and WEFE component.



3 Macroeconomic models and the WEFE nexus

This section reviews the selected papers, dividing them into different categories while also providing a brief introduction for each type. It then closes by summarizing the linkages between the various methodologies and the WEFE nexus, while discussing their criticalities as well as strengths.

3.1 Computable General Equilibrium (CGE) models

Computable General Equilibrium (CGE) models are macroeconomic tools that combine economic theory with real-world data to study the impact of structural changes (e.g., factors endowment, shifts in sectoral employment, changes in productivity patterns) and exogenous shocks (e.g., financial crises, climate-related disasters) on economic systems, and test alternative policies to mitigate them.

These models represent the functioning of a real economy through a set of structural equations, which describe the optimal behavior of agents and, in turn, the endogenous dynamics of the system. Standard CGE models assume different economic agents, namely a government, private households, and businesses from various sectors, which interact in competitive markets as follows:[3]

- households purchase services and products from the business sector to maximize their utility and supply labour and capital inputs;
- firms buy inputs from the households (e.g., labour and capital) and other business (e.g., intermediate goods) to produce goods and services, which are then used either as intermediate production factors or for final consumption. They set their demand for inputs and sale prices to minimize costs and maximize profits;
- the government collects taxes from firms and households to provide them with subsidies and other transfers.

In a closed economy, these models can account for consumers' choices, firms' behaviors, the related interdependences and feedbacks. Nevertheless, this framework can also be extended to include the foreign sector, which opens the domestic economy to trade input factors, goods, and services with the rest of the world.[4]

As stated before, CGE models consist of a system of equations whose equilibrium quantities and prices are computed as the simultaneous outcome of market equilibrium in all sectors. In other words, their solution satisfies the Walrasian general equilibrium rule, which implies that supply and demand are perfectly balanced in all the interconnected markets of the economy (e.g., market clearance condition).

At the same time, CGE models incorporate real-world economic data through a calibration process. The values of the structural parameters, which remain unchanged over time, are set to reproduce the regularities observed in real economies (e.g., the share of production inputs in each sector) or by using previous empirical studies as a reference point. As a result, they allow quantifying production possibilities, welfare, different aspects of trade and consumption of the simulated economy (Arora, 2013).

Once the model is initialized with real-world data at a given base year, the system converges to a first-best equilibrium which serves as *baseline* scenario. Subsequently, when policy changes and economic shocks are introduced (e.g., the *counterfactual* scenario), the model finds a new

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[3] For a detailed specification, consider the work of Wing (2011).

[4] For a deeper look at the regionalization of CGE, please refer to Pwc Economics and Policy team (2014).

set of prices and goods/factors allocations such that a new equilibrium is reached, either considering a single point in time (e.g., static model) or over a time interval (e.g., dynamic model).[5] Lastly, both static and dynamic CGE models measure the difference between the baseline and the alternative scenario by producing key economic metrics such as GDP, income, household consumption and employment.

Among the different CGE models, the Global Trade Analysis Project (GTAP)[6] is one of the most well-known. Founded in 1992, the GTAP project encompasses a global network of researchers and policymakers that offers theoretical and analytical resources to conduct quantitative analysis on international policy issues. Starting from a multi-regional, multi-sector CGE model with perfect competition and constant returns to scale (the standard GTAP model), the network offers a wide range of extensions. For instance, as explained in detail by Corong et al. (2017), the user can decide which variables to consider as exogenous or endogenous (e.g., the closure option) in each simulation since different assumptions might be more suitable for different time horizons (e.g., fixed wage rate in short-run analyses versus fixed employment level in long-run simulations).

Another important tool provided by the GTAP community is the related database,[7] through which users can have access to an updated collection of tables on national accounts (e.g., sectorial Input-Output tables, Social Accounting Matrixes) and macroeconomic data (e.g., trade, tariffs, foreign investment, labour force, energy volumes and emissions) at the global level. Indeed, the effort in providing such consistent data have been rewarded by a frequent utilisation of the GTAP database as the main source in other applied research models, such as GLOBE (McDonald et al., 2007; Thierfelder and McDonald, 2012), a series of single country CGEs connected one to another through their trading relationships.

Under the perspective of a nexus approach, CGE models offer an important contribution in analysing input-output linkages between sectors and countries (Bardazzi and Bosello, 2021), as well as factors' allocation across economic sectors (Nechifor and Winning, 2017). Indeed, CGE models consist of a multi-sectoral and multi-factor view of the economy, in which all markets clear at the end of the simulation period (Nechifor and Winning, 2017). The effects of economic growth and changes in the population are internalized in the model by tracking and forecasting the accumulation of capital stock, the evolution of labour supply and its productivity, and the adjustment in prices required to balance markets under given resources and technological constraints (Ge et al., 2014; Zhang et al., 2019). On the demand side, such socioeconomic developments are translated into changes in the final demand of the different agents (e.g., households, government, and firms) according to their spending behavior.

3.1.1 CGE models and the WEFE nexus

WE – Water and Energy. Before going into the details on the side of our review, it is worth recalling that in 2019, the global hydropower production from water sources accounted for 6% of the primary energy mix, preceded only by fossil fuels (79%) and biomass (6.4%).[8] Furthermore, water can enter either as a direct or indirect input into energy production (e.g., as hydro power, hydroelectricity and ocean energy for the direct case, as thermoelectric power for the indirect

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[5] In the case of a dynamic CGE model with forward-looking expectations, the calibration procedure requires additional caution since the equations also contain the future values of variables. For further details on this issue, see the discussion provided by Arora (2013).

[6] For further details, please visit the original website: `https://www.gtap.agecon.purdue.edu/`.

[7] The latest version is presented online at the website: `https://www.gtap.agecon.purdue.edu/databases/v10/index.aspx`.

[8] Source: `https://ourworldindata.org/energy-mix`. The combination of coal, (natural) gas and oil forms the fossil fuels category.

case), which makes its substitutability with other factors relatively complex. As a result, most of the literature on the water-energy nexus in the field of CGE focuses on the potential future distress in energy production due to water scarcity related to climate change.

Considering the direct use of water, the water scarcity topic represents a central research focus within the water-energy nexus literature (Su et al., 2019). By including water as an input factor in all economic sectors (together with energy), Teotónio et al. (2020) develop a case study on Portugal by projecting its GDP in 2050 under different water availability scenarios as a direct consequence of climate change (e.g., the RCP 4.5 and RCP 8.5 scenarios).[9] Results for 2050 indicate that when the priority for water consumption is given to other sectors, rather than power generation (that is, when competition exists), the economic impacts are stronger when trans-boundary water competition with Spain is taken into consideration as this intensifies water scarcity in Portugal (-0.9% of real GDP vis-à-vis -0.7% of real GDP without the trans-boundary competition effect).

Looking from another perspective, Basheer et al. (2021) analyse the economic implications of water supply fluctuations by considering it as a stochastic process affecting the electricity generation from hydropower dams and the availability of water resources for both industrial and agricultural production. Focusing on a case study over the Nile Basin (e.g., Egypt, Ethiopia, and Sudan, a region where water resources are limited and highly variable), the authors estimate the economic impact induced by the construction of the Grand Ethiopian Renaissance Dam (GERD) in terms of water availability, hydroelectric generation and irrigation water capacity when the flow of the river is uncertain.

Similarly, Sun et al. (2021) argue that introducing a carbon tax can indirectly change the water footprint by improving energy use. To test this hypothesis, the authors consider the effects of such regulation on the Chinese water footprint and find that it can effectively reduce the projected value of this externality by 2030. Interestingly, despite the overall improvement in water use, the tax registers opposite impacts in different economic sectors, as primary industries show an increase in water consumption while both secondary and tertiary sectors decrease its use. Nevertheless, when considering a different measure of water use, e.g., the Virtual Water Content (VWC),[10] then all the economic sectors would benefit from the carbon tax, with a greater impact on the secondary industries.

On the side of the indirect use of water, Su et al. (2019) address still water scarcity issue by considering the impact of water management improvements on water shocks in China. By upgrading the industrial water recycling technologies and decreasing pipeline leakages by 5%, the analysis shows that such technological upgrade would increase the water use efficiency by 16% (compared to the baseline case with no improvements) and, consequently, reduce water demand for economic activities, also including energy production. Conversely, focusing on the energy sector, Zhou et al. (2016) study the effects of different tax rates on fossil fuels to promote improvements in energy production and water use, finding a sharper transition to clean energy at higher tax rates.

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[9] The Representative Concentration Pathways (RCP) scenarios are projected time series of emissions and concentrations of greenhouse gases (GHGs), aerosols and chemically active gases, as well as land use/land cover up to the year 2100. Each RCP provides one possible scenario that would lead to the specific radiative forcing stabilization level at the end of the century (e.g., 2.6, 4.5, 6.0, or 8.5 Wm^{-2}). For a detailed overview, please refer to `https://www.ipcc-data.org/guidelines/pages/glossary/glossary_r.html`.

[10] Lower VWC values correspond to less water consumed per monetary unit of a product.

WF – Water and Food. At the global level, agriculture consumes approximately 70% of all freshwater resources available worldwide,[11] whereas the overall industrial system (e.g., the sum of agriculture and the other economic sectors) absorbs 19% of total water withdrawals.[12] Hence, the need to preserve this fundamental resource motivates the development of economic models with water as a primary input, to set priorities among alternative uses (e.g., economic versus non-economic ones) and define proper water management and distribution policies, as addressed by Dudu et al. (2018). According to these authors, economic models dealing with water management still suffer from important deficits related to the peculiar characteristics of water resources in economic terms. Firstly, water is a non-market good in most countries and has, therefore, no price. Second, the linkage between macroeconomic and hydrological models still finds no extensive application in the literature.

Still in Dudu et al. (2018) water is treated as an indirect input in the production system by linking the CGE framework to a biophysical model, where water enters explicitly into the agricultural sector, affecting its total factor productivity. In other words, no specific water cycle module was combined withthe CGE model but the results of the biophysical model were used to influence the technical efficiency of agricultural production (more specifically, of the irrigated industry). Interestingly, the same framework could also be extended to the water-energy nexus by accounting for the outcoming data from the biophysical model to both agricultural and hydro-energy production functions.

On the side of treating water as a direct factor of production into a macroeconomic framework, still according to Dudu et al. (2018), it would require three concatenated elements: the (real) volumetric price of water, the income generated by water, and the distribution of this income among different economic agents (e.g., the owners of water resources, farmers, landowners, etc.). However, as stated by Bardazzi and Bosello (2021), water is often a free or, at best, under-priced resource, and defining a real price is not an easy job. Nonetheless, a criterion used to disentangle the value of water from land takes the price difference between irrigated and non-irrigated crop productions, where the difference represents the contribution of water (Bardazzi and Bosello, 2021). Examples of a direct implication of water as an input factor are given by the GTAP-W (Calzadilla et al., 2011) and the GTAP-BIO-W (Berrittella et al., 2007) models. While the former introduces water as an explicit production factor of irrigated agriculture, the latter includes water as an endowment of the economy through the concept of virtual water, namely the quantity of water embodied in each non-food consumer good.

Lastly, Nechifor and Winning (2017) carry out a study in which they explore the reverse implications of food production on water resources by considering the impact of different socio-economic development scenarios[13] on crop production and, hence, on future water distress. By introducing a global dynamic CGE model (RESCU-Water) with freshwater as an explicit factor of production, their framework distinguishes between irrigated and rainfed crop productions, thus allowing for a differentiated specification of yield improvements of the two land types. Interestingly, their results show that the efforts to mitigate global warming will not stop the increasing trend in water withdrawals at the global level by 2050. Overall, their findings highlight the need for more efficient water technologies to control crop production and determine a more sustainable use of freshwater resources in the future.

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[11] Source: `https://www.worldbank.org/en/topic/water-in-agriculture`.

[12] Reference year 2017. Source: `https://ourworldindata.org/water-use-stress`.

[13] That is, following O'Neill et al. (2014), the Shared Socioeconomic Pathways (SSPs) describe plausible alternative trends in the evolution of society and natural systems over the 21st century at the global and regional level. These trends combine pathways of future radiative forcing and the associated climate changes with alternative pathways of socioeconomic development (e.g., at different population and economic growth rates).

FE – Food and Energy. In 2019, bioenergy (e.g., biofuels) accounted for almost 1% of the global energy mix.[14] The vision of food as a potential energy source plays a predominant role in the CGE literature focusing on the food-energy linkages (Bardazzi and Bosello, 2021).

For instance, the GTAP-BIO model developed by Birur et al. (2008) explicitly accounts for biofuels as a product of the agricultural sector and consequently compete against food in the overall crop production. Indeed, by extending the work of Burniaux and Truong (2002),[15] the authors define biofuels as an energy input complementary to petroleum, which implies that both sectors participate in the production of energy. Furthermore, following the work of Lee et al. (2005), the authors integrate the GTAP-BIO database used to feed the model with an additional dataset on crop production[16] at Agro-Ecological Zone (AEZ) level[17] to account for detailed data on land. According to Birur et al. (2008), the extended database completes the biofuel module and gives accurate estimates of land-use competition between food and biofuel production.

Further extending the GTAP-BIO framework, Taheripour et al. (2013b) introduce a distinction between irrigated and rainfed crop activities at the AEZ level by exploiting the biophysical data developed by Portmann et al. (2010). Starting from a standard GTAP framework, where each industry produces only one commodity and each commodity is produced only by one industry, they move to an extended model with an agricultural multiproduct sector (i.e., the aforementioned GTAP-BIO model, following Birur et al., 2008; Taheripour et al., 2010) that produces biofuels with two different industries, one irrigated and one rainfed.

Overall, the consideration of biofuels as an energy source poses a direct follow-up question in terms of environmental impacts, such as the emissions coming from ethanol biofuels, which have been explored in the GTAP-BIO-ADV framework developed by Tyner and Taheripour (2013). Moreover, bioenergy and food also can be seen as competitors when considering land over-exploitation. Indeed, the simultaneous growth in food and bioenergy demand registered during the latest decades has put tremendous pressure on land regeneration, which can result in significant land-use change, with possible unfavourable impacts on the environment (Birur et al., 2008).

WEF – Water, Energy and Food. Following the GTAP framework, an interesting application covering the entire WEF concept as a whole is provided by Taheripour et al. (2013a), who introduce water among primary production factors in their GTAP-W-BIO model.[18] Specifically, they consider water as an explicit input into irrigated crop production while defining distinct production functions for irrigated and rainfed crops, as well as for biofuels and petroleum energy sectors (the GTAP-BIO framework in Taheripour et al., 2013a).

WEFE – Water, Energy, Food and Ecosystems. We can further extend the WEF nexus by including an additional aspect, namely the Ecosystems. Since water and crop issues are closely related to ecosystem dynamics, in the next paragraph we focus on those studies that consider the direct impact of climate change on ecosystems' characteristics, such as soil salinity (Osman

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[14] In the same year, oil registered the highest share (31%). Source: `https://ourworldindata.org/energy-mix`.

[15] The GTAP-E model, where "E" stands for Energy, provides a comprehensive definition of the energy production sector and analyses the environmental impacts of fossil fuels utilization in terms of CO2 emission (further modified by McDougall and Golub, 2009).

[16] Including data on covered land by type (e.g., forest, pastureland and cropland), harvested land, and detailed maps on forestry activity.

[17] The agro-ecological zones are defined as homogenous and contiguous areas with similar soil, land, and climate characteristics (`https://www.fao.org/nr/gaez/programme/en/`). Results are presented in a regular raster format of 5 arcminutes (about 9x9 km at the equator) grid cells. Selected maps related to AEZ classification, soil suitability, terrain slopes and land cover are provided at 30 arcseconds (0.9x0.9 km) resolution (`https://gaez.fao.org/`).

[18] That is, following the work of Berrittella et al. (2007).

et al., 2019) and erosion (Sartori et al., 2019), and the agricultural production (Kahsay et al., 2017; Khan et al., 2020; Vatankhah et al., 2020) .

So far, the literature on CGE models has been mainly devoted to the environmental effects of climate change on future GDP, agriculture productivity and private consumption. For instance, by considering both biophysical and economic modelling, Sartori et al. (2019) estimate the economic impact of soil erosion due to increasing water levels on the world economy, which accounts for an annual cost of eight billion US dollars to global GDP.

Ecosystem characteristics can also be considered in the CGE models to improve the evaluation of policies promoting food security and human health. For example, Osman et al. (2019) illustrate the importance of including water quality in the analysis of water systems and assess the impacts of investments to improve its quality in Egypt. The outcoming results underline significant potential economic benefits from addressing irrigation-water quality problems. In other words, by improving water quality, even without reducing water requirements, Egypt could experience a significant increase in the production of high-value crops such as fruits, vegetables and rice, which would also improve food security.

Moving to the effects of climate change on agricultural production, Khan et al. (2020) evaluate the long-term impact of climate-induced damages on crop production in Pakistan. The projected loss in wheat and rice production will account for more than nineteen billion dollars in Pakistan's real GDP by 2050, followed by a consequent increase in commodity prices and a decrease in private domestic consumption. Since agriculture is one of the dominant sectors of that economy, a decline in crop production due to climate change will have a multiplier effect on the entire system (e.g., from agriculture-related activities to other industries such as manufacturing and services). Vatankhah et al. (2020) find similar results in another case study of Iran, where the authors highlight an increase in production factors' prices in response to an overall production decline due to unfavourable climatic conditions.

Extending a CGE framework at the meso level, Kahsay et al. (2017) focus on the Nile River Basin and evaluate the combined effects of trade liberalization and climate change on economic growth and water resource availability in that area. Following Calzadilla et al. (2011), they examine both short and long-term effects of climate change by implementing a GTAP-W model that distinguishes between rainfed and irrigated agriculture and includes water as an input factor of irrigated lands. Their results show that although climate change will modestly improve water supply in the next decade, this increase will benefit the Nile basin countries by enhancing the agricultural production in new land endowments. Such advancements, coupled with trade liberalization, will improve the economic growth and welfare of the Nile basin region in the short term. Nevertheless, climatic effects are expected to worsen long-term water scarcity, hence water-saving policies enhancing irrigation efficiency at both country and basin levels will be of primary importance in alleviating water distress.

In conclusion, introducing the role of the Ecosystem into the WEF nexus opens a natural discussion on the connection with the food dimension, given the relevance of the former on food production and security. Furthermore, water has a consequent direct link in the discussion, as it is a natural resource and an element of the ecosystem. Accordingly, CGE models consider this connection by analysing the consequences of climate change on the biophysical characteristics of water. Lastly, concerning the energy sector, no direct connections have been found in the review. That highlights a gap in the literature on a fundamental research area dealing with the impact of unfavourable climatic conditions (e.g., floods and catastrophic events) on energy security, as well as the value of land conversion from the natural environment into an energy source (e.g., natural gas, biomass production, etc.).

3.2 Integrated Assessment Models (IAMs)

Integrated Assessment Models (IAMs) study the effect of human economic activity on natural earth systems. Specifically, this theoretical framework models economic growth dynamics considering climate change, energy and land use (Yang et al., 2016b). Since, in general, their core is the relationship between Greenhouse Gases (GHGs) emissions in climate systems and the impact of climate change on social-economic systems, they provide relevant insights on the economic policies that can mitigate or adapt to global warming. In other words, IAMs combine scientific and socio-economic aspects of climate change and assess policy options to control it (Cretì and Fontini, 2019).

Such an interdisciplinary approach is formalized analytically under specific assumptions that range from the economic environment, the economic growth and population dynamics, technological change, land use management, fossil fuel emissions, and atmosphere and oceans concentration dynamics. In other words, they juxtapose a standard economic growth framework to a climate/environmental box, internalizing the externality produced by human activities (e.g., GHGs emissions) and affects, in turn, the economic system productivity.

In this type of approach, the major distinction is between three main groups[19]: policy-optimisation models, policy-evaluation models and policy guidance models. The first type includes a strictly formal, unidimensional assessment of "better" and "worse" outcomes and uses this to select the "optimal" policy from a large number of "what-if" exercises. Conversely, the policy-evaluation models (simulation models) study the consequences of a set of specific policies in a "what-if" exercise. Lastly, policy guidance models focus on identifying those policies that can satisfy specific constraints, subjectively defined.

IAMs build scenarios prescribing targeted GHGs stabilization levels in the long-term time horizon. They evaluate the social cost of possible mitigation interventions by comparing economic activity measures (e.g., aggregate consumption) of baseline and mitigation scenarios. Specifically, the models' outputs consist of numerical simulation results, which strictly rely on the models' assumptions, the historical data used for the initial calibration and the design of the different scenarios (Yang et al., 2016a). One of the most important and, at the same time, critical outcomes of IAMs is the assessment of the optimal *Social Cost of Carbon* (SCC), representing the economic cost caused by the emission of an additional ton of carbon dioxide or its equivalent (Nordhaus, 2017). Over the years, different political and scientific institutions, from the European Union (EU) to the Intergovernmental Panel on Climate Change (IPCC), have based the design or assessment of medium and long-term policy plans on such models.

Among the most known and widely used IAMs, we can list the Dynamic Integrated model of Climate and the Economy (DICE) (Nordhaus, 1992, 1994) along with its regional version, the Regional Integrated model of Climate and the Economy (RICE) (Nordhaus and Yang, 1996), the Climate Framework for Uncertainty, Negotiation and Distribution (FUND) model[20] (Tol, 1996, 1997) and the World Induced Technical Change Hybrid (WITCH) model (Bosetti et al., 2006). Concerning high-resolution IAMs,[21] we find: the Asia Pacific Integrated Model (AIM) (Fujimori et al., 2014), the Asia-Pacific Integrated Assessment/Computable General Equilibrium (AIM/CGE) model (Fujimori et al., 2017), the Global Change Analysis Model (GCAM),[22] the Integrated Global System Model (IGSM) (Sokolov et al., 2005)[23], the Integrated Model to Assess

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[19] A detailed discussion is provided by Kebede (2016).

[20] Specific review of the publications related to the FUND model can be found at the link: `http://www.fund-model.org`.

[21] High-resolution models include the representations of energy, agricultural/land use systems, all anthropogenic sources of emissions and the climate system. They can differ in spatial resolution, degrees of detail in earth and energy systems design or economic assumptions.

[22] Applications and extensions of this model are available at the link: `http://www.globalchange.umd.edu/gcam/`.

[23] Further details are provided at the link: `https://globalchange.mit.edu/research/research-tools/`

the Global Environment (IMAGE),[24] the Model for Energy Supply Strategy Alternatives and their General Environmental Impact (MESSAGE)[25] (Schrattenholzer, 1981) and the Regional Model of Investment and Development (REMIND) (Luderer et al., 2015). Lastly, it is also worth mentioning the TIMES model[26] which provides a complete description of the energy sector and dynamics.

Even though these models are widely used because of their holistic perspective and ability to provide relevant climate-economic policy insights, they suffer from some limitations. Among others, Ackerman et al. (2009) highlight that the discount rates used for assessing climate change long-term impacts are too high, underlying that the values assigned favor short-term decisions and underestimate the relevance of intergenerational environmental issues. Concerning the latter point, Gambhir et al. (2019) review the criticisms surrounding the use of IAMs for policy-relevant recommendations on long-term mitigation pathways. Specifically, they focus on the lack of transparency in the key underlying assumptions of the models, such as energy resource costs, constraints on technology take-up and demand responses to carbon pricing.

Regarding the use of IAMs in WEF nexus, Larkin et al. (2020) raise concerns about their ability to represent the interconnections between water, energy and food. In their view, IAMs may fail to capture the scale and the rate of shifting social, geographical and political contexts that shape how innovations upscale. Nevertheless, other authors recognize IAMs as useful modelling tools for investigating the WEF nexus (McCarl et al., 2017) as well. For instance, IAMs can provide insights for analysing water scarcity and security, where different water uses are taken into account (Rising, 2020). Consequently, they can be effective ways to study the trade-off in the WEFE systems in light of water scarcity, thanks to their quantitative approach and ability to provide relevant outcomes to support decision-making. Lastly, IAMs can assist long-term investment decisions in the WEFE nexus field by quantifying related costs and benefits, even though it is fundamental to acknowledge the need for more research on integrating economic decision-making structures with biophysical models (Kling et al., 2017).

3.2.1 IAMs and the WEFE nexus

WE – Water and Energy. Water and energy policies are usually conceived separately, but energy represents an input in the water supply system, while water is used to directly obtain energy as well as being essential in the energy generation process. This case represents a good example of the need to assess the two resources through an integrated approach.

Among others, the model developed by Bouckaert et al. (2011) incorporates a water module with the global TIAM-FR energy system model, which is built on the same structure as the TIMES model. This work shows that global electricity generation may double by 2050, with an energy mix characterized by a consumption of water three times larger than the actual levels, reaching a barely sustainable scenario. Davies et al. (2013) analyse the global demands for water in electric power production over this century by incorporating water demands into a reference scenario. Using GCAM, the authors estimate the water withdrawals and consumption of the electricity sector in 14 geopolitical regions and study different related uncertainty (including technological change) with projections till 2095. Their results underline that the water with-

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`global-framework`.

[24] Model website link: `https://models.pbl.nl/image/index.php/IMAGE_framework`.

[25] Further details can be found at the link: `https://previous.iiasa.ac.at/web/home/research/researchPrograms/Energy/MESSAGE.en.html`.

[26] The TIMES (The Integrated MARKAL-EFOM System) model generator combines two different but complementary approaches to model energy: a technical engineering approach and an economic approach. It is used for "the exploration of possible energy futures based on contrasted scenarios". Additional details available at the link: `https://iea-etsap.org/docs/Documentation_for_the_TIMES_Model-Part-I_July-2016.pdf`.

drawal intensity of electric power production can be expected to decrease in the near future due to capital stock turnover in the power sector, the ongoing switch from flow cooling systems to evaporative cooling ones, and the deployment of advanced electricity generation technologies. Furthermore, the decrease in water withdrawal rates is accompanied by an increase in the consumptive use of water for cooling, as evaporative cooling systems typically have greater rates of water consumption than flow systems.

Liu et al. (2015) follows a similar approach to study the case of the US, where water withdrawal for electricity generation accounts for approximately half of total freshwater withdrawal. By applying the GCAM model to explore the electricity and water systems at the state level, they provide further insights into the WE nexus in the US. The GCAM-USA allows estimating future state-level electricity generation and consumption, and their associated water withdrawals and consumption under a set of seven scenarios with extensive detail on the generation fuel portfolio, cooling technology mix, and their associated water use intensities. The results underline that even if the scenarios project a significant expansion in electricity generation in the US, as population grows, the water withdrawals of the American electric sector will decline by 42%-91% by 2095, while water consumption will increase by 4.2%-80%. Such variations stem from various factors, mostly related to cooling technology mix, fuel portfolio, population, water-saving technology, and electricity trading options. Population change has a positive relationship with the electric sector water demand variation, especially in the South, where increasing relocation of the population is projected. Mitigation through renewable energies substantially reduces water demand, more in the East with respect to the West. Nevertheless, climate mitigation strategies focusing on CCS and nuclear power will have less favorable water consumption effects.

Zhou et al. (2018) combine the AIM/CGE framework with global hydrological models to provide consistent WE nexus analyses. The choice of the AIM/CGE structure allows them to account for different sectors (energy, waste, health and agriculture /land use) and regions (in the Asia-Pacific region) and provide environmental policies via future scenario simulation. In such a context, the authors project future thermoelectric cooling-water requirements in 17 global regions with no hydrological constraint on water availability, joint with the H08 global hydrological model.

To improve the representation of economic sub-sectors and their interactions, as well as to evaluate the synergies or co-benefits emerging from the *Resource-Energy-Water* nexus, Zhang et al. (2019) integrate the Material/Energy/Water Flow Analysis (MEWFA) into MESSAGEix. The former extends the traditional Material Flow Analysis (MFA) – which aims to quantify the flow and stocks of material or substances in a system – to the context of the WE nexus. That allows the inclusion of the material-energy-water nexus into the MESSAGEix modelling framework, developed to run different IAMs under a variety of energy systems.[27] The authors apply the methodology to the Chinese steel industry and estimate the effects of improved energy and material efficiency in this sector between 2010 and 2050. In particular, they forecast a reduction of GHG emissions (-7% of CO2 emissions) and future energy and water consumption (-7% and -8%, respectively). Nevertheless, their analysis highlights a potential negative spillover due to the resource-energy-environment nexus, which indicates a contemporaneous increase in water withdrawals[28] and PM2.5 emissions (+14% and +20%, respectively).

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[27] The general framework of the MESSAGE models allows a comprehensive assessment of the major energy challenges, the development of energy scenarios and the identification of socioeconomic and technological response strategies to these challenges. Further information can be found at the link: `https://previous.iiasa.ac.at/web/home/research/researchPrograms/Energy/MESSAGE.en.html`. Models in the MESSAGEix framework (Huppmann et al., 2019) can range from very simple to highly detailed (e.g., the MESSAGE-GLOBIOM global model). The framework can be applied to analyse scenarios of the energy system transformation under technical-engineering constraints and political-societal considerations.

[28] Water withdrawals indicate the total volume of water recovered (and partly returned) to the environment,

WF – Water and Food. The modelling of the WF nexus in IAMs is focused on the impacts of climate change on crop yields. Nevertheless, the estimation of the effects of water shortages on irrigated crop yields is still a challenge due to the complex nature of the water supply and management system.

Blanc et al. (2017) integrate a crop yield reduction module and a water resources model into the MIT Integrated Global System Modelling (IGSM) framework, which accounts for the interactions between humans and the earth system. The structure of IGSM combines the effects of the anthropogenic activities, as outcomes of the evolution of economic, demographic, trade and technological processes, e.g., GHGs emissions, air and water pollutants and land use/cover changes, with sub-models describing earth systems, thus by accounting for physical, dynamical and chemical processes in the atmosphere, land and freshwater systems, ocean and cryosphere. By adding the crop yield reduction module and a water resources model in such a structure, the authors assess the effects of climate and socioeconomic changes on water availability for irrigation in the US and the subsequent impacts on crop yields by 2050 while accounting for climate change projection uncertainty.

WEF – Water, Energy and Food. In the context of the Water-Energy-Food (WEF) nexus, one of the first analytical tools developed to analyse the interlinkages and interconnections between all the three resources, has been the CLEW (Climate, Land, Energy and Water) modelling framework, created by the International Atomic Energy Agency (IAEA).[29] This integrated assessment quantitative tool allows addressing simultaneously food, energy, and water security issues while taking into account the indirect impact of those resources on the climate and how climate change may affect the their future exploitation. Among its various applications , Hermann et al. (2012) show that a coordinated approach to increase water, energy, and food security is essential. Their case study of Burkina Faso demonstrates that agricultural policies have considerable implications for energy use, whereas energy policies are strongly interrelated with water constraints. More specifically, providing increased amounts of energy to the agriculture sector in Burkina Faso results in multiple benefits, not only in terms of improved yields but also through a reduced need for agricultural land expansion in the future. Current land expansion rates of 4% per year are not sustainable and need to be reduced. Nowadays, only about 32 ktoe, e.g., less than 0.1% of total primary energy, are used in the agricultural sector. Increasing this percentage will make way for a number of positive developments for the country without unduly compromising its overall energy balance.

Another relevant case study is the one presented in Yang et al. (2016a), investigating the WEF nexus in the Indus River of Pakistan by extending a hydro-agro-economic model with an agricultural energy use module. Their results show that the negative impacts of climate change on agricultural water and energy use can be mitigated via more flexible surface water allocation policies, which allow for larger crop and hydropower production and a reduction in energy use. Moreover, that will reallocate water consumption from groundwater to surface water at the basin level.

Bonsch et al. (2016) instead provide an analysis of the role of bioenergy in the future energy mix. Such perspective is relevant in the field of the WEF nexus since large-scale bioenergy cultivations affect land exploitation and water consumption. The complexity of such relation refers mostly to productivity. Irrigated bioenergy production provides higher yields and can reduce the pressure on land. However, irrigation water requirements may increase the degradation effects of freshwater ecosystems. Such implications are studied with the Model of Agricultural

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while water consumption is the quantity of water used and not returned to the ecosystem.

[29] Further details available at the following link: `https://www.iaea.org/topics/economics/energy-economic-and-environmental-analysis/climate-land-energy-water-strategies`.

Production and its Impacts on the Environment (MAgPIE).[30] The results indicate that producing 300 EJ/yr of bioenergy in 2095 from dedicated bioenergy crops is likely to double agricultural water withdrawals if no explicit water protection policies are implemented.

Walsh et al. (2016) examine the trade-offs associated with fuel and food production from algae through the implementation of three pathways (the co-production of commodity food products along with diesel fuel via an oil extraction and upgrading process, the thermochemical conversion of whole algal biomass to diesel fuel via hydrothermal liquefaction, and the use of the algal biomass as food). The study finds that it is possible to realize significant emissions savings and avoid land-use change by shifting a portion of global food production to a high-yield crop such as algae. However, that is insufficient to offset the potential increase in production emissions due to higher meat and dairy production. Thus the co-rendering of a fuel product is necessary to generate ongoing emissions savings.[31]

Miralles-Wilhelm and Muñoz-Castillo (2018) applied the GCAM model in the region of Latin America and the Caribbean. The authors study the case of the Paris Climate Agreement, focusing on the near and medium-term implications of the Paris pledges on the WEF nexus. Under the emissions mitigation scenario explicitly modelled to represent the Paris pledges framework, potential conflicts regarding the use of nexus resources may be exacerbated by the induced changes in the energy and food sectors that would impact water availability and use.

Kim et al. (2016) and de Vos et al. (2021) use the same modelling structure. In the first case, the authors study the scarcity of fresh water while accounting for the interactions between population, economic growth, land, energy, and water resources. In this framework, water becomes a binding factor in agriculture, energy, and land use decisions in a global IAM and has profound implications on the optimal international responses to water scarcity, particularly in the local use of land and the trade of agricultural commodities. de Vos et al. (2021) focus on quantifying the competing water demands between food production, freshwater ecosystems, and utilities (energy, industries and households). The potential impacts and trade-offs are computed for different SSP scenarios. The study estimates that an additional 1.7 billion people could potentially face severe water shortages for electricity, industries, and household consumption if priority is given to food production and environmental flows. Up to 33% of river length in the hotspots risks not meeting environmental targets when prioritizing other water demands in the nexus. Up to 41% of the local food production might be lost due to competing water demands.

Moving to the country level, Schlör et al. (2018) use an IAM to study the heterogeneity of the WEF nexus in Germany and its management through social learning and decision-making processes.

Lastly, van Vuuren et al. (2015) study the relationship between technology and Sustainable Development Goals (SDGs). In particular, they use the IMAGE model to analyse how different combinations of technological measures could contribute to achieving the SDGs. The modelling framework of IMAGE allows the investigation of large-scale and long-term interactions between human development and the natural environment while also providing strategies for global environmental changes based on the assessment of options for mitigation and adaptation. The authors design different pathways to achieve SDGs objectives[32] simultaneously, but all of them require substantial transformations in the energy and food systems while also changing the approach to progress and policies' design. For example, the decoupling of CO2 emissions from

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[30] Lotze-Campen et al. (2008) and Popp et al. (2010).

[31] Further details and supplementary information are available at the link: `https://iopscience.iop.org/article/10.1088/1748-9326/11/11/114006/meta`.

[32] The objectives can be summarized by the following categories: eradicating hunger, providing universal access to modern energy, preventing dangerous climate change, conserving biodiversity, and controlling air pollution. Notice that the partial or complete achievement of all objectives can be seen as a way to achieve optimization in the WEFE nexus.

economic growth needs to proceed at 4% to 6% a year over the next decades to meet the climate target of a 2°C maximum temperature increase by 2100. That requires a transition in the existing energy system. In agriculture, an average productivity increase of around 1% a year is necessary to provide sufficient food for everyone and limit biodiversity loss. Moreover, by 2050, around 60% of all energy would need to come from non-CO2 emitting energy sources, such as renewables, bio-energy, nuclear power, and fossil fuel combined with CO2 capture.

WEFE – Water, Energy, Food and Ecosystems. Focusing on the entire WEFE nexus, Veerkamp et al. (2020) stress its importance for the future of biodiversity and ecosystem services projections to inform decision-makers about possible options for their conservation in Europe. To do so, they use two IAMs, the IMAGE-GLOBIO[33] and the CLIMSAVE IAP (Integrated Assessment Platform)[34] under four socio-environmental scenarios. The first model allows for environmental assessments thanks to the combination of the IMAGE framework, which simulates the global environmental consequences of human activities, with GLOBIO, quantifying global human impacts on biodiversity and ecosystems. The second model explores the complex multi-sectoral issues surrounding impacts, vulnerability, and adaptation to climate and socio-economic change across Europe within the fields of agriculture, forestry, biodiversity, water, coastal and urban ones.

Similarly, Kebede et al. (2021) use the CLIMSAVE IAP to demonstrate the trade-offs and synergies across food, water, land, and ecosystems (FWLE) in the EU. Their results show that food production is likely to be the main driver of a future change in Europe's landscape. Agriculture and land-use allocation coevolve through a complex network of cross-sectoral interactions with cascading effects on other sectors such as forestry, biodiversity, and water under different projections. While sustaining the current level of food production at the European level could be achievable under most climate and socio-economic scenarios, there are significant regional differences. Among the European countries, Spain, Portugal, Southern Italy, Romania, Bulgaria. and Poland are water-stress hotspot areas due to climate change. For some scenarios, the same occurs on the side of biodiversity vulnerability for alpine areas in continental Europe, Denmark, southern Italy and France, due to the decline in arable habitats and climate suitability for some species. Conversely, countries such as Ireland, Romania, southern Finland, and alpine areas in Scandinavia can experience significant improvements.Concerning the coastal and fluvial floods, the hotspot areas are mainly concentrated in the western EU because of a projected increase in their precipitation levels. Land use diversity shows a major decline in the Mediterranean, specifically in south-east France and north-west Italy, driven by changes in the agricultural land use. Food production is declining in parts of southern and northern Europe, while the expansion of intensive agriculture in some areas leads to an increase in production in northern and western ones, making these regions key agricultural lands for maintaining Europe-wide baseline level production under various climate scenarios.

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[33] More detailed information regarding the model is available at the link: `https://www.globio.info/`.

[34] The tool is described in detail at the link: `https://climate-adapt.eea.europa.eu/metadata/tools/climsave-integrated-assessment-ia-platform`.

3.3 Agent-Based Models (ABMs)

Agent-Based Models (ABMs) depart from the representative agent assumption and focus on the complex nature of real phenomena. The simulated system is populated by a multitude of heterogeneous agents interacting autonomously with each other following adaptive behaviors (e.g., rule of thumb or learning procedures). Macro results are then obtained by aggregating individual micro transactions in decentralized local markets and then used in scenario analysis to study the endogenous response of the system to exogenous shocks (Tesfatsion, 2003).

Following Dawid and Delli Gatti (2018), we can define ABMs as "an encompassing modelling approach building on the interaction of (heterogeneous) agents whose expectation formation and decision-making processes are based on empirical and psychological insights". At the same time, Dosi and Roventini (2019) state that when the economy is conceived as a complex evolving system – that is, an ecology populated by heterogeneous agents (such as firms, workers, banks) with continuously changing interactions – it is easy to see why "the more is different". Indeed, the assumption of a micro representative agent is not sufficient to describe real-world aggregate dynamics because agents' complex interactions create, at the macro level, new phenomena as well as hierarchies. That generates a lack of isomorphism between the micro and the macro level and explains why ABMs are useful approaches to model complex economies from the bottom-up while simultaneously maintaining robust empirically-based micro-foundations.

Bazghandi (2012) summarizes the main advantages of ABMs. Firstly, they can capture emergent phenomena resulting from the interaction of individual actors. Secondly, they provide a natural description of a system composed of "behavioral" entities. Lastly, they are cost and time-saving, and flexible as well. On this side, Hammond (2015) stresses that ABMs' flexibility can help researchers in addressing the following challenges: heterogeneity, spatial structure, individual interaction, and adaptation.[35]

As in many other modelling techniques[36], the accuracy and the completeness of the inputs of ABMs influence the nature of the output. Grüne-Yanoff (2009) points out that such models tend to be good instruments for theorizing, providing potential functional explanations, but not for inferring causal explanations about the real world. Nevertheless, Leombruni and Richiardi (2005) address those critiques and provide solid reasons for rejecting the perceived lack of mathematical rigor and the difficulty of estimating ABMs. Another issue with ABMs is that they model, by definition, the dynamics of a system at the level of its agents and not at the aggregate one. Accordingly, it is straightforward to say that simulating the interactions and behavior of multiple agents in a large system can be extremely time-consuming. Finally, Windrum et al. (2007) state that, while the neoclassical community has consistently developed a core set of theoretical models and applied these to a range of research areas, the ABM community has produced a wide range of alternative models over the years. Furthermore, they are difficult to compare since they differ in terms of both the theory and the phenomena they investigate.

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[35] On this point, Hammond (2015) states that ABMs can model "individual-level adaptation [...], whether it takes the form of biological adaptation (as in an addiction process or physiological changes due to weight gain) or of behavioural adaptation (as in learning)".

[36] such as CGE models, IAMs, and DSGE models.

3.3.1 ABMs and the WEFE nexus

WF – Water and Food. ABMs have been mainly used to assess the link between water and food by considering agriculture. Dobbie et al. (2018) focus on the case of rural Malawi and employ an ABM to investigate community food security and variation among livelihood trajectories. The authors show how to integrate context-specific data within the modelling structure to fit development policies and programs addressing food security in different communities. Subsequently, they develop a model considering the multi-dimensional nature of the problem. Their findings indicate that population growth and increased rainfall variability will lead to a significant reduction in food stability by 2050, with occasional farmers suffering most of the negative effects.

At the same time, Bazzana et al. (2021a) study the impact of Climate-Smart Agriculture (CSA) on food security and analyse how social and ecological pressures – such as climate change – affect the adoption of water and soil practices in rural Ethiopia. The authors highlight that ABMs can provide a substantial advantage for future policy analyses since they allow to model the individual adaptation paths of each farmer under different scenarios. Overall, they find that CSA adopters have higher food security under climate projections, and this depends on the topology of their social network and the integration of the decentralized agricultural markets. However, CSA cannot compensate for severe climate change, and further mitigation policies are needed.

Lastly, Schouten et al. (2014) employ two complementary methods for performing sensitivity analysis under different scenarios in a spatially explicit rural agent-based simulation. The authors provide a comprehensive guide for studying the impact of agricultural policies on the socioeconomic and ecological aspects of individual farmers and farms in a rural region. Their results show that a mixed approach to sensitivity analysis leads to a better understanding of the model's behavior and improves the description of the simulation's response to changes in inputs and parameter settings. That is particularly useful for studying potential policy interventions in the ABM-simulated systems.

WEF – Water, Energy and Food. Focusing on the whole Water-Energy-Food (WEF) nexus, which depicts how natural resources are employed in the framework of economic development and social needs, we consider the domain of ecological economics that, in the words of Costanza (1989), handles the linkages between ecological and economic systems in the widest sense. Costanza (1989) stresses the importance of considering neoclassical environmental economics and ecological impact studies only as subsets of a wider topic and encourages new ways of analysing the relationship between ecological and economic systems, hence ecological economics. Indeed, as Heckbert et al. (2010) explain, ecological economics is about interconnected social and environmental spheres, and models must include the intrinsic feedback and adaptation mechanisms of these systems. Accordingly, ABMs provide a powerful tool for representing autonomous and heterogeneous entities, each with its own dynamic behaviour. The interaction between agents and the environment results in emergent outcomes at the macro level, which allow analysing complex systems in a quantitative way.

A first example of ABMs effectiveness in studying the WEF nexus emerges in Smajgl et al. (2016), who synthesize the results of the Mekong Region Simulation (Mersim) model (Smajgl and Ward, 2013). Relying on the analyses produced by a panel of experts from different disciplines, the authors develop an ABM for the Mekong region to investigate the heterogeneous response of the simulated households to a set of environmental changes. As well as finding policy-relevant system criticalities, the model reveals how interventions in single WEF sectors can create new, or change existing, cross-sectoral synergies.

Along these lines, Molajou et al. (2021) introduce a socio-hydrological ABM to investigate the impact of agricultural activities on the anthropogenic drought of Lake Urmia in Iran. The authors employ the results of interviews and previous analyses to model farmers' choices on crop type selection, energy demand, and water exploitation, including the effects of financial constraints on those decisions. Overall, their findings indicate that unfavorable economic conditions increase water-intensive crops because of their higher profits, thus reducing surface water and boosting energy consumption to exploit groundwater sources.

At the same time, Li et al. (2017) focus on Chinese urban development and WEF supply, consumption and management. In particular, the authors introduce an ABM to simulate and analyse how social interactions affect the distribution of urban WEF consumption. The model includes three types of agents: households, who can only consume WEF, firms, which demand and supply WEF, and a government, which can control the demand for WEF. In this context, the authors advocate for a central authority coordinating or limiting the demand for WEF by private agents since an uncontrolled behaviour would lead to resource shortage and hinder the sustainable development of a city.

Lastly, Gebreyes et al. (2020) and Bazzana et al. (2021b) develop ABMs to analyse the effects of land competition on WEF availability. Focusing on the case of eucalyptus plantation in Ethiopia, Bazzana et al. (2021b) explore the complex non-linear decision of land-use allocation between cash (e.g., the eucalyptus plantation) and food crops. Indeed, while eucalyptus plantations have a higher monetary value, they generate a negative externality on the surrounding fields by reducing their fertility. Accordingly, the authors investigate the highly non-linear game-theoretical problem through an ABM and assess the fundamental role played by the government in coordinating agents' actions and maximizing the overall welfare. At the same time, Gebreyes et al. (2020) study the WEF nexus via analysis of the competition between water and energy infrastructures (specifically, water canals and electric grid development). Considering environmental heterogeneity, the authors show how hydropower infrastructure construction can create land competition between rural communities and the energy sector.

WEFE – Water, Energy, Food and Ecosystems. Balbi and Giupponi (2010) make the case for an agent-based modelling approach to analyse the adaptation of socio-ecosystems to climate change. Being ABMs characterized intrinsically by an interdisciplinary approach, they are useful tool to combine social and environmental models and embed the impact of micro-level decision-making in the system dynamics. At the same time, they can simultaneously study how collective responses can emerge from policies since they can look upon adaptive behaviour and heterogeneity in the system's components.

Smajgl et al. (2011) highlight the importance of ABMs as an instrument to study socio-ecological processes since they can explicitly simulate the consequences of human decision-making processes. To fill a research gap, the authors develop a framework of methods to parametrize the behaviour of human agents. The latter was then extended in Smajgl et al. (2015) where we find a social simulation to model the complexity and the cognitive demands related to Payments for Ecosystem Services (PES),[37] which have been recently introduced in the context of the current expansion of Chinese rubber monocultures. Their findings indicate that the current PES scheme is likely to produce perverse incentives if not followed by effective monitoring and enforcement. Moreover, the burden of potential environmental success would fall entirely on rubber farmers.

Lastly, An (2012) reviews the decision models used in coupled human-environment agent-based simulations, which range from highly empirically based ones (e.g., derived through trend extrapolation, regression analysis, expert knowledge-based systems, etc.) to more mechanistic or

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[37] PES are incentives paid to economic agents (e.g., farmers) for managing their resources (e.g., land) while maintaining or providing a certain level of ecological services.

processes-based ones (e.g., econometric models, psychosocial models). The author concludes that modelling human decisions and their environmental consequences in ABMs is still a combination of science and art. He also recognizes the difficulty to compare different agent-based models, given the high variability in developing and presenting such models.

3.4 Dynamic Stochastic General Equilibrium (DSGE) models

The Dynamic Stochastic General Equilibrium (DSGE) models are macroeconomic modelling tools with solid microeconomics foundations and consistency in terms of real-world business cycle dynamics.[38] Such a mix allows economists to operate with empirical models characterized by a robust theoretical background, which makes them suitable for policy design purposes.[39] However, a mathematical closed-form solution is not available in most cases, and the outcomes of the models are obtained via numerical simulation. Nevertheless, the quick evolution of computational techniques solved such a drawback and allowed DSGE models to be considered flexible and effective tools nowadays.

The structure of DSGE models is grounded on the following assumptions: all the agents are perfectly aware of the functioning of the economic system, know the rules followed by policy-makers and expect the economy to behave the same way in the future (Bayoumi, 2018). The economic agents (households and firms) make decisions by solving an infinitely forward-looking inter-temporal optimization problem, where households maximize their utility and firms their profits, under a further set of assumptions regarding their preferences, technology, information, fiscal and monetary policies regimes (Fernández-Villaverde et al., 2016). Prices assure market clearance in all sectors and reflect the maximization process of agents' objective functions. Lastly, aggregate fluctuations depend on exogenous technological progress and unexpected changes in public policies.

Going into detail, DSGE models accounts also for uncertainty by adding a dynamic and stochastic component to the CGE framework. Such a feature is crucial for the dynamical properties of the model, not only in the short and medium term but also in the long run, since agents must internalize the effects of unexpected random shocks in their decisional process (Tonini et al., 2013). These stochastic processes are not limited to technological progress or government decisions (which are the main focus of researchers) but also extend to the structural parameters of the model, thus allowing the analysis of the dynamic consequences of any permanent or temporary perturbation of their value. However, productivity shocks are the fundamental driving forces of uncertainty in the conventional DSGE framework (Korinek, 2018).

Over the years, DSGE models have been utilized as a standard tool in various fields of economics, linking their structure to economic growth theory, labour market economics, game and contract theory, fiscal theory, monetary and capital market theory, and international trade theory (Tonini et al., 2013). Such traditional perspective changed thanks to the interest of researchers in studying the effects of different sources of uncertainty in the field of environmental and natural resources, such as the case, among others, of Bukowski and Kowal (2010). In their work, the authors incorporate two different categories of shocks: one describing the model's economic behavior and the other the effects of greenhouse gasses (GHG) abatement policies.[40]

One of the positive features of these models is their mathematical rigor, which also expose them to criticism as well (Christiano et al., 2018). Indeed, as for other economic models, some

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[38] The DSGE models rely on deep structural parameters that are invariant to changes in economic policy. Accordingly, they are not subject to Lucas' critique (Hurtado, 2014). For further details see, among others, Korinek (2018) and Bayoumi (2018).

[39] Public institutions employ DSGE models to study the transmission mechanisms of policy interventions and shocks in the field of monetary and fiscal policy, inflation, and business cycle dynamics.

[40] We will provide further discussion on specific literature in the next paragraphs.

inconsistencies and ad hoc assumptions have been at the centre of the academic debate. On this side, Korinek (2018) provides a critical evaluation of their benefits and costs by grouping them into conceptual methodological restrictions and quantitative ambitions. In the former case, the author focuses on the peculiarities of such models, namely dynamic characteristics, stochasticity, and general equilibrium properties, while the latter refers to the models' aim to describe the macroeconomy in an engineering-like fashion.

Compared to CGE models, which are only calibrated, DSGE models are both calibrated and estimated. In the former case, structural parameters are specified using commonly accepted values or chosen to allow the model to match long-run trends in real-world data. On the contrary, in the second situation, parameters are estimated on historical real-world time series, which are selected according to the chosen modelling structure.

As stated before, the impact of exogenous shocks is obtained via a simulation process. They are designed as unexpected changes in specific variables and can refer to variations in production technology (e.g., a reduction in total factor productivity), fiscal shocks (e.g., an increase in public expenditure, investments, or tax rates), or involve financial aspects such as money supply.

The stochastic shock is designed based on average statistics[41] and replicated over many simulations to produce impulse response functions, showing the reaction of the model variables to a one-time shock.[42] The effect of different policies is studied using counterfactual simulations, which allow comparing model outcomes with and without a certain event.[43] Another way to reach such a purpose is using the impulse response functions.

The capability of the DSGE models in studying the simultaneous impacts of different policies and shocks on the macroeconomy makes them a powerful instrument for the WEFE assessment. However, the use of DSGE models in such a field is yet to be developed by researchers. More in general, there are applications of these models to environmental themes and energy, while none explicitly on ecosystems' topics. The food issue is investigated by studying agriculture and fisheries. Lastly, in our review we found a unique case regarding water.

3.4.1 DSGE models and the WEFE nexus

E – Energy. DSGE models have been extensively applied in the energy field to investigate two main issues: evaluate the influence of the energy sector on the economy and understand the impact of energy consumption on climate change.

Bukowski and Kowal (2010) develop one of the first applications in this field. In their work, they design a multisector DSGE model to assess the macroeconomic impact of a diversified package of GHGs mitigation policies in the Polish economy. Focusing on the interlinks between the origin and spending of the environmental measures, they evaluate their impact not only in terms of macroeconomic variables such as GDP or employment but also on agents' welfare. Moreover, by considering different mitigation levers – ranging from investments in energy capacity (fuel switch), industry or agriculture interventions and energy or fuel efficiency improvements – they construct a macroeconomic version of marginal abatement curves. Such outcomes allow them to assess the macroeconomic impact of policies in terms of abatement potential and compare them under alternative fiscal frameworks. In particular, they study this point by analysing the model's response to two different types of shocks, which they introduce as an autoregressive (AR) process. The first group refers to shocks driving the cyclical behavior of the model, namely changes in productivity, labour supply intensity, government consumption, and foreign demand.

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[41] Namely, correlations between variables, standard deviations, autocorrelations.

[42] Such type of option is mostly used to perform qualitative analysis, thus to study the magnitude and response of the variables to certain shocks.

[43] An example could be the evaluation of the long-run performances of the model with and without a specific tax.

Conversely, the second type analyses GHGs abatement policies, encompassing increases in energy efficiency, shocks to emission intensity of production, and changes in public subsidies for energy investments.

Similarly, Golosov et al. (2014) design a DSGE model with a climate change externality stemming from the use of fossil energy. Even though their main focus is to identify the marginal damage function of emission externalities, they also find the optimal tax on fossil fuels and the first-best market (dynamical) allocation of different energy sources. In their model, future output, consumption, and the stock of CO2 in the atmosphere are stochastic since aggregate outcomes depend on the damage function, whose mapping with the climate variable is uncertain. From an analytical point of view, this translates into the definition of a specific scaling parameter, capturing the expected damage from carbon emissions and affecting agents' decisions on investments in adaptation and climate control technologies. Regarding energy, the authors consider three different sources and their respective degrees of substitutability. On this side, the model allows for studying how various sources of energy matter on future climate and consumption paths.

Focusing on the relationship between energy, emissions, and finance, Punzi (2019) provides the first example of an Environmental DSGE (E-DSGE) model. In this framework, the economy is characterized by heterogeneous production sectors, with two different types of firms and related financing sources. In particular, low-carbon emissions firms borrow funds via bank loans, while high-carbon ones use equity and credit instruments to finance their production. The government imposes environmental constraints on pollution, and high-carbon emission firms must buy production permits. In this framework, the author studies the effect of monetary, technology, and financial shocks on the economy. The most relevant outcome is that the green sector benefits most from a positive financial shock because of the easing in the borrowing conditions. In contrast, an improvement in productivity combined with a looser monetary policy does not affect green firms, which, conversely, experience losses in the long term.

The work of Blazquez et al. (2019) is an example of a DSGE model centered on energy production. Its goal is to assess the impact of specific reforms on the economy of Saudi Arabia while also considering the macroeconomic effects of energy price shocks and energy policies, such as domestic energy price reforms and the deployment of renewables. This framework shows how DSGE models can be used to study an economy which relies on a specific natural resource, both in the domestic and the foreign market, and is also a world leader in its production.[44] Four representative firms producing tradable and non-tradable final goods, electricity, and energy services characterize the economy. Furthermore, the resource sector comprehends three different energy sources: oil, gas, and renewable energy. The authors then investigate four shocks: productivity changes in tradable and non-tradable goods and production shocks to oil and natural gas prices.

Tavakoli et al. (2020) present a similar approach to assess the effects of oil shocks on economic fluctuations in an oil exporting country. In particular, they develop and estimate a DSGE model of the Iranian economy, assuming that the government acquires all the oil revenues, which depend entirely on foreign export and are subject to exogenous shocks. They then investigate two different policies to manage the financial flows coming from oil sales. On the one hand, they assume that oil revenues go directly into the government budget, which allocates them between spending and investments. In that case, oil shocks affect the economy without any control. On the other hand, oil revenues are set aside in a National Development Fund, which invests a small portion of its assets in public investments. As a result, exogenous shocks in oil prices lead to moderate fluctuations with steady recoveries, protecting the economy against abrupt changes (Tavakoli et al., 2020).

Lastly, Devarajan et al. (2017) analyse the case of a low-income country, like Niger, to derive

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[44] Saudi Arabia is the world's second-largest holder of proven oil reserves after Venezuela, with approximately 16% of the global stock (Blazquez et al., 2019).

optimal budget rules in the face of volatile revenues from natural resources. Under the assumption of autoregressive shocks affecting the price of natural resources, they suggest saving windfall revenues in a sovereign fund and using the interest income to support national consumption.

F – Food. DSGE models investigate the food component focusing on the agricultural production. Among the few available, Walker (2017) provides a unique example on this topic, developing a DSGE model for the understading of agricultural supply shocks and their amplification through financial frictions. The author considers the case of the Kenyan economy, assuming that its GDP entirely yields from the agricultural sector, with farms being the only firms, and the only input factors are labour and fertilizers. In a perfectly competitive market, they produce a single type of wholesale good, which is sold on both foreign and domestic markets. Entrepreneurs recover the financial resources for production domestically, borrowing them from households via financial intermediaries. The model incorporates aggregate risk in the form of stochastic weather conditions, allowing the design of shocks in the agricultural sector. One of the principal outcomes is that the examined supply shocks are exacerbated by the financial accelerator, which worsens the trade-off between moderating inflation and stabilizing output. In this sense, such a framework allows drawing attention to the importance of agricultural policy design effects in an increasing weather uncertain framework.

Along the same line, Colla-De-Robertis et al. (2019) focus on fisheries in the Spanish community of Galicia. They develop a counterfactual analysis of a less stringent EU policy on fisheries (Common Fisheries Policy – CFP) between 1986 and 2012. In particular, they model the regulation as a technological constraint which affects the probability of fishing instead of the days of fishing. Accordingly, they introduce the related shock as a reduction in the maximum number of days at sea. Moreover, they assume that the size of the fishery stock affects the total factor productivity of the economy and, on the biological side, this evolves according to an age-structured population. Hence, additional unexpected shocks affect the mortality rate of fishes. Lastly, after estimating the model on the Galician fleet, Colla-De-Robertis et al. (2019) find that a less stringent CFP would have increased the fishing activity and the working hours between 1986 and 2012. However, that would have reduced the sector profitability, lowering wages and the return of capital.

FE – Food and Energy. The relationship between food and energy is studied within the DSGE framework focusing on the agricultural sector. In this field, Permeh et al. (2017) develop a large multi-sector DSGE model for the Iranian economy to study the relationship between oil price and agriculture. The economy encompasses three interconnected sectors[45]: agriculture, non-agriculture, and oil, with the former two being characterized by sticky prices and the latter following a stochastic path. At the same time, two different types of households are considered: urban and rural, both of which consume agricultural and non-agricultural goods. Lastly, import and export flows enter this analysis together with subsidies on imported agricultural goods. The authors then focus on the de-agriculturalization phenomena subsequent to an increase in the oil price, the so-called Dutch disease.[46] An exogenous increase in the oil price, by boosting government revenues and central bank foreign reserves, reduces the real exchange rate. As a result, tradeable goods (such as agriculture and industry) suffer from the competition from cheaper foreign products, while non-tradeable goods (such as construction) benefit from it.

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[45] For example, agriculture employs a Constant Elasticity of Substitution (CES) production function that combines the energy of oil products with chemical fertilizer.

[46] The Dutch disease occurs when a resource boom reduces the internal incentives to produce and the international competitiveness of domestically produced non-resource tradable goods (Mien and Goujon, 2021).

Lastly, the model of Bukowski and Kowal (2010) (already included in the energy paragraph) provides further insights into the agricultural sector.[47] Given the framework structure, it represents a valuable attempt to model energy and food together – even though the focus remains on energy and climate – and the implications on the food component are investigated indirectly via considerations of the agriculture sector.

W – Water. Li and Swain (2016) represent, to the best of our knowledge, the only example of a DSGE model investigating water issues. In particular, the authors study the effects of water resilience on economic growth and welfare dynamics in South Africa. The model assumes a representative household that derives its utility from the consumption of final goods and water. At the same time, aggregate production follows a Cobb-Douglas function employing labour, physical capital and groundwater stock. The dynamics of the latter depend on: its natural recharge, the extraction rate for human consumption, and a stochastic disturbance with zero mean and constant variance, which follows an autocorrelation process over time. In addition to that, the model accounts for stochastic precipitations, affecting the groundwater recharge rate and the surface water flow. Accordingly, modelling both the surface water flow and the groundwater recharge as stochastic structures allow the authors to examine how uncertainty affects future water resilience, economic growth, and welfare.

Within this framework, the economic effects of different climate change scenarios[48] and uncertain precipitations are assessed. In particular, the assumption of distinct water uses between productive and residential sectors allows them to derive the shadow (resilience) value of surface and groundwater stock and investigate the existing trade-offs between consumption and investments, water extraction and resilience services, industrial and residential use of water. Overall, their findings indicate that capital accumulation can promote long-term development, despite the increased future water scarcity. Nevertheless, a high discount factor, reducing investments, is not sustainable in the long run. Lastly, an increase in precipitation variation negatively affects water resilience and the expected dynamic welfare.

3.5 Macroeconomic models in the WEFE nexus: strengths and weaknesses

3.5.1 Computable General Equilibrium models

Under the nexus framework, CGE models offer a reliable and simple tool to analyse the interlinkages across sectors and countries, while also providing a general overview of a macroeconomic system in which all markets reach long-term equilibrium through price and quantity adjustments. Furthermore, such a comprehensive theoretical framework is an excellent instrument for policy evaluation, given the opportunity to run separate simulations and compare different scenarios with (e.g., the policy-induced scenario) and without (e.g., the baseline scenario) policy intervention.

Nonetheless, this well-known macroeconomic framework faces several limits. For instance, the underlying neoclassical assumptions of CGE models do not allow considering agents' heterogeneity, changes in factors' allocation, or the presence of technological barriers (Alavalapati et al., 1998; Allan et al., 2007). Furthermore, the normative nature of these models does not involve, by default, the inclusion of any statistical testing or inference, thus undermining their robustness and realism in real-world terms. In addition, CGE models are also heavily dependent

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[47] Specifically, the authors describe it as "agriculture and manufacture of food products".

[48] The scenarios comprehend different discount rates and climate change effects, leading to the creation of four different cases: light/high discounting, with/without climate change.

on calibration data, meaning a lower predictive power as projections move far away from the starting point.

Nowadays, a comprehensive method including all dimensions of the WEFE nexus is still lacking in the literature, with the most extensive model being the GTAP-BIO-W one (Berrittella et al., 2007; Taheripour et al., 2013a). Despite this research gap, several attempts have been made to combine at least two WEFE aspects and link CGE to biophysical models, namely Dudu et al. (2018) and Taheripour et al. (2013b). Those works provide evidence on the alternative frameworks that can be used to complete the inclusion of all nexus dimensions. However, the extensive amount and variety of information needed to run such integrated models hamper the accomplishment of this research objective.

Overall, the simplicity and reliability of the CGE models have favoured their diffusion, making them the principal approach in the analysis of the single components of the WEFE nexus. However, their strong theoretical assumptions, the lack of a comprehensive investigation of the WEFE nexus (e.g., focused on the entire nexus rather than the single components), and the stylized calibration procedure, reduce their predictive power.

3.5.2 Integrated Assessment Models

The IAMs structure perfectly suits the intrinsic framework of the WEFE nexus. Their ability to connect different complex layers, ranging from socioeconomic to physical ones, while also assuring the possibility of developing policy scenarios, represents their main strength. As stated by McCarl et al. (2017), understanding and managing the WEF nexus require the design of new integrated modelling appraoches..

Among the limits of the IAMs, there is the difficulty to assign a proper discount rate for climate change impacts. As stated by Ackerman et al. (2009), these models usually relays on rates too high for the long-term decisions, underestimating the intergenerational environmental issues. Moreover they are subjected to incomplete information in assigning monetary values to the benefits of climate mitigation and often they are not able to reflect the nature of technical change that is socially determined and path-dependent.

Over the years, they have been extensively applied to study the relationship between climate and the economy, leading to the creation of a global scientific community. Specifically, the structure of the high-resolution IAMs, developed in different spatial resolutions and detail in earth and energy systems, can be considered the one with the highest potential in terms of WEFE nexus modelling. As shown in our qualitative analysis (Tables 1, 2 and Figure 3), IAMs rank first in both WEF and WEFE nexus fields because of their ability to integrate land dynamics and management (which, in turn, affects agriculture and food production) with energy and water issues.

On the side of the WEF nexus, the integration of the hydro-agro-economic model with specific agricultural and energy frameworks, such as the case of Yang et al. (2016a), produces outcomes that can support decision-makers to address better complex macroeconomic choices, ranging from water basin management to the design of subsidies to the bioenergy sector (see, among others, Bonsch et al. (2016) and de Vos et al. (2021)). In addition to that, the possibility of IAMs to project the impact of different climate policies on the economy allows researchers to investigate them also under the nexus perspective. At the same time, we find only two works which focus on the WEFE nexus: Veerkamp et al. (2020) and Kebede et al. (2021). The former assesses the entire nexus by combining two different IAMs, while the latter analyses the outcomes of an IAM with impact indicators representing key nexus interactions.

The need to capture long term social preferences and behaviors underline the structural limitations of this kind of macroeconomic framework, such information availability, discount rate and technological development in the long term. Nevertheless, the presence of a global scientific community, the high spatial resolution of recent models and their inherent ability to integrate land dynamics and management with energy and water issues give IAMs the highest potential in terms of WEFE nexus modelling.

3.5.3 Agent-Based Models

ABMs are simulations of the economy based on the interactions of a large number of heterogeneous agents that behave according to specified rules, and their aim is to allow for a more flexible and realistic characterization of socio-economic systems. Differently from top-down models characterized by strong assumptions (e.g., DSGE models where the system is already at equilibrium), ABMs assume heterogeneous agents interacting in decentralized markets. Accordingly, agents have limited information on other market participants and must deal with it using heuristics, adaptive expectations, or learning algorithms (Tesfatsion, 2017).[49] As Dawid and Delli Gatti (2018) state: "uncertainty is due to the sequential nature of the market economy [...] and to the ever-changing conditions of demand and supply". In this sense, ABMs provide a powerful tool for analysing the time required for real agents to internalize and adapt to an entirely new and unexpected state of the world.

Among the limitations of ABMs is that their development is extremely time-consuming, since they model the dynamics of a system at the agents and not aggregate level, simulating related interactions and behaviors in a large system Grüne-Yanoff (2009). Also, choosing the right number of parameters and behaviors themselves can be a challenge, in terms of programming as well as on the theoretical level, since including too many parameters would make the model less valuable.

Focusing on the nexus, such a framework is well suited to study and understand the role of complexity in shaping real-world phenomena. Indeed, our analysis categorized five ABMs in the field of the WEF nexus and four focusing also on the ecosystems (Tables 1 and 2). They are particularly fit for the ecosystems part since it implies, by definition, heterogeneous actors and a system of interactions and feedback among them. Making a step further and considering the WEFE nexus, ABMs are proven to be a valuable tool to model how agents behave, interact, and adapt to external pressures and changes in the environment. ABMs allow for a more flexible and realistic characterization of socio-economic systems and are particularly well suited for investigating the role of complexity and non-linearities in the WEFE nexus. However, the lack of a common theoretical framework prevents their diffusion among researchers, which use them only to investigate specific case studies rather than developing a global model. In this sense, the field is completely open to new contributions in that direction.

3.5.4 Dynamic Stochastic General Equilibrium models

DSGE models work similarly to standard IAMs. However, unlike the latter, they explicitly incorporate uncertainty about the future by introducing shocks to output, consumption, or climate damages (Farmer et al., 2015). While this is their peculiarity, it also limits them in the modelling framework size. Indeed, such a drawback reduces their policy performance, especially in the design of detailed policy analysis. Focusing on the set-up of exogenous stochastic shocks, it relies on the computation and use of average statistics obtained from different sources, which are then used in multiple simulations. Alternatively, researchers use impulse response functions to show how the model responds to those exogenous shocks. While CGE models perform better

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[49] For example, ABMs assume that firms do not have complete control over their demand functions and must decide their optimal production (or price) levels following simple or more advanced rules. As a result, there will always be a certain degree of uncertainty around whether they will be able to reach the equilibrium.

on the policy side – since they allow tracking the flows of factors of production and goods in the economy while also considering their relative prices – their main limitation is the representation of the financial sector, leading to a loss of information regarding the effects of monetary policies. On this side, DSGE models compensate for this issue while incorporating the impact of exogenous stochastic shocks.

Based on such a structure, researchers interested in modelling uncertainty in the WEF and WEFE nexus frameworks can choose between two different approaches in the general equilibrium models field. If their goal is more interdisciplinary and policy-oriented, the CGE structure represents a better tool. On the other hand, if the focus is more risk-oriented, thus aimed at understanding how an economy is affected by uncertain events, DSGE models seem to be a better solution. However, DSGE forecasts are comparable in terms of their accuracy to existing macroeconometric models for a small number of variables (Arora, 2013). In addition to that, modelling and simulating DSGE frameworks can also be technically demanding.

It is straightforward to see the lack of applications of DSGE models in the WEF and WEFE nexus that emerges from our analysis (Table 2 and Figure 3). Nevertheless, there are several examples of DSGE models focusing on the single components of the WEFE nexus, especially in the case of energy, while no articles employ multiple nexus components.[50] One possible explanation can be related to the "financial nature" of DSGE models, which are used mostly to study this dimension rather than those connected to the field of the WEF and WEFE nexus.

4 Conclusions

Understanding the WEFE nexus paradigm requires the design of studies able to analyse all its different physical layers, economic facets, and spatial scales. The effective coupling of various macroeconomic modelling frameworks plays a central role in defining policy measures capable of addressing the nexus complexities and related criticalities. This work lists some of the most relevant scientific publications in the field of macroeconomic models for the WEFE nexus, intending to provide an overview of the state of the art of the last twenty years.

On the basis of a review performed by searching specific target words in the principal online research repositories (such as Scopus, Science Direct,and Google Scholar, among others), we selected 58 papers published from 2002 to 2021. We decided to focus on four different types of macroeconomic models: Computable General Equilibrium (CGE) models, Integrated Assessment Models (IAMs), Agent-based Models (ABMs) and Dynamic Stochastic General Equilibrium (DSGE) models.

Over the reference time interval, CGE models rank first with 19 publications. At the same time, IAMs cover most of the WEF and WEFE nexus in their integrity. Conversely, DSGE models focus mainly on the energy side, even though such association heavily relates to climate change, GHGs emissions, mitigation and adaptation policies, and temperature variability. Lastly, also ABMs perform well at the WEF level, focusing in particular on ecosystems as a single component.

On the side of the WEF and WEFE nexus modelling, the structure of IAMs is the best suited to represent the nexus complexity, while DSGE models majorly focus on single components. Nevertheless, DSGE models appear to be better for the accounting of the randomization of exogenous shocks. However, much more effort has to be undertaken by those researchers interested in modelling the WEFE nexus with this kind of tool. Indeed, we find references to the WEFE complete nexus only for two components at the same time, namely water and energy, but most of the DSGE models focus on a single WEFE component.

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[50] Tables 1 provides all references duly classified for each resource component and nexus.

From a policy perspective, CGE models and ABMs seem to be the more suitable options. The most relevant strength of the firsts is their ability to incorporate the intrinsic characteristics of an economy as well as to account for interlinkages across sectors and countries. On the side of ABMs, the opportunity to model different agents' behavior allows scholars to define theoretical frameworks better approximating reality. On the other hand, the integrated approach characterizing the IAMs suits better the purpose of understanding the WEFE nexus as a whole, thanks to a well-defined combination of physical and economic structures.

To conclude, it is worth acknowledging that further research effort must be undertaken on the side of the macroeconomic modelling in the field of the WEFE nexus. We recognize that each model type considered in this review can be a relevant tool for policy purposes in this filed. Strengths, as well as weaknesses, arise at different levels of the analysis. Thus, each model has to be used carefully in its specific context. Lastly, the different perspectives should be combined to design a complete set of research outcomes, to better address future theoretical and empirical challenges in the WEFE context.

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