AWESOME

WATER-ECOSYSTEM-FOOD

LITERATURE REVIEW OF MACROECONOMIC MODELS FOR WEFE NEXUS ASSESSMENT

February, 2022

This project is part of the PRIMA Programme supported by the European Union, having received funding from it under grant agreement No 1942

PRIMA
PARTNERSHIP FOR RESEARCH AND INNOVATION IN THE MEDITERRANEAN AREA

Programme Call: PRIMA Call 2019 Section 1 Farming RIA
Project Number: 1942
Project Title: AWESOME
Partners: POLIMI (Project Coordinator), AUEB, YVC, UH, AF, RWTH, FEEM

Work-Package: WP3
Deliverable #: D3.1
Deliverable Type: Document
Contractual Date of Delivery: 28/02/2022
Actual Date of Delivery: 26/02/2022
Title of Document: Literature review of macroeconomic models for WEFE nexus assessment
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Content of this report: A review of the state of the art on the macro economic models applied in the field of the WEFE nexus

Availability: This report is public.

Document revisions		
Author	*Revision content*	*Date*
Chiara Castelli, Marta Castellini, Camilla Gusperti, Ilenia Gaia Romani, Sergio Vergalli	D3.1_v01	
Ricarda Lothmann	D3.1_v01 – QC reviewer 1	Feb. 14, 2022
Maria Cristina Rulli	D3.1_v01 – QC reviewer 2	Feb. 17, 2022
Chiara Castelli, Marta Castellini, Camilla Gusperti, Ilenia Gaia Romani, Sergio Vergalli	D3.1_v02	Feb. 22, 2022
Michele Mauri, Elena Matta	Revision	Feb. 26, 2022

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LIST OF ACRONYMS

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
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

EXECUTIVE SUMMARY

The Deliverable D3.1 consists of a review on the use of macroeconomic models in the field of the WEFE nexus, with the aim to provide an overview of the state of the art, while also studying how uncertainty and risk are approached. After a brief introduction about the main macroeconomic models used to study the WEFE nexus, a detailed list of scientific publications is provided by year, theme, main results and contribution in the form of an annex to this document.

A qualitative analysis is then performed to understand which are the most studied topics and how they are combined. The same rationale is applied at macroeconomic models' level. In addition to that, we discuss how different forms of uncertainty are considered and related risks are assessed. Conclusions focuses on future research possibilities in the macroeconomic modelling field in the field of the WEFE nexus.

In terms of contribution to the AWESOME project, this work allows to understand the novelty of the activities undertaken in the field of the WP3, "Macroeconomic models".

1. INTRODUCTION

By its conceptualization at the Bonn conference in 2011, the Water, Energy and Food nexus, (WEF nexus, hereafter) refers to the complex interconnections between water, energy and food (Daher et al., 2021 and Simpson & Jewitt, 2019). Indeed, the tight interconnectedness across water, food, and energy has gained increasing attention in research and decision-making communities becoming even more relevant in contexts of expected climate change and population growth.[1]
Specifically, the WEF nexus describes the relation of natural resources use in the context of social needs and economic development, and it is strongly characterized by feedback loops and externalities because of the adaptive behaviors of agents to external social and ecological pressures and environmental changes (Heckbert et al., 2010 and An, 2012).
The subsequent acknowledgement of the role of the ecosystems as essential structures for the WEF components, and the related nexus, has then led to the formalization of the Water, Energy, Food and Ecosystem (WEFE) nexus.
The entwined connections of the nexus components represent a challenge for those economists involved in the modelling activity. Such complexities require the combination of economic principals 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.
Integrating and optimizing the components of the WEFE nexus in line with economic theory, while also aiming at developing empirical applications, is not an easy task. Economists are required to develop modelling frameworks able to resemble as much as possible the dynamics of each WEFE element while also considering their nexus. To achieve this goal, the cooperation with other sciences is crucial at both theoretical and empirical level. Physical models and disaggregated models are developed with the aim to describe the framework of each WEFE component in the most effective way, while also providing key inputs for economy wide models.
Different spatial dimensions are investigated and then combined in an unique interconnected modelling system to provide information on the geographical scope of the analysis. Modelling choices in this field are crucial. Geographical dependences 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 for decision makers must be acknowledged as well. To achieve this goal, researchers must have a deep knowledge of the modelling tools and realistic perspectives during the conceptualization of the main research question.

[1] Among others, Godfray et al. (2010) provide a detailed discussion regarding the importance of analyzing the WEF nexus in light of external stressors (such as population) and drivers (i.e climate change).
[2] On this side, Sherwood et al. (2020) address this topic focusing on the modeling of the dynamic interactions of both human and non-human system, discussing the emergence of the sub-discipline of biophysical economics.

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 single nexus components.
Such ability can also be enriched in terms of informative quality if uncertainty[3] is taken into account. The latter can be either explicitly considered in the modelling structure or simulated thanks to the development of alternative scenarios. In both cases, its introduction in a nexus framework entails further modelling effort at different levels. Ideally, the conceptualized structure must be able to account for different types of uncertainties, ranging from those characterizing the economic and political framework, to the ones related to the physical features of the natural resources involved. The WEFE components are characterized by different forms of uncertainty in terms of availability and evolution, which also interacts due to the presence of the nexus. Accounting for these interdependences and interlinkages means delivering complex mathematical and probabilistic modelling structures.
The main purpose of this work is to provide a structured analysis of the macroeconomic models in the field of the WEFE nexus, with the aim to understand the state of the art, the related criticalities and opportunities of improvements in this field, while also focusing on how risk and uncertainty are approached in each of them. To this end, we focus our attention on four different types of macroeconomic models: the Computable General Equilibrium (CGE) models, the Integrates Assessment Models (IAMs), the Agent Based Models (ABM) and the Dynamic Stochastic General Equilibrium (DSGE) Models.
The review of the scientific literature was performed by searching specific target words in the main online research repositories (such as Scopus, Science Direct, Web of Science and Google Scholar, among others). The identification of the studies of interest was designed on the basis of a combination of different words characterizing the WEFE nexus as well as the expression "macroeconomic models". All the outcomes were then collected in an excel file (available as appendix of this document) to provide a complete database of scientific references. Each item of the database was classified according to different categories: general information (title, year, authors, doi address and journal name), main information (modelling type, key words, methodology, unit of analysis (which includes geographical scale and time horizon), thematic content (overview and main findings) and uncertainty and risk. The research articles included in the excel database were then sourced by macroeconomic modelling type. For each of the latter, we provide in this document a summary regarding the main features of the respective modelling structure. Then, a brief review of the collected publications is presented focusing on the components and combinations of the WEFE nexus. To do so, we follow first the original definition of the WEF nexus and then add the fourth dimension, i.e. the Ecosystem one, so that the whole WEFE nexus is considered. A short qualitative analysis is done

[3] Further detail regarding risk and uncertainty will be provided in a specific paragraph in Section 3.

with the aim to assess the evolution overtime of the research in terms of modelling types and number of publications, while also studying the distribution across models of the research in the field of the WEFE components and the nexus. After a brief discussion regarding the use of macroeconomic models in the WEFE nexus, a specific paragraph is also devoted on how such models approach uncertainty and risks related to the WEFE nexus and its components.

With this work we contribute to the literature by complementing already existing reviews of the state of the art in the field of the economic modelling for the study of the WEFE nexus, providing a detailed analysis regarding the macroeconomic models applied to this topic in the recent years.

There are several analyses on this field and most of them address the topics of WEF and WEFE nexus discussing efforts in the economic modelling activities. Among others, McCarl et al. (2017) reviewed models used in the field of the WEF nexus, focusing on related challenges, while also discussing the importance of accounting uncertainty. One of the most relevant outcomes of their analysis is the recognition of a need of a new entire family of models, defined as integrated WEF nexus modelling frameworks. The literature review developed by de Andrade et al. (2021) analyses scientific publications in the WEF field focusing on sustainable development, while also discussing how risk and uncertainty are approached. In a specific section, they organized reviewed articles summarizing case studies with respect to continents, to provide a regional perspective of the topic of interest. In addition to that, their review collects definitions of most relevant concepts in the WEF nexus context sourced from the publications included in their analysis. Endo et al. (2020) focused on review articles in the field of the WEF nexus, categorizing them into five groups: comprehensive review articles, targeted review articles, synthesis articles, articles that assessed the interlinkages, trade-offs and/or synergies and nexus case studies. Fernandes Torres et al. (2019) designed a literature review with the aim 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) reviewed 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 developed in the framework of the WEFE nexus. Our analysis identifies four specific modelling types, which are among the most representative in terms of modelling approaches, 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 refers 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 are the ones with the highest number in the fields of the WEF and WEFE nexus, followed by ABMs. CGE models mostly address combinations of two components of the WEFE nexus, while the DSGE models focus on considering in general only one component.

The report is organized as follows: section **Errore. L'origine riferimento non è stata trovata.** describes the literature review, section 3 analyses the performed review with a qualitative analysis to provide a clear picture of the state of art, while also discussing about criticalities, strengths, especially related to the topics of risk and uncertainty. Section 4 concludes.

2. MACRO-ECONOMIC MODELS

2.1 Computable General Equilibrium (CGE) models

Computable General Equilibrium (CGE) models are macroeconomic models that combine 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 behaviour 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 different sectors, which interact in competitive markets as follows[4]:

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

In a closed economy, these models can account for consumers' choices and firms' behaviours, as well as for the related interdependences and feedbacks. Nevertheless, this framework can also be extended to include a foreign sector, which opens the domestic economy to trade of input factors, goods, and services with the rest of the world.[5]

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 (market clearance condition).

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

[5] For a deeper overlook on the regionalization of CGE, please refer to PwC Economics (2014).

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 fed with such 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 (the *counterfactual* scenario), the model finds a new set of prices and goods/factors allocations such that a new equilibrium is reached, either considering a single point in time (i.e. static model) or over a time interval (i.e. dynamic model).[6] 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)[7] 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 multiregional, multisector 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 in Corong et al. (2017), the user can decide which variables to consider as exogenous or endogenous (i.e. 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,[8] through which users can have access to an updated collection of tables on national accounts (i.e. 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 (McDonal et al. 2006; Thierfelder, 2011), 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

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

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

[8] For which the latest version is presented online at: https://www.gtap.agecon.purdue.edu/databases/v10/index.aspx

factors' allocation across economic sectors (Nechifor and Winning, 2017). Indeed, CGE models consist of a multi-sectoral and multi-factor view of an 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 captured by tracking the accumulation of capital stock, the evolution of labour supply and its productivity, as well as the adjustment in prices required to balance markets under given resources and technological constraints (Ge et al., 2014; Zhang, 2018). On the demand side, such socioeconomic developments are translated into changes in the final demand of the different agents (i.e. households, government, and firms) according to their spending behaviour.

Furthermore, this theoretical framework allows producing clear and comprehensible results to understand the effects of policies, thanks to the explicit definition of the counterfactual scenario (Allan et al., 2007). Moreover, CGEs are mainly developed focusing on the production side of the economy and, hence, can be powerful tools to test for policy changes, which are primarily supply-side problems. However, this theoretical simplification of real economies has some drawbacks since real-world firms face several economic and technical barriers in adopting new technologies, which are not considered in the conventional CGE framework (Allan et al., 2007). These barriers include, for instance, imperfect information and transition costs, which are neglected in the optimization processes of the neoclassical framework.

Further limitations (as mentioned in Ge et al., 2014 and Bardazzi and Bosello, 2021) relate to the normativity nature of CGE. The omission of any statistical testing or inference technique and the inclusion of several model assumptions may be quite unrealistic in real-world terms. Specifically, the exogenous nature of technological change (Farmer et al., 2015), the definition of rational and homogeneous economic actors, as well as the presence of fixed prices and fixed inputs shares in the production process (Alavalapati et al., 1998) provide optimal features in terms of mathematical tractability but does not necessarily reflect reality. In addition, CGE models heavily depend on calibration data (Bardazzi and Bosello, 2021) and require a large number of initial parameters, which can lower the predictive power of the model as projections move far away from the starting point (Allan et al., 2007). Another common problem of CGEs is the treatment of economic issues at a country-yearly scale, whereas several economic phenomena often take place at a sub-national and interannual level (Shannak et al., 2018). Despite these limitations, the widespread application of CGE models in the Nexus literature relies on the fact that they offer a valuable tool to analyse inter-sectoral linkages and synergies, which are priorities of the nexus approach (Willenbockel et al., 2016).

2.1.1 CGE models and the WEFE nexus

WE – Water and Energy

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%)[9]. More generally, water can enter either as a *direct* or *indirect* input into energy production (i.e. as hydropower, hydroelectricity, and ocean energy for the direct case, as well as thermoelectric power for the indirect case), which makes its substitutability with other factors relatively complex. As a result, most of the literature on the water-energy nexus focus on the potential future distress in the production of energy emerging from water scarcity due to climate change.

Direct use of water. Water scarcity is a research focus within the water-energy nexus literature (Su et al., 2019). By including water as an input factor in all economic sectors (including energy), Teotonio et al. (2021) consider a case study on Portugal by projecting its GDP in 2050 under different water availability scenarios as a direct consequence of climate change (i.e. the RCP 4.5 and RCP 8.5 scenarios)[10]. 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 transboundary 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 transboundary competition effect).

Looking at uncertainty from another perspective, Basheer et al. (2021) analyse the economic implications of considering water supply as a stochastic process that can affect the electricity generation from hydropower dams, as well as the availability of water resources for both industrial and agricultural production. Focusing on a case study over the Nile Basin (i.e. 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 river inflow capacity is uncertain.

Similarly, Sun et al. (2021) argue that the introduction of 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 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

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

[10] The Representative Concentration Pathways (RCP) scenarios can be seen as 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 year 2100. Each RCP provides one possible scenario that would lead to the specific radiative forcing stabilization level at the end of the century (i.e. 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.

in water consumption whereas both secondary and tertiary sectors decrease its use. Nevertheless, when considering a different measure of water use, i.e. the Virtual Water Content (VWC),[11] then all the economic sectors would benefit from the carbon tax, with a greater impact on the secondary industries.

Indirect use of water. Water scarcity is also analysed as an indirect source of energy. Su et al. (2019) address this 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.

WF – Water and Food

At the global level, agriculture consumes approximately 70% of all freshwater resources available worldwide,[12] whereas the overall industrial system (i.e. the sum of agriculture and the other economic sectors) absorbs 19% of total water withdrawals.[13] 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 (i.e. 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 suffers from important deficits related to the peculiar characteristics of water resource in economic terms. Firstly, water is a non-market good in most countries, and hence it has no price. Second, the linkage between macroeconomic and hydrological models still finds no extensive application in the literature.

Indirect treating of water management. Dudu et al. (2018) introduce water as an indirect input in the production system by linking the CGE framework to a biophysical model, where water enters explicitly in the agricultural sector by affecting its total factor productivity. In other words, the authors do not include a specific water cycle module in the CGE model but use the results of the biophysical model to affect 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.

[11] Lower VWC values correspond to less water consumed per monetary unit of a product.
[12] Source: https://www.worldbank.org/en/topic/water-in-agriculture.
[13] Reference year 2017. Source: https://ourworldindata.org/water-use-stress

Direct treating of water management. According to Dudu et al. (2018), introducing water as a direct factor of production into a macroeconomic framework 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 (i.e. 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 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 goods.

Lastly, Nechifor and Winning (2017) carry on an interesting study in which they explore the reverse implications of food production on water resources by considering the impact of different socio-economic development scenarios[14] 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. Accordingly, 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.

[14] 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 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 (i.e. biofuels) accounted for almost 1% of the global energy mix[15]. The vision of food as a potential source of energy 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),[16] the authors define biofuels as an energy input complementary to petroleum, which implies that both sectors participate in the production of energy.

Furthermore, the GTAP-BIO database used to feed the model is added with an additional dataset on crop production[17] at Agro-Ecological Zone (AEZ) level[18] to account for detailed data on land (following the work of Lee et al. 2005). According to Birur et al. (2008), the extended database completes the biofuel module and gives accurate estimates on 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 AEZ level by exploiting the biophysical data developed by Portmann et al. (2010). Specifically, 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, and Taheripour et al., 2010) that produces biofuels with two different industries, one irrigated and one rainfed.

Overall, the consideration of biofuels as a source of energy 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 can also be seen as competitors when considering land overexploitation. 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).

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

[16] The GTAP-E model, where "E" stands for Energy, provides a comprehensive definition of the energy production sector and analyzes the environmental impacts of fossil fuels utilization in terms of CO_2 emission (further modified by McDougall and Golub, 2007).

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

[18] 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 arcminute (about 9 x 9 km at the equator) grid cells. Selected maps related to AEZ classification, soil suitability, terrain slopes and land cover are provided at 30 arc-second (0.9 x 0.9 km) resolution (https://gaez.fao.org/).

WEF – Water, Energy and Food

Following the GTAP framework, an interesting application covering the entire WEF concept is provided by Taheripour et al. (2013a), who introduce water among primary production factors in their GTAP-W-BIO model[19]. 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., 2013b).

The additional Ecosystems dimension

We can further extend the WEF Nexus by including an additional aspect, namely the Ecosystem. Since water and crop issues are closely related to ecosystem dynamics, we focus on studies that consider the direct impact of climate change on ecosystems' characteristics, such as soil salinity (Osman et al., 2019) and erosion (Sartori et al., 2019), and the agricultural production (Khan et al., 2020; Vatankhah et al., 2020; Kahsay et al., 2018).

So far, the literature on CGE models has mainly focused on 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 by 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 enter in 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 water 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 large 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 19 billion dollars on 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 (i.e. from agriculture-related activities to other important industries such as manufacturing and services). Vatankhah et al. (2020) find similar results in another case study on Iran, where the authors find an increase in production factors prices in response to an overall production decline due to unfavourable climatic conditions.

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

Extending a CGE model at a meso level, Kahsay et al. (2018) 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 of new land endowments able to improve the agricultural production. Such improvements, coupled with trade liberalization will enhance the economic growth and welfare of the Nile basin region in the short-term. Nevertheless, climatic effects are expected to worsen future long-term water scarcity, so that water saving policies improving irrigation efficiency at both country and basin levels will be of primary importance in alleviating water distress.

In conclusion, introducing the role of Ecosystem into the WEF nexus opens to 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, also, 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, with respect to the energy sector, no direct connections have been found in the review. This highlights a gap in the literature on fundamental research areas 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 (i.e. natural gas, biomass production etc.).

2.2 Integrated assessment models (IAMs)

Integrated assessment models (IAMs) study the effect of human economic activity on natural earth systems. These frameworks are able to model the economic growth dynamics while also accounting for climate, energy and land use (Yang et al., 2020). Since, in general, their core is the relation between greenhouse gas (GHGs) emissions in climate systems and climate change impacts on social-economic systems (Yang et al., 2020), they provide insights on economic policies able to mitigate or to adapt to global warming. In other words, IAMs combine scientific and socio-economic aspects of climate change, assessing policy options to control climate change (Cretì & Fontini, 2019).

Such interdisciplinary approach is formalized analytically under specific assumptions, ranging from: the economic environment, the economic growth and population dynamics, technological change, land use management, fossil fuel emissions and atmosphere and oceans concentrations' dynamics. In these types of approaches, the major distinction is between three main groups[20]: *policy-optimisation models*, *policy-evaluation models* and *policy guidance models*. The first type of model includes

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

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. Policy guidance models instead focus on identifying those policies able to satisfy specific constraints, subjectively defined.

In general, IAMs build scenarios prescribing targeted GHGs stabilization level in the long-term time horizon. They evaluate the social cost of possible mitigation interventions by comparing economic activity measures (e.g. macroeconomic consumption) of baseline and mitigation scenarios. Specifically, the models' numerical outputs consist of numerical simulation results, which strictly relies on the models' assumptions, the historical data use of initial calibration and the design of the different scenarios (Yang et al. 2016). One of the most important and at the same time critical outcome of IAMs (such as the DICE, RICE, FUND and PAGE models) is the assessment of the optimal "social cost of carbon", which represents 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 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) model (Nordhaus, 1992 and 1994) along with its regional version, the Regional Integrated model of Climate and the Economy (RICE) model (Nordhaus and Yang, 1996), the Climate Framework for Uncertainty, Negotiation and Distribution (FUND) model (Tol, 1996 and 1997)[21] and the World Induced Technical Change Hybrid (WITCH) model (Bosetti et al., 2006). Concerning high resolution IAMs[22], we find: the Asia Pacific Integrated Model (AIM) (Fujimori et al., 2014), the Asia-Pacific Integrated Assessment/Computable General Equilibrium (AIM/CGE) (Fujimori et al., 2017), the Global Change Analysis Model (GCAM)[23], the Integrated Global System Model (IGSM) (Sokolov et al., 2005)[24], the Integrated Model to Assess the Global Environment (IMAGE) model[25], the Model for Energy Supply Strategy Alternatives and their General Environmental

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

[22] 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.

[23] Applications and extensions of this model are available at the following link http://www.global-change.umd.edu/gcam/

[24] Further details are provided are the following link https://globalchange.mit.edu/research/research-tools/global-framework

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

Impact (MESSAGE)[26] (Schrattenholzer, 1981) and the Regional Model of Investment and Development (REMIND) model (Luderer et al., 2015). Finally, it is also worth mentioning the TIMES model[27] which provides a complete description of the energy sector and dynamics.

Even though these models are widely used thanks to their holistic perspective and their ability to provide relevant climate-economic policy insights, they show some limitations. Ackerman et al. (2009) highlight that the discount rates used for the assessment of climate change long-term impacts are too high, underlying that the values assigned favour short-term decisions underestimating the relevance of intergenerational environmental issues. Concerning the latter point, Gambhir et al. (2019) reviewed the criticisms surrounding the use of the integrated assessment model for policy-relevant recommendations on long-term mitigation pathways. Specifically, they focused 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) raised concerns in their ability to represent properly the interconnections between water, energy and food. In their view, IAMs may fail to capture the scale and rate of shifting social, geographical, and political contexts that shape how innovations upscale. On the other hand, other authors recognise IAMs as useful modelling tools for the WEF (McCarl et al., 2017). For instance, IAMs are able to provide insights for the analysis of water scarcity and water security, where different water uses are taken into account (Rising, 2020). Consequently, IAMs can be effective tools to study trade-offs in WEFE systems in light of water scarcity, thanks to their quantitative approach and ability to provide relevant outcomes to support decision-making.

More in general, 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 of more research activity on the integration of economic decision-making structures with biophysical models (Kling et al., 2017).

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

[27] The TIMES (The Integrated MARKAL-EFOM System) model generator combines two different, and complementary, approaches to modelling 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 this link: https://iea-etsap.org/docs/Documentation_for_the_TIMES_Model-Part-I_July-2016.pdf

2.2.1. IAMs in the WEFE nexus

WE – Water and Energy

Water and energy policies are usually conceived separately: 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 with a specific integrated approach. Among others, the model developed by Bouckaert et al. (2012) incorporates a water module with the global TIAM-FR prospective energy system model, which in turn is built on the same structure as the TIMES model. This work shows that globally the electricity generation may double by 2050, with an energy mix characterized by a consumption of water three times larger than the actual level, reaching a barely sustainable scenario. Davies et al. (2013) analyse global demands of water for electric power production over this century, by incorporating water demands into a reference scenario. Using GCAM, the authors were able to estimate electricity sector's water withdrawals and consumption in 14 geopolitical regions, studying different related uncertainty (including technological change) with projections till 2095. The results underline that the water withdrawal 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, as well as 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 once through flow systems.

A similar approach was then developed by Liu et al. (2015) studying the case of the USA, where water withdrawal for electricity generation accounts for approximately half the total freshwater withdrawal. By applying the GCAM model to explore the electricity and water systems at the state level, they were able to provide further insights on the WE nexus in the USA. The GCAM-USA allowed to estimate 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 the electricity generation of the USA, as population grows the water withdrawals of the American electric sector decline by 42%–91% by 2095, while water consumptions increase by 4.2%–80%. Such variations are a result of different factors, mostly related to cooling technology mix, fuel portfolio, population, water-saving technology, and electricity trading options. Population change has a positive relationship with electric sector water demand variation, especially in the South, where increasing relocation of population is projected. Mitigation through renewable energies substantially reduces water demand, more in the East respect to the West. Nevertheless, climate mitigation strategies focusing on CCS and nuclear power will have less favourable water consumption effects.

A different modelling framework was used by Zhou et al. (2018) with the aim to combine IAMs and global hydrological models and provide consistent WE nexus analyses. In this case, the authors use the framework of the Asia-Pacific Integrated Model Computable General Equilibrium Model (AIM/CGE) to project future thermoelectric cooling-water requirements, in 17 global regions with no hydrological constraint on water availability, and the H08 global hydrological model. The structure of the AIM/CGE model allows the authors to account for different sectors (energy, waste, health and agriculture /land use) and regions (in Asia-Pacific region) and provide environmental policies via future scenario simulation.
To improve the representation of subsectors and their interactions as well as to evaluate the synergies or co-benefits of resource/energy/water efficiency, climate, and air quality across sub-sectors, Zhang et al. (2019) integrate the Material/Energy/Water Flow Analysis (MEWFA) and the related nexus approach into MESSAGEix. The former structure associates the traditional Material Flow Analysis (MFA), which aims at quantifying the flow and stocks of material, in terms of demand and supply, to the context of water and energy. This allows the inclusion of the material-energy-water nexus within the MESSAGEix modelling framework, which in turn is designed to run different models, characterized by a variety of energy systems.[28] The authors' aim was to estimate potential for energy and material efficiency improvement, emission reductions of GHG and air pollutants, resource-energy-environment nexus, by introducing the process technologies to quantify the future activity of energy and water consumption, emissions GHG and air pollution and associated co-benefits and trade-offs in China's iron and steel industry during the period 2010-2050.

WF – Water and Food

The modelling via IAMs of the WF nexus was mainly focused on the impacts of climate change on crop yields. Nevertheless, the estimation of the impact of water shortages on irrigated crop yields is still a challenge, due to the need of modelling the complex water supply and management system. Blanc et al. (2017) integrated 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 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, i.e. 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

[28] 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 find a the following 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.

the atmosphere, land and freshwater systems, ocean and cryosphere. By adding the crop yield reduction module and a water resources model in such structure, the authors were able to assess the effects of climate and socioeconomic changes on water availability for irrigation in the USA, as well as subsequent impacts on crop yields by 2050, while also accounting for climate change projection uncertainty.

WEF – Water, Energy and Food

In the context of 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, developed 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 both how and extent to which we are using these resources impact our climate as well as how changes in climate may affect our prospects for harnessing these resources in the future. Among the various applications of this tool, Hermann et al. (2012) show that a coordinated approach to increase water, energy and food security is essential. Their case study of Burkina Faso showed that agricultural policies have strong implications for energy use, whereas energy policies are found to be strongly interrelated with water constraints. More specifically, providing increased amounts of energy to the agriculture sector in Burkina Faso, can result 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. Currently only about 32 ktoe, less than 0.1% of total primary energy, is used in the agricultural sector. Increasing this percentage will make way for a number of positive developments for the country, without too negatively affecting the overall energy balance of the country.

Yang et al. (2016) investigate 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 negative climate change impacts on agricultural water and energy use can be mitigated via more flexible surface water allocation policies, allowing for larger crop and hydropower production. In addition to that, the use of surface water at the basin level increases, while the opposite effect occurs for groundwater and energy use.

An analysis on the role of bioenergy in the future energy mix is provided by Bonsch et al. (2016). Such perspective is relevant in field of the WEF nexus since large-scale bioenergy cultivation have implications in terms of 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 degradation effects of

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

freshwater ecosystems. Such implications are studied with the Model of Agricultural Production and its Impacts on the Environment (MAgPIE).[30] The results emphasize that producing 300 EJ/yr of bio-energy 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 examined 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 thermo chemical conversion of whole algal biomass to diesel fuel via hydrothermal liquefaction, the use of whole algal biomass as food). The study found that by shifting a portion of global food production to a high-yield crop such as algae, significant emissions savings can be realized by avoiding land use change. However continuous, non-land use change, emissions savings are insufficient to offset potential production emissions and increased meat and dairy production. Thus the co-rendering of a fuel product is necessary to generate ongoing emissions savings[31].

Miralles-Wilhelm & Muñoz-Castillo (2018) applied the GCAM model in the region of Latin America and Caribbean. The authors study the case of the Paris Climate Agreement, specifically exploring the near-term 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.

The same modelling structure was used by Kim et al. (2016) and de Vos et al. (2021). In the first case the authors study scarcity of fresh water, while also accounting for interactions between population, economic growth, land, energy and water resources simultaneously. In this framework, water becomes a binding factor in agriculture, energy and land use decisions in integrated assessment models and implications for global responses to water scarcity, particularly in the land use decisions and trade of agricultural commodities. De Vos et al. (2021) focused on quantifying the competing water demands between food production, freshwater ecosystems and utilities (energy, industries and households). The potential impacts and trade-offs are estimated for different SSP scenarios. The study estimate that an additional 1.7 billion people could potentially face severe water shortage for electricity, industries and households, if food production and environmental flows were to be prioritized. 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.

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

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

Moving to country level, a good example is provided by Schlör et al. (2018). In their work the IAM approach is used to study the heterogeneity of the WEF nexus and to manage it in Germany through a social learning and decision-making process.

The relation between technology and sustainable development goals (SDGs) is studied in van Vuuren et al. (2015). The IMAGE model is used to analyse how different combinations of technological measures could contribute towards the achievement of the SDGs. The modelling framework of IMAGE allows to analyse 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 adaption. Different pathways were designed by the authors 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.

More specifically, decoupling of CO2 emissions from economic growth needs to take place at 4% to 6% a year, over the next decades, to meet the climate target of a 2 °C maximum temperature increase by 2100. This requires a transition in the existing energy system. In agriculture, an average productivity increase of around 1% a year would be needed to provide sufficient food for all, whereas limiting 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 finally on the entire WEFE nexus, Veerkamp et al. (2020) stressed out its importance for the future of biodiversity and ecosystem services' projections to inform decision making and policies about possible options for their conservation and sustainability in Europe. To do so, they used two IAMs, the IMAGE-GLOBIO[33] and the CLIMSAVE IAP (Integrated Assessment Platform)[34] under four socio-environmental scenarios. The first model allows environmental assessments, thanks to the combination of the IMAGE framework, which simulates the global environmental consequences of human activities, while GLOBIO quantifies global human impacts on biodiversity and ecosystems. The second model, instead, is a tool which allows to explore the complex multi-sectoral issues surrounding impacts, vulnerability and adaptation to climate and socio-economic change across Europe within the agriculture, forestry, biodiversity, water, coastal and urban sectors.

[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. The achievement of all of them or of a mix of them can be seen as way to achieve optimization of WEFE nexus.

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

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

Also, Kebede et al. (2021) use the CLIMSAVE IAP to demonstrate the trade-offs and synergies across the food, water, land and ecosystems (FWLE) in the European region. The results show that food production is likely to be the main driver of Europe's future landscape change dynamics. Agriculture and land use allocation is driven by complex cross-sectoral interactions with cascading effects on other sectors such as forestry, biodiversity, and water under the various scenarios. While sustaining current levels 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 found to be water stress hotspot areas due to climate change. Due to the decline in arable habitats and climate suitability for some species under some of the scenarios, alpine areas in continental Europe and Denmark as well as southern Italy and France are potential hotspots for biodiversity vulnerability. Countries such Ireland, Romania, southern Finland and alpine areas in Scandinavia are projected to observe a significant improvements in terms of biodiversity. Concerning the coastal and fluvial flood, the hotspot areas are concentrated particularly in western Europe, due to significant increase in precipitation. Land use diversity shows a major decline in the Mediterranean, like southeast France and northwest Italy, driven by changes in agricultural land use. The food production is declining in parts of southern and northern Europe, while the expansion of intensive agriculture in some areas leads to an increase of production in northern and western Europe, making these regions key agricultural lands for maintaining Europe-wide baseline level production under various climate scenarios.

2.3 Agent Based Models (ABMs)

Agent-Based Models (ABMs) depart from the representative agent assumption and focus instead on the complex nature of real phenomena. In these models, the simulated system is populated by a multitude of heterogeneous agents that interact autonomously with each other following adaptive behaviours (e.g. rule of thumb or learning procedures). Macro results are then obtained by aggregating individual micro transactions in decentralized local markets and are used in scenario analysis to study the endogenous response of the system to exogenous shocks (Tesfatsion, 2003).
Following Dawid and Delli Gatti (2018), ABMs are “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 "behavioural" 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 us with 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 the behaviour 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 both in terms of the theory and the phenomena they investigate.

2.3.1. ABMs and the WEFE nexus

WF - Water Food

Moving along the WEF dimensions, ABMs have been mainly used to assess the link between water and food, 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 in an ABM to fit development policies and programs addressing food security in different communities. Subsequently, they develop a model considering the multi-dimensional na-

[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 CGEs, IAMs, and DSGEs.

ture of the problem. Their findings indicate that population growth and increased variability in rainfalls 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) propose an ABM to 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 of sensitivity analysis leads to a better understanding of the agent based model's behaviour and improves the description of the simulation's response to changes in inputs and parameter settings. This is particularly useful for studying potential policy interventions in the ABM-simulated systems. The authors conclude stressing the importance of developing methods for sensitivity analysis for agent based models, not only from a scientific point of view but also in term of support to policy makers.

WEF - Water Energy 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 which, 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 encourage new ways of analysing the relationship between ecological and economic systems, hence ecological economics. As Heckbert et al. (2010) explain, in fact, ecological economics is about interconnected social and environmental spheres, and models must include the intrinsic feedbacks 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 hence 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 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 unfavourable 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. By modelling the complex interactions between these agents, the author advocate for a central authority coordinating or limiting the demand for WEF by private agents since an uncontrolled behaviour would lead to resources shortage and hinder the sustainable development of a city.

Lastly, Gebreyes et al. (2020) and Bazzana et al. (2021b) develop a series of 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 (i.e. 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 an agent-based 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 the rural communities and the energy sector.

The additional Ecosystems dimension

As previously stated, this literature review has decided to approach the traditional Water-Energy Food nexus while also adding a fourth dimension, namely the ecosystem. From the point of view of ABMs, several works have been developed focusing on this dimension.

Balbi and Giupponi (2010) make the case for agent-based modelling approach to analyse the adaptation of socio-ecosystems to climate change. This clearly calls for an integrated approach which can consider environmental, economic, and social dimensions. According to the authors, agent-based modelling, being an interdisciplinary approach, is a 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 certain 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. With the intention of filling a research gap, the authors develop a framework of methods to parametrize the behaviour of human agents.

Following the proposed framework, Smajgl et al. (2015) use an agent-based 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 a potential environmental success would fall entirely on rubber farmers.

Lastly, An (2012) carried out a review of 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 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 carry out a comparison of different agent-based models, given the high variability in developing and presenting such models.

[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.

2.4 Dynamic Stochastic General Equilibrium (DSGE) Models

In the field of the general equilibrium (GE) models we find two different categories. CGE models, which are the larger representations of this group and widely used for policy analysis. The second are the Dynamic Stochastic General Equilibrium (DSGE) models, which, respect to the former, are more employed in research activities.

Dynamic stochastic general equilibrium models are macroeconomics' tools characterized by strong microeconomics foundations and consistency in terms of business cycles dynamics.[38] Such mix allows economists to operate with empirical models characterized by good theoretical background and suitable for policy design purposes.[39]. On the other hand, a mathematical closed form solution is not found in most part of the cases, thus outcomes of the models are mostly obtained via numerical methods. Such drawback is overcome by the quick evolution of computational techniques, which have allowed the DSGE models to be considered nowadays flexible and effective tools.

The modelling structure of the DSGE grounds on the following perspective: all agents considered in the model are perfectly aware on how the economy works and know the rules that the policymakers follow. Furthermore, the economy is expected to behave in the same manner in the future (Bayoumi, 2018). In detail, the economic agents (households and firms) undertake decisions by solving infinitely forward-looking intertemporal optimization problems (where households maximize their utility and firms their profits), under assumptions related to preferences, technology, information and fiscal and policies regimes (Fernández-Villaverde et al., 2016). The economic equilibrium is reached defining levels in prices assuring the maximization of the agents' respective objective functions. GDP fluctuations depends on technological progress as well as policies.

Uncertainty is introduced adding a dynamic and stochastic component to the CGE framework. Such feature is crucial for the dynamic properties of the model, not only in the short and medium, but also in the long run, and also allows the accounting of random shocks (Tonini et al., 2013). Any parameter of the model can be shocked. This allows the analysis of dynamic consequences of any permanent or temporary disturbance. In general, researchers are interested in studying uncertainty related to technological progress and/or government's decisions. In conventional DSGE approach, the fundamental driving force of uncertainty are productivity shocks (Korinek 2018).

Over the years DSGE models have been utilized as a standard tool in various fields of economics, linking into their structure the economic growth theory, labour market economics, game and contract theory, fiscal theory, monetary and capital market theory and international trade theory (To-

[38] The DSGE models structure is characterized by deep parameters that should be invariant to changes in economic policy, so in principle they are not subject to the *Lucas critique* (Hurtado 2014). For further details see, among others, Korinek (2018) and Bayoumi (2018).

[39]DSGE models are mostly used by public institutions to study the transmission mechanisms of policy interventions and of shocks, specifically in the fields of monetary and fiscal policy, inflation and the business cycle assessment.

nini et al., 2013). Such traditional perspective changed thanks to the interest of researchers in studying the effects of different sources of uncertainties in the fields of the environment and natural resources, such as the case, among others, of Bukowski & Kowal (2010). In their work, the authors incorporated two different categories of shocks, one describing model's cyclical behavior and the other greenhouse gasses (GHG) abatement policies.[40]

One of the positive features of this type of models is their transparency. Their clear mathematical and empirical structure is of course a virtue, but also exposes them to criticism (Christiano et al., 2018). As for the other economic models, some 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 refers to the peculiarities of such models, thus dynamics, stochasticity and general equilibrium, while in the latter writes about the models' aim to describe the macroeconomy in an engineering-like fashion.

Respect to CGE models, which are only calibrated, DSGE models are calibrated and estimated. They are specified using commonly accepted values, or chosen to allow the model matching the long-run averages in the data. In the case of estimation, parameters are identified as outcomes of the estimation performed on sample of historical data consistent with the modelling structure.

The impact of exogenous shocks is obtained via simulation process. They are designed as unexpected change in specific variables. They can indeed refer to technological change in production process (thus, focusing on total factor productivity), fiscal shocks, thus affecting on tax rates, or involve financial aspects such as money supply.

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

The capability of DSGE of 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 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. Food issue is investigated studying agriculture and fisheries. There is a unique case regarding water.

[40] Further discussion on specific literature will be provided in the next paragraphs.
[41] 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

2.4.1. DSGE models and the WEFE nexus

Energy

DSGE models have been applied in the energy field mostly related to two main issues: understanding the role of energy sector on the economy and the impact of energy consumption on climate change. One of the first applications in this field has been developed by Bukowski & Kowal (2010). In their work, they designed a multisector DSGE model with the aim to assess the macroeconomic impact of the diversified package of GHG mitigation levers on Polish economy. By applying a DSGE framework to climate policy issues and focusing on the interlinks between origin and spending of environmental measures, they evaluated their impact not only on macroeconomic variables, such as GDP or employment, but also on agents' welfare. In addition to that, by considering different types of mitigation levers, ranging from investments in energy capacity (fuel switch), industry or agriculture interventions, and energy and fuel efficiency improvements, they were able to construct the macroeconomic versions of marginal abatement curves. Such outcomes allowed the authors to assess the macroeconomic impact of individual policies in terms of abatement potential, which in turn have been then assessed under alternative fiscal frameworks. Under this framework, they performed different types of shocks, introduced as autoregressive (AR) stochastic processes. The first type refers to those driving model's cyclical behavior, thus productivity shocks, intensive labor supply shock, government consumption shock and foreign demand shock. The second type refers to types of GHG abatement policies, which ranges from energy efficiency shocks, shock to emission intensity of production and changes in public subsidies for energy investments. After developing a business as usual scenario, they construct alternative ones regarding GHG abatement micro-package composition and alternative energy packages.

A similar perspective is presented in Golosov et al. (2014), who designed a DSGE model with an externality, through climate change, from using fossil energy. Even though their main focus was on the identification of the formula of the marginal externality damage of emissions, they also identified the optimal tax on fossil fuels and the optimal and market paths for the use of different sources of energy. In their model, future output, consumption, and the stock of CO_2 in the atmosphere are stochastic. This is due to the fact that the output depends on the damage function, whose mapping with the climate variable is characterized by uncertainty. Analytically, this translate in the definition of a specific scaling parameter capturing the expected damages from carbon emission, which then is also endogenized in the model associating it to investments in adaptation and climate control technologies. Regarding energy, the authors' considered three different sources and their respective degree of substitutability. On this side, the model allows to study how different sources of energy provision matter on future climate and consumptions paths.

The relation between energy, emissions and finance is investigated by Punzi (2018), who developed an Environmental DSGE (E-DSGE) model. The economy is characterized by heterogeneous production sectors. Two different types of firms, and related financing sources, are considered: low carbon emissions firms, which borrow funds via bank loans and high carbon ones, which are finance either with bank loans or by issuing equities. The government imposes environmental constraints in terms of pollution, thus high-carbon emission firms are required to buy permits to produce. Monetary, technology, and financial shocks are studied with the aim to understand the effect on the firms. The most relevant outcome is that the green sector is supported in their borrowing activities in the case of a positive financial shock. In contrast, a positive technological shock combined with an easier monetary policy, does not provide an effective impact on the green firms, which can also experience losses in the longer term.

The work of Blazquez et al. (2019) is an example of a DSGE model specifically devoted to energy. Its goal is to assess the impact of economic 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 kind of framework shows how a DSGE can be used to study an economy which deeply rely on some resources, both for its inner and foreign market, while also being the second world producer of this kind of resources.[44] Four representative firms producing tradable and non-tradable final goods, electricity and energy services characterize the economy. Furthermore, the resource sector is composed of three different energy sources, namely oil, gas, and renewable energy. Four types of shocks are investigated: productivity shocks in tradable and non-tradable goods production, shocks to oil and natural gas prices.

A similar approach is presented by Tavakoli et al. (2020). Their aim is to assess the effect of oil shocks in an oil exporting country. The Iranian economy is studied under two different policies for oil revenues volatility. The oil inventory is owned by the government and the domestic input is not essential for oil production, thus all the output is exported. The oil price is exogenous and shocks are random. Two options are investigated. In the first, oil revenues are quickly exhausted and investments are undertaken in the oil sector, while nothing is set aside the National Development Fund. In this case revenues goes directly in the government budget, which in turn is allocated between spending and investments, and oil shocks affect the economy without any control. In the second case, oil revenues are destined in the oil fund and a small portion of the fund's assets is reinvested in each period. The exogenous oil shock leads to a longer and slower economic growth, protecting of the economy against the fluctuations (Tavakoli et al., 2020).

The same issue analyzed by Tavakoli et al. (2020) was addressed also by Devarajan et al. (2017), with a more general framework. In this work, the authors analyze the case of a low income country, like Niger, to derive budget rules in the face of volatile public revenues from natural resources. As of Tavakoli et al. (2020), their aim was to identify a strategy to save the revenue windfall in a sovereign fund and use the interest income to support national consumption. The shock on the price of the national resource is modelled as a AR(1) process.

[44] Saudi Arabia is the world's second-largest holder of proved oil reserves, after Venezuela, holding roughly 16% of total global reserves (Blazquez et al., 2019)

Food

The food component is investigated with DSGE models focusing mostly on the agricultural production. Among the few available, a good example is provided by Walker (2017), who developed a DSGE model with the aim to understand agricultural supply shocks and their amplification by financial frictions. Specifically, they considered the case of the Kenyan economy, assuming its GDP is entirely created by the agricultural sector, thus farms are the only firms, and that the only input factors are labor and fertilizers. In a perfect competitive market, they produce a single type of wholesale good, which is sold on both foreign and domestic markets. Financial resources for the entrepreneurial activity are sourced domestically, borrowing from households via financial intermediaries. The model incorporates aggregate risk considering stochastic weather conditions, allowing the design of shocks on the agricultural sector. One of the main outcomes is that investigated supply shocks are exacerbated by the financial accelerator, leading to a worsening of the trade-off between moderating inflation and stabilizing output. Such frameworks allow drawing attention on the importance of agricultural policy design effect in an increasing weather uncertain framework.
A specific case on fisheries is provided by Colla-De-Robertis et al. (2019). Their work study what would have happened if a relatively looser fisheries policy had been implemented in the EU. The choice of such structure, respect to the traditional ones, is due to the fact that fishery policy followed in the EU are decentralized, thus single planner frameworks are not appropriate for describing fleet responses. This approach allows to include aggregate economic phenomena in a context where individual economic agents are rational and characterized by a forward-looking optimizing behavior, while also considering policy shocks in fisheries' sector. Policy is conceived as a measure regulating indirectly the maximum number of days at sea for vessels. The related shock is introduced as a reduction in the maximum number of days at sea. In this way, the model induces an increase (reduction) in household's disutility due to labor. The approach introduces the regulation as a technological constraint, which in turn is modeled as a lottery in household preferences. In this way, they choose a probability of fishing instead of days of fishing. Furthermore, the size of the fishery stock affects the total factor productivity of the economy. On the biological side, stock evolves according to an age-structured population. Conversely, the unexpected shock affects the total mortality rate.

FE - Food and Energy

The relation between food and energy is studied considering the agricultural sector. In this field, Permeh et al. (2017) developed a multi-sector DSGE (large DSGE) for the Iranian economy with the aim to study the relation between oil price and agriculture. The economy is characterized by three sectors: agriculture, non-agriculture, and oil. Imports and exports' flows are considered, together with subsidies on imported agricultural. Price stickiness in agriculture and non-agriculture were in-

cluded. Specifically, they focused on the *de-agriculturalization* phenomena. In the case of oil exporting countries, the effect of oil revenues boom on real sector, has consequences on factors' prices and price indices. In the case of high oil price scenarios, tradeables (such as agriculture and industry) are weakened and non-tradeables (such as construction) are strengthened. In such framework, the effects of higher oil prices, modelled as exogenous shocks, on agricultural variables, such as production, imports, exports, inflation, and consumption, are studied. Two different types of households are considered: urban and rural. Agricultural goods and non-agricultural goods (domestic and imported ones) are included in the households' utility function. Prices are in general described as a AR(1) process. Energy used in agriculture is modelled with a constant elasticity of substitution (CES) production function, combining the energy of oil products and chemical fertilizer. Authors focused their consideration on Dutch disease[45] topic.
Finally, the model of Bukowski & Kowal (2010), already included in the energy paragraph, provides outcomes also for the agricultural sector.[46] Due to the structure of their framework, we can also state this work represents a good attempt to model energy and food together, even though the main focus remains energy and climate, while implications on food component is investigated via the consideration of the agriculture sector.

Water

Li & Swain (2016) represent the unique example, at the current state of the art, investigating water issues with a DSGE framework. Specifically, the authors aim is to study the effects of water resilience on the economic growth and on the dynamic welfare with special reference to
South Africa. Different climate change scenarios are performed[47] and future precipitation are uncertain[48]. Implications in the field of economic growth and sustainability are considered focusing on the ground water case. The main drivers of water scarcity depend on population growth and global warming effect from climate changes. Labor, physical capital are state variables while groundwater stock is assumed to be stochastic. In the case of the latter, its dynamics depends the natural recharge, the extraction rate and a stochastic disturbance with zero mean and constant variance, which may be autocorrelated over time. In addition to that, the model accounts for stochastic precipitation, which both affects the groundwater recharge rate and surface water flow. Thus, modelling both surface water flow and groundwater recharge as stochastic structures, allow the authors

[45] The Dutch Disease occurs when a resource boom reduces the internal incentives to produce, and/or the international competitiveness of, domestically produced non-resource tradable (exportable and importable) goods (Mien & Goujon 2021).
[46] Specifically the authors describe it as "agriculture and manufacture of food products".
[47] The scenarios are designed setting different parameters' levels for the utility discount rate, the withdraw of surface water and water natural recharge rate, leading to the creation of four different cases: light/high discounting with/without climate change effect.
[48] Uncertainty in the surface water flow and groundwater recharge rate would affect growth (Li & Swain, 2016).

to examine how the uncertainty affects future water resilience, economic growth and dynamic welfare. Different optimal trade-offs are investigated: the first refers to consumption and investment, the second to water extraction and resilience service, and the third industrial and residential use of water. The differentiation between productive and residential water use allows to focus on growth and welfare effects of ground water in the presence of rapid population growth. The authors derive the shadow (resilience) value of the surface and groundwater stock, and the dynamic average utilitarian measure for sustainability measurement.

2.5 Summary of reviewed papers.

The following table lists all the scientific publications included in our review emphasizing their respective features in terms of WEFE components.

Table 1 – Summary of scientific papers reviewed this section organized for macro modelling type and detailed for each WEFE nexus component: water (W), energy (E), food (F) and ecosystems (EC).

Reference		W	E	F	EC
ABMs:	An et al.,(2012)				X
	Balbi et al.,(2010)				X
	Bazzana et al.,(2021)	X		X	
	Bazzana et al.,(2021)	X	X	X	
	Dobbie et al.,(2018)	X		X	
	Gebreyes et al.,(2020)	X	X	X	
	Heckbert et al.,(2010)	X	X	X	
	Li et al.,(2017)	X	X	X	
	Molajou et al.,(2021)	X	X	X	
	Schouten et al.,(2014)	X		X	
	Smajgl et al.,(2011)				X
	Smajgl et al.,(2015)				X
	Smajgl et al.,(2016)	X		X	
CGE Models:	Basheer M. et al.,(2021)	X	X		
	Berrittella et al.,(2007)	X		X	
	Birur D. et al.,(2008)		X	X	
	Burniaux et al.,(2002)		X		
	Calzadilla A. et al.,(2011)	X		X	
	Dudu H. et al.,(2018)	X		X	
	Kahsay et al.,(2017)				X
	Khan et al.,(2020)				X
	Nechifor V. et al.,(2017)	X		X	
	R Osman et al.,(2019)				X
	Sartori et al.,(2018)				X
	Su Q. et al.,(2019)	X	X		
	Sun et al.,(2021)	X	X		
	Taheripour F. et al.,(2013)		X	X	
	Taheripour F. et al.,(2013)	X	X	X	
	Teotónio et al.,(2020)	X	X		
	Tyner W. et al.,(2013)		X	X	
	Vatankhah et al.,(2019)				X
	Zhou Y. et al.,(2016)	X	X		
DSGE Models:	Blazquez et al.,(2019)		X		
	Bonsch et al.,(2016)	X	X	X	
	Bukowski et al.,(2010)		X		
	Chuan-Zhong et al.,(2016)	X			
	Colla-De-Robertis et al.,(2019)			X	
	Devarajan et al.,(2015)		X		
	Golosov et al.,(2014)		X		
	Permeh et al.,(2017)		X	X	
	Punzi(2018)		X		
	Tavakoli et al.,(2020)		X		
IAMs:	Blanc et al.,(2017)	X		X	
	Bouckaert et al.,(2012)	X	X		
	Bonsch et al. (2016)	X	X	X	
	Davies et al.,(2013)	X	X		
	de Vos et al.,(2021)	X	X	X	
	Hermann et al.,(2012)	X	X	X	
	Kebede et al.,(2021)	X	X	X	X
	Liu et al.,(2015)	X	X		
	Miralles-Wilhelm et al.,(2018)	X	X	X	
	Schlör et al.,(2018)	X	X	X	
	Son (2016)	X	X	X	
	van Vuuren et al.,(2015)	X	X	X	
	Veerkamp et al.,(2020)	X	X	X	X
	Ethan Yang et al.,(2016)	X	X	X	
	Zhang et al.,(2019)	X	X		
	Zhou et al.,(2018)	X	X		

3. DISCUSSION

In this section, we provide an analysis on the basis of our review, with the aim to understand the state of the art in the field of interest of this document.
After a brief qualitative analysis, we discuss each type of investigated macroeconomic model on the side of the WEFE nexus, as well as regarding how they respectively deal with risk and uncertainty. With reference to the latter, we provide a theoretical summary on the topic and a brief discussion on how uncertainty of each component of the WEFE nexus and the nexus itself is approached. In addition to that, the excel file attached to this document, consists of a summary of each paper and a specific section on how risk and uncertainty are addressed.

3.1 Qualitative analysis

In our review, we selected 58 papers focusing on the macroeconomic modelling in the field of the WEFE nexus, on the basis of searching activity on specific target words (WEF, WEFE and macroeconomic models)[49] in the main online research repositories (such as Scopus, Science Direct, Web of Science and Google Scholar, among others).
Specifically, we found 13 ABMs, 19 CGE, 10 DSGE and 16 IAMs over a time horizon from 2002 to 2021 (Figure 1). Figure 2 provides an overview regarding the evolution across time, showing a concentration in the research activity in all models starting from 2015. This confirms the increasing interest by the scientific community involved in macroeconomic models in the field of the WEFE nexus and its related facets.
Following Table 2, Figure 3 and Figure 4 summarize the distribution of the models across the WEFE single components, WEFE combinations and WEFE nexus.

Table 2 – Number of selected papers organized per model type and WEFE components

	WEFE single components				WEFE combinations			WEFE nexus		
Models	W	E	F	EC	W+E	E+F	W+F	W+E+F	W+E+F+EC	Total
ABMs				4			4	5		**13**
CGE		1		5	5	3	4	1		**19**
DSGE	1	7	1			1				**10**
IAMs					5		1	8	2	**16**
Total	**1**	**8**	**1**	**9**	**10**	**4**	**9**	**14**	**2**	**58**

[49] As mentioned in the introduction, the identification of the studies of interest was designed based on a combination of different words characterizing the WEFE nexus, as well as the word macroeconomic models. By doing so, we had the chance to focus our interest on the nexus topic respect to the single components. This choice implies the exclusion of most part of the single components' models, favoring those more in line with our scope. In some cases, models focusing on a single component were considered due to their relevance or to the fact that the model type is yet to developed at WEF o WEFE nexus level.

A separate note is that of the analysis carried out at the level of WEFE nexus single components, hence water, energy, food and ecosystem considered each on its own. 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 is analyses by CGE and IAM models, followed by ABMs. Moving from the single components to the nexus as a whole, WEF (without ecosystem) is studied mostly by IAMs, followed by ABMs. Finally, the WEFE nexus is approached in its entirety only by the IAM models.

In general, we can state that the WEFE combination studied the most is the one that of the analysis of WEF nexus carried out through IAMs, followed by ABM models. On the other hand, DSGE models focused mostly considering only one of the single components of the nexus.

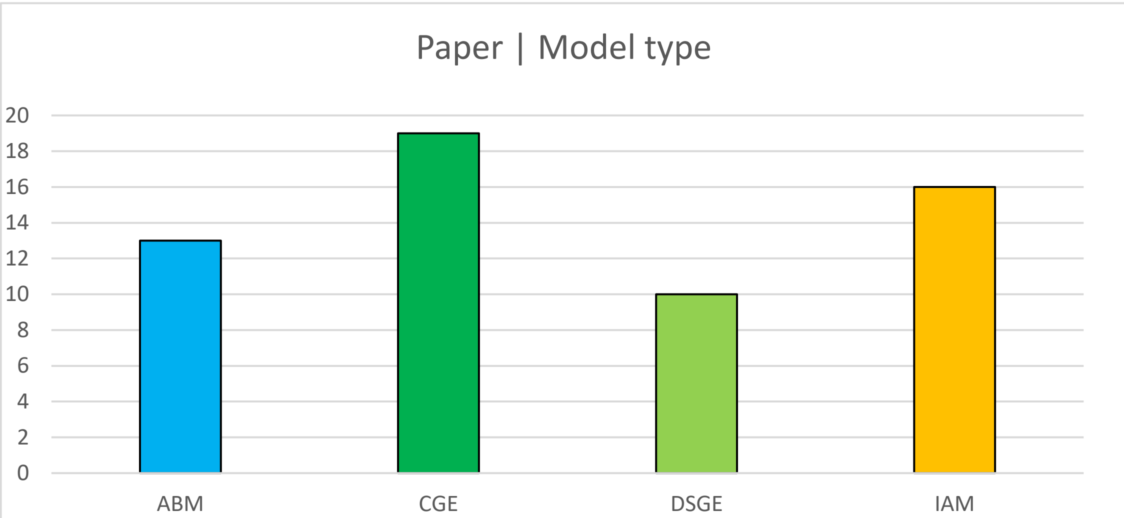

Figure 1 – Number of reviewed papers organized per model type

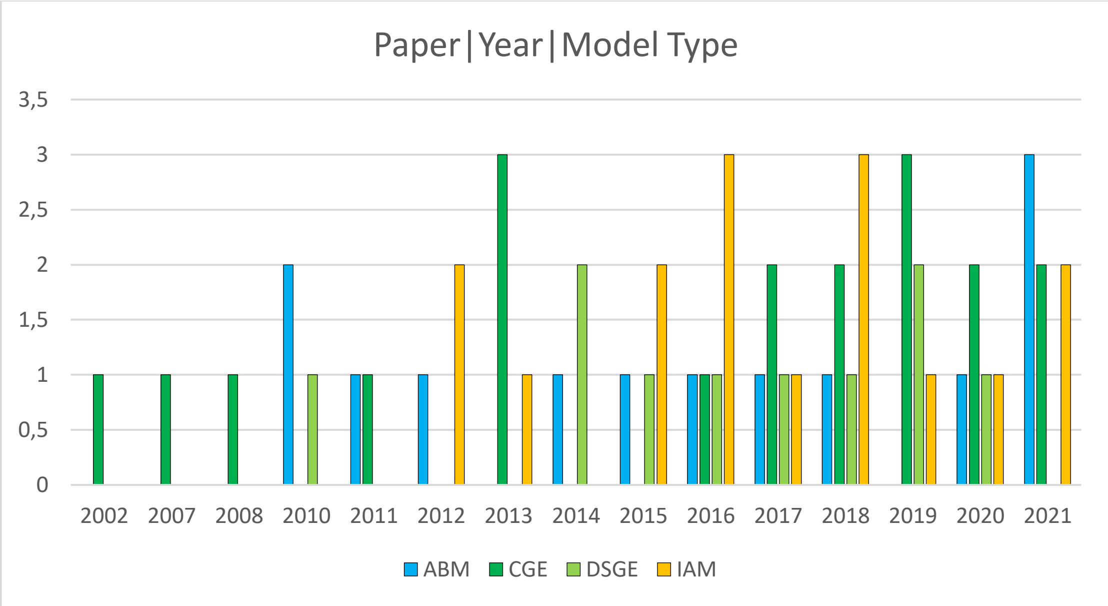

Figure 2 –Overtime evaluation of the number of reviewed papers organized per model type.

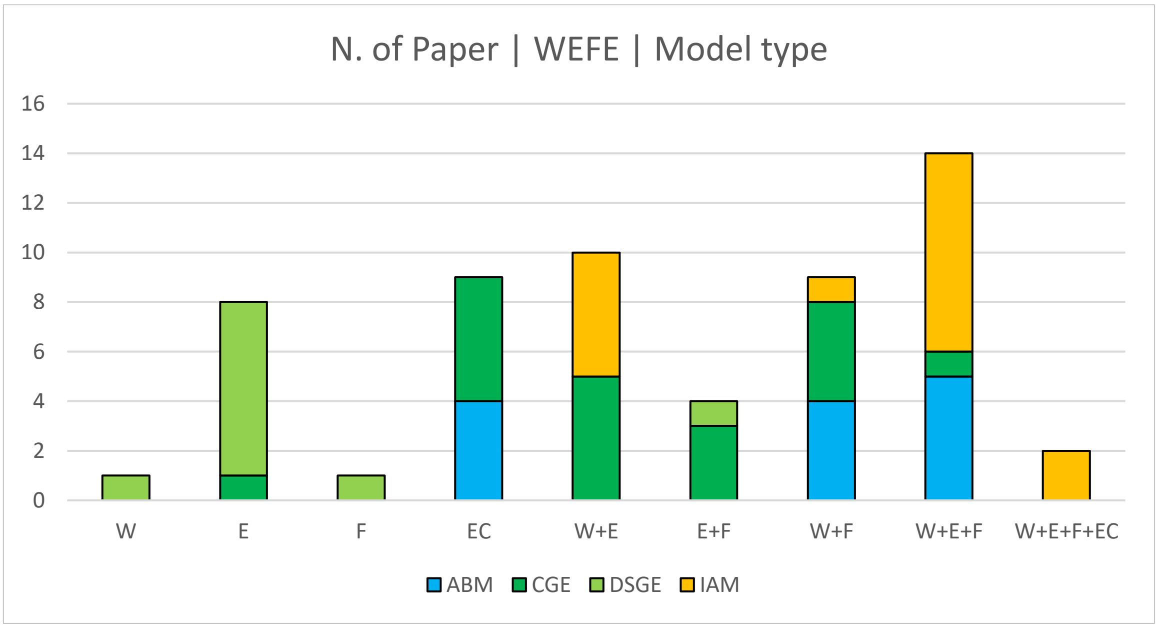

Figure 3– Number of reviewed papers organized per WEFE component, WEFE combinations and model type.

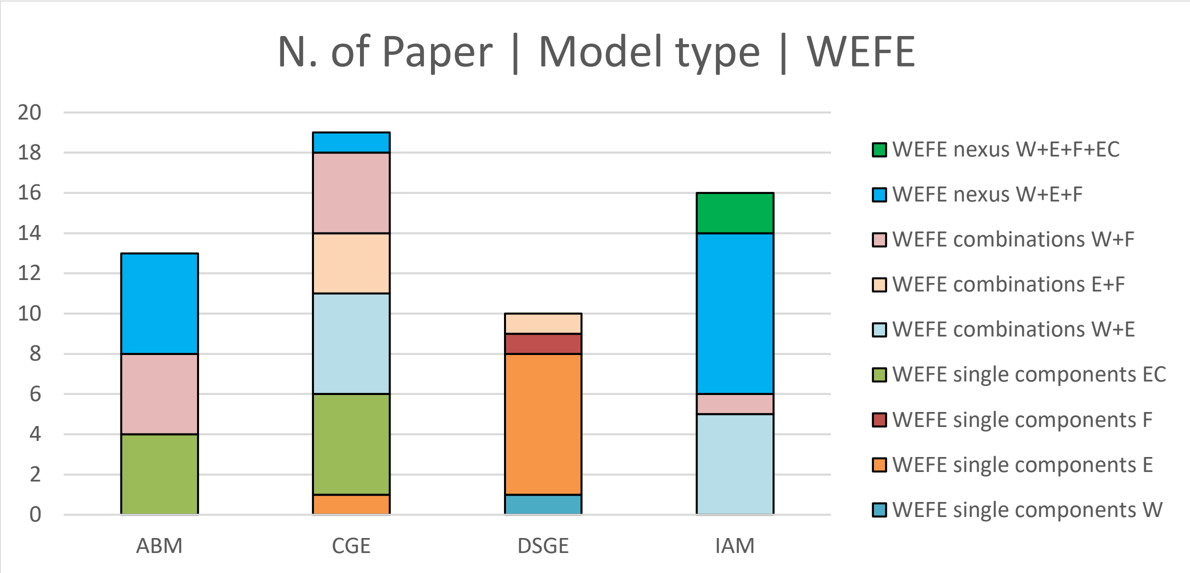

Figure 4 – Number of reviewed papers organized per model type and WEFE components

3.2 Macroeconomic models in the WEFE nexus

Computable general equilibrium models

Under the nexus perception, CGE models offer a reliable and simple tool to analyse the interlinkages across sectors and countries, providing a general overview on the macroeconomic system, where all markets are cleared (i.e. through prices and quantities adjustments) at the end of the simulation period.

Furthermore, such a comprehensive theoretical framework can also be considered as an instrument for policy evaluation, due to the possibility to run two separate simulations, namely one with no policy intervention (i.e. the baseline scenario) and another with (i.e. policy-induced scenario), thus allowing for comparison.

Nonetheless, several limits seem to emerge in the implementation of this well-known macroeconomic framework. For instance, a first critique considers the underlying neoclassical approach on which CGE are built on, which does not take into account both agents' heterogeneity as well as changes in factors' allocation (Alavalapati et al., 1998), nor the presence of technological barriers (Allan et al., 2007). Furthermore, the normativity nature of these models does not implement, by default, the inclusion of any statistical testing or inference, which seems quite unrealistic in real world terms. In addition, CGE models are also heavily dependent on calibration data, meaning that they lower their predictive power as projections move far away from the starting point.

Yet, a comprehensive method including all dimensions of the WEFE Nexus still lacks in literature. The most extensive model, which address for the WEF Nexus, is the GTAP-BIO-W model (Berrittella et al., 2007; Taheripour et al., 2013a). Despite this research gap, several attempts have been made to combine at least two WEFE aspects by combining CGE to biophysical models, thus providing considerable 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 model hampers research in accomplishing this task.

A last comment considers uncertainty, as it is also a specific focus of this specific review. As previously discussed, the normativity nature of the CGE framework does not imply, at least in principle, for the presence of stochastic processes. Indeed, only the paper of Basheer et al. (2021) addresses for randomization by introducing a hydrologic model based on uncertainty to estimate water availability, then used as input of CGE simulations. On the other hand, few more papers explore affine concept to the one of uncertainty, that is risk. Specifically, this is done by including multiple simulation scenarios, which differ one another by some key variables, such as water scarcity (Teòtonio et al., 2021; Su et al., 2019), socio-economic projections (Nechifor and Winning, 2017;Kahsay et al., 2018), energy market regulations (Zhou et al., 2016) and chances in agricultural productivity (Kahn et al, 2020).

IAMs

The IAMs structure perfectly suits to the intrinsic framework of the WEFE nexus. Their ability to connect different complex layers, ranging from socio-economic ones to physical ones, while also assuring the possibility to develop policy scenarios, represents their main strength. As also stated by McCarl et al. (2017), the understanding and management of the WEF nexus, require the design of new WEF nexus integrated modelling frameworks. This can be the potential new challenge for this kind of models.

Over the years, they have been widely applied in the study of the relation between climate and the economy, leading to creation of a global scientific community. Specifically, the structure of the high resolution IAMs, developed in different spatial resolution 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 on both WEF and WEFE nexus fields. This is due to their ability to integrate land dynamics and management, which in turn affect agriculture and food production, with energy and water issues. Concerning WEF nexus, the integration of hydro-agro-economic model with specific agricultural and energy use ones, such as the case of Yang et al. (2016), obtained 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. In addition to that, the IAMs possibility to project the impact on the economy of different climate policies allows to study their respective impact at the WEF level. Moving to the WEFE nexus, we found two cases: Veerkamp et al.(2020) and Kebede et al. (2021). In the former, the assessment of such nexus is reached combining two different IAMs, while in the latter the outcomes of an IAMs are then analyzed with impact indicators representing the key nexus interactions.

Concerning the inclusion of uncertainty and the study of risk in this kind of models, it is worth bringing considering the discussion provided by Golub et al. (2011). In most cases, IAMs deal with parametric uncertainty respect to the stochastic one[50], where the former refers to the case in which there is incomplete knowledge on the relevant parameters, such as climate sensitivity. Many IAMs study simulate uncertainty via uncertainty propagation. Numerically, this is done using Monte Carlo analysis joint with probability distributions of input parameters. In this way, multiple source of uncertainty can be considered simultaneously. However, such framework grounds on an implicit assumption of uncertainty propagation, under which the decision maker is unaware of the multiplicity future contingencies and does not adjust his/her decisions according to risk preferences. Furthermore, it is not clear how it influences optimal choices.[51] On the modelling side, this structure is approached applying discrete uncertainty modeling, which allows solving this kind of problems by simplifying the representation of uncertainty. By doing so, usually only one single uncertain parameter is considered.

More in general, we can say that including uncertainty in IAMs framework is not an easy task, since for some variables it is not easy to quantify. In addition to that obtained scenarios cannot be interpreted statistically to provide specific uncertainty ranges.

In terms of context, most of the reviewed works study different socioeconomic and GHGs emissions scenarios, to assess the effect of a changing climate on the economy and vice versa. In the baseline (reference) scenario different climate policy (that aim to mitigate climate change) can be implemented and see how the model answer in term of economic and climate variables.

ABM

ABMs are simulations of the economy based on the interactions of a large number of heterogeneous agents according to specified rules, which aim at allowing more flexible and realistic characterizations of socio-economic systems. Differently from top-down models characterized by strong assumptions and the lack of uncertainty (e.g. DSGE models where the system is already at the equilibrium), ABMs assume heterogenous agents that interact 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). For example, 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.

[50] In this case, the persistent randomness of systems is completely resolved in the future.
[51] We remand further details regarding this discussion to the work Golub et al. (2011) and Golub et al. (2014)

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 analyzing the time required for real agents to internalize and adapt to entirely new and unexpected state of the world.

Focusing on the nexus, such a framework is effectively 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 on ecosystems[52] (Tables 1 and 2). ABMs are particularly fit for the ecosystem 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, with its complex interconnections between natural resources, social needs and economic development, ABMs are proven to be a valuable tool to model how agents behave, interact, and adapt to external pressures and changes in the environment.

Lastly, uncertainty is an intrinsic characteristic of these models since agents have limited information on the system in which they operate (i.e., they are bounded rational). In other words, they can internalize only observed shocks in their decision process without anticipating future and unforeseen developments.[53] Accordingly, the policymaker plays a fundamental role in steering and coordinating the behavior of agents and in anticipating the optimal response of the system to future shocks. Since ABMs are solved through numerical simulation, the optimal policy is found by performing a Monte Carlo analysis, in which the performance of the system is tested under different assumptions on the parameters governing the behavior of the central planner. A similar reasoning applies also to sensitivity analysis, where the focus is on the time required for real agents to internalize and react to entirely new and unexpected states of the world under different sets of parameters.

DSGE

DSGE models work similarly to standard IAMs. However, unlike existing traditional IAMs, DSGE models explicitly incorporate uncertainty about the future through the introduction of shocks to output, consumption or climate damages (Farmer & Teytelboym, 2015). While this is the peculiarity of such models, it also limits them in the modelling framework size. Such drawback reduces the policy performance of the model, especially in the design of detailed policy analysis. The set up of the exogenous stochastic shocks relies on the computation and use of average statistics obtained from many simulations. Alternatively, impulse response function can be used to show the how the model re-

[52] An (2021) defines ecosystems as coupled human and natural systems, while Heckbert et al. (2010) focus on ecological economics.

[53] In this sense, they (partially) fail to deal with Lucas' critique (Lucas, 1976). Nevertheless, the rational expectations hypothesis appears to be a strong assumption, even rejected by real-world data (Fagiolo & Roventini, 2016).

sponds to such shocks. While CGE models perform better 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 such issue, while also allowing to incorporate the effect of exogenous stochastic shocks.

On the basis of such structure, researchers interested in modelling uncertainty in the WEF and WEFE nexus frameworks using DSGE models, have first to make some initial choices. If their goal is more interdisciplinary and policy oriented, 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 more suited choice. However, it must be also acknowledged that the DSGE forecasts are comparable in terms of their accuracy to certain macroeconometric models for a small number of variables (Arora, 2013). In addition to that, such activity is also technically demanding.

Focusing specifically on how uncertainty is introduced, according our review summarized in section 2, most of the models investigate uncertainties on the sides of technological progress and/or government's decisions, via productivity shocks and/or monetary shocks. On side of the WEFE nexus and its components, uncertainty in the field of energy is investigated analyzing the effects energy efficiency shocks, shocks to emission intensity of production, changes in public subsidies for energy investments (Bukowski & Kowal, 2010) and shocks to oil and natural gas prices (Blazquez et al., 2019 and Tavakoli et al., 2020). Concerning the latter, implications on the side of food production are also studied considering the energy as an input factor for the agricultural sector, thus accounting for energy prices' uncertainty (Permeh et al., 2017). In addition to that, uncertainties affecting the food component are also analysed considered stochastic weather conditions (Walker, 2017), or policy shocks in the fisheries' sector (Colla-De-Robertis et al., 2019). Finally, water scarcity is addressed in relation of uncertain precipitations (Li & Swain, 2016).

The lack of application of the DSGE models in the field of the WEF and WEFE nexus arises in our qualitative analysis as well (Table 2 and Figure 3). There are several examples of applications to the WEFE nexus single components, especially in the case of energy, while there are no cases studying multiple nexus components.[54]

One possible explanation can be related to the "financial nature" of the DSGE, which are mostly used to study financial topics respect to the ones connected to field of the WEF and WEFE nexus.

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

3.3 Risk and uncertainty in the macroeconomic modelling of the WEFE nexus

In the framework of the WEFE nexus, it is also important to mention which can be the main sources of uncertainty and risk for each of the single component, while also discussing how these are approached within the structures of the macroeconomic models' part of our review. To this end, after providing a general overview regarding the main concepts of uncertainty and risk, we analyze such topic for each component of the nexus, with the aim to investigate how related interactions, interdependences and tradeoffs can be approached in an uncertain framework. Detailed notes regarding how risk and uncertainty are addressed by each paper included in our analysis are provided in a devoted section of the attached excel file.

An overview on risk and uncertainty in the economic literature

In economic literature, the distinction between risk and uncertainty is provided by the seminal work of Frank Knight (Knight, 1921). *Risk* is defined as "the possibility of alternative outcomes whose probabilities are capable of measurement", while *uncertainty* "is the possibility of alternative outcome whose probabilities are not capable of measurement". While both the two share the common aspect regarding the dependency on future randomly events, defined also as "states of nature", the main difference lies on the fact that risk is measurable and its measurability stems from the availability of likelihood or probability information (Griffin, 2016). However, Knight itself, and following inspections undertaken by the scientific community, converged to the fact that the decision making calculous is not dramatically altered when stochastics involves risk but not uncertainty (Griffin, 2016). Other relevant concepts into this field refer to the definition of ambiguity and deep uncertainty. Camerer & Weber (1992) define *ambiguity* as "the uncertainty about probability, created by missing information that is relevant and could be known" (Snow, 2010). Concerning *deep uncertainty*, Lempert et al. (2003) describe it as the situation in which: "analysts do not know, or the parties to a decision cannot agree on, (1) the appropriate conceptual models that describe the relationships among the key driving forces that will shape the long-term future, (2) the probability distributions used to represent uncertainty about key variables and parameters in the mathematical representations of these conceptual models, and/or (3) how to value the desirability of alternative outcomes". The measuring of risk via probabilities has led to possibility of accounting for it in agents' preferences. By defining a certain degree of risk aversion, economists are able to incorporate the agents' preferences about variability, thus their human behavior respect to risk. The higher the risk aversion, the more agents are willing to pay to reduce it. The study in this field involves the need of identifying a priori the different states of nature relevant for the decisional process, which is turn is solved taking into account the variance of the consequences only.

Risk and uncertainty in the WEFE nexus and its components

Even though each of the nexus components is characterized by respective unique peculiarities, it also shares with the others some common features in terms of uncertainty and risk. For instance, all of them are strictly related to the variability of weather, which in turn is influenced by the climate. They are strongly affected by population and economic dynamics as well countries regulations, which in turn lead to consequences on the former.

To provide a more effective analysis on this side, we start from the general concept of capital asset. As discussed by Conrad & Rondeau (2020), the value of a capital stock derives from the future possibility to deliver a flow of benefits, through the production of goods and services. This definition can be easily applied in the field of natural resources as well, leading to the identification of the natural capital concept and related value. [55] In such framework, the flow process can be characterized by uncertainty associated to the biophysical nature of the specific resource, while also be related to different exogenous risks, such as connected to politics, policies, regulation, population growth, economic development or technologic progress.

In general, the higher is the risk within the framework of a nexus component and/or regarding the relation with the others, the more economic measures designed by regulators can help to reduce the uncertainty transmitted to the related and connected economic markets. Policymakers are called to deal with risks affecting resources in many different dimensions: scarcity and productivity influence the resources economic values and prices, which in turn depends on agents' preferences, population dynamics and institutional framework. If substitutes and/or complementary resources are available, the related uncertainty may have also direct consequences on the associated nexus components.

As also stated by McCarl et al. (2017), the acknowledgement of accounting for such different types of uncertainties, "raise needs for stochastic modeling and/or broadly scoped alternative future scenario analysis, as commonly done in climate change analysis with scenarios spanning different future levels of greenhouse gas emissions". To this end, in what follows we provide a brief overview regarding how uncertainty and risk are addressed in the papers included in our review.

Water

When we think about water, several concepts can be associated to this resource, from rainfalls, to water reservoirs or see basins as well. However, the list is wider and complex. Some elements are interconnected one with each other and heavily affected by exogenous forces. Rainfalls, for instance, are subject to seasonality. Their variability has increased due to climate change, leading to

[55] More specially, "in an integrated environmental-economic accounting system, natural capital would be the extension of the economic notion of (produced) capital to the natural environment, i.e. the 'stock' of natural (eco-)systems that yields a flow of valuable (ecosystem) goods or services into the future". *Source*: https://unstats.un.org/unsd/envaccounting/londongroup/meeting21/towards%20a%20definition%20of%20natural%20capital%20-%202nd%20draft.pdf

high risk of floods and/or droughts. In addition to that, atmospheric pollution translates into a decrease of water quality, leading to environmental damages affecting food production, soil degradation and reservoir contamination. On the other hand, the latter is influenced by economic activity, which comprehends agriculture sector. Uncertainty related to the hydrological cycle has effects also on the energy sector, which in turn affects the latter due to the growing emission of GHGs, thanks to the consumption of energy produced with fossil fuels.

In this framework, economic forces play a central role: water demand determines the speed of water reservoir exploitation, which in turn heavily depends on technological progress and technology availability. In general, we can say that the stochastic aspects of hydroclimatic forcing and their propagation within water-limited ecosystems (Katul et al., 2007) play a central role in modelling water as a resource. In this context, modelling uncertainty via the use of stochastic processes is done by investigating water biophysical dynamics, economic prices, demanded and supplied quantities, technological progress as well as via extraction problems. Rainfall dynamics can be studied using a Poisson process (see among others, Onof et al., 2000 and Cowpertwait et al., 2007). Water availability can be modelled using river system models, whose temporal resolutions enable simulation of the spatial and temporal constraints, while also capturing the consequences of stochastic hydrology. Concerning our review, in general, water is studied as a unique component in the DSGE model framework, while we found 5 CGE models and 5 IAMs studying it combined with energy and 4 CGE models, 4 ABM and 1 IAMs associating it with the food component.

In terms of uncertainty, the following issues are addressed. Water scarcity, is introduced assuming stochastic variation in precipitations or different climate scenarios. Water technology is considered on the extraction side and on the infrastructural ones. Different scenarios can be projected regarding groundwater physical structure as well as technological change evolution overtime.

Water demand is addressed considering crop production scenarios, in most cases using SSP frameworks, or as input for the energy production. In the latter case, uncertain energy demand can affect the need of water. On the other side, when water is considered as an input, as the case of hydropower production, uncertainties related to water scarcity and water technologies affects the energy component. Regarding information, ABMs are designed to manage contexts characterized by incomplete and asymmetric information. This translates into effects on the side of water consumption choices as well as decision making. Regarding shocks, which are more in the field of expertise of the DSGE models, we found the model developed Chuan-Zhong & Swain (2016), where stochastic groundwater stock, stochastic withdraw of surface water and stochastic precipitations are considered at the same moment, allowing to providing insights on how uncertainty affects future water resilience, economic growth and dynamic welfare.

Energy

Energy can be defined as the capability to do work or as whatever enables a body to work (Cretì & Fontini, 2019). It can take different forms, such as mechanical, thermal, radiant and be sourced from different origins, such as fossil fuels combustion or by exploiting renewable resource like sun or wind. Considering the economic dimension, this framework translates into a multitude of implications, which range from dynamics related to the general concept of markets, thus demand, supply and prices, to the discussion concerning natural resources overexploitation, especially in terms of natural ecosystems' conservation as well as climate change effects. Clearly, energy plays a fundamental role at all economic levels, from individuals' everyday lives to countries' macroeconomic performances, so that its security has always been a constant priority in maintaining international stability. In such a framework, uncertainty ranges from the energy supply side, thus regarding the exploitation of renewable energy source for the production of green energy or related to extraction problems for fossil fuels, and/or the demand side, which may depend on population and economic growth.

In our review, energy is considered as unique component in the majority of DSGE models (i.e. 7 out of 10), even though it must be also acknowledged that many of these cases also investigating climate issues, as well as in one CGE model. In terms of combinations with other components, energy is discussed in the 64% of paper dealing with either WEF or WEFE concepts, thus underlining its relevance also in the nexus literature. In terms of uncertainty, energy supply is subjected to exogenous economic fluctuations, especially related to international oil and gas prices as well as to total factor productivity and population dynamics. Moreover, due to the relevancy of fossil fuels CO^2 emissions with respect to the overall economic footprint, the energy sector is also addressed to the estimation of damage functions in order to produce optimal carbon tax rates under different climatic scenarios.

Food

Food security has always been at the center of the world debate. This nexus component is surrounded by a multiplicity of uncertainties and related risks. Extreme weather events translate in agricultural shocks, affecting food commodities production and thus related prices. Such growing climate uncertainty implies risks for entire food supply chain, from farmers to agricultural traders and food manufacturers, till final consumers. On the other hand, food demand is driven by population dynamics, which in turn depends on many uncertain elements.

Considering possible uncertainties on the supply side, the first relates of course to production issues. Water uncertainty affects crop productivity. The high is the one surrounding the former, the more will be the volatility of food prices. Other shocks affecting agricultural production can be related to technological production factors, such as the case of African countries, which are highly dependent of the import of machineries or fertilizers. Both in the two examples, the price of oil plays a central role. In first place its volatility affects transport costs, while under a different perspective it serves as input to in food cultivation and processing. In such a complex context, we can classify the following main elements of uncertainty: climate uncertainty, technological uncertainty, prices uncertainty and demand uncertainty.

Concerning our review, at macroeconomic level, food is studied as unique component in the DSGE model framework, while in the same framework it is also combined with energy. There are 4 CGE and ABMs and 1 IAMs studying it combined to water, while association with energy occurs in 3 CGE models and 1 DSGEs (Table 2).

On the side related to uncertainty, as the case of the other nexus components, projections of future scenarios in terms of population growth, technological change and climate change are considered to assess the effect on food production and demand. Here also, integration with physical model allows the introduction of stochasticity. The role of incomplete information is address at farm level by ABMs. In the DSGE framework, uncertainty on food production is considered in two ways: the first refers to the introduction of a shock on the price of the input factors, while the second via the design of a policy shock. Regarding the former, the study focuses on the reaction of the agricultural sector respect to possible shocks on the side of oil or energy prices. In such framework, shocks are modelled as a AR(1) process. Regarding policies, we found an example specifically developed to assess the effect of the European Common Fisheries Policy. The policy shock, was conceived as a reduction in the maximum number of days at sea, which in turn affects the household utility due to labor implications.

Ecosystems

Ecosystem can be identified by meaning of two characterizing elements, i.e. biotic and abiotic components, which represent respectively all living organisms (such as plants and animals) as well as non-living ones (such as soil, minerals, water sources, and the local atmosphere) of a specific geographic area. Hence, although not directly included in the original WEF structure, the Ecosystem dimension is already intrinsically present in the nexus framework as provider of natural resources (i.e. water and primary energy sources) that are implemented directly or indirectly in the production of food and other goods. Moreover, the inclusion of atmosphere as part of the natural system further extends the nexus discussion to the potential impact of changes in the climate conditions, which are mainly driven by the rise of the atmospheric temperature.

In modelling terms, the complexity of estimating both availability and residuality of all these resources, as well as their biophysical characteristics, requires the cooperation with natural scientists to provide for reliable physical models that are able to describe the aforementioned data.

Concerning our review, in the field of a macroeconomic modelling, ecosystems are studied in 5 CGE models and 4 ABMs, although their interdependences with Water, Energy and Food dimensions should be imputed in many more cases, at least indirectly.

With respect to uncertainty, the majority of studies addressing for explicit ecosystem components consider the availability of different scenarios with respect to specific elements, such as soil erosion and water quality, as well as under different changes in the climatic conditions, which can significantly affect the overall countries' macroeconomic performance (e.g. in terms of GDP, production and private consumption) either positively or negatively depending on the willingness of countries to invest in preserving the natural system.

WEF and WEFE nexus

The introduction in literature of the WEF Nexus underlines the rising request of the international scientific community to address for the risk of global resources' shortage under a comprehensive approach that takes into account the different challenges linked to the management of each dimension as one. Nonetheless, as frequently emerged during this review, the discussion of a specific nexus component has naturally led to the introduction of a second element of the triad, due to the strong implicit interdependence characterizing the nexus components, which has been only further amplified by the inclusion of the ecosystem dimension.

In dealing with uncertainty, the study of the WEF nexus still represents a challenging theoretical exercise (Yung et al., 2019), as the analytical introduction of stochasticity is such integrated framework can lead to complex mathematical forms that are not easy to solve numerically. To overcome to this issue, several studies investigate the nexus building multilevel and multistage models, where macroeconomic models are linked to external biophysical models describing specific nexus elements. Concerning our review, we found 1 CGE model, 5 ABMs and 8 IAMs studying the WEF nexus and only 2 IAMs in a WEFE nexus framework. Among these, few studies address for the examination of different scenarios on both climatic and non-climatic drivers as well as with respect to the potential land-use competition between food and energy crop destination.

4. CONCLUSIONS

The understanding of the WEFE nexus paradigm can be achieved with the design of studies analysing all its different physical layers, economic facets as well as spatial scales. The effective coupling of different macroeconomic modelling frameworks plays a central role in the design of economic measures able to address the nexus complexities and related criticalities.

In this work, we list some of the most relevant scientific publications in the field of macroeconomic modelling of the WEFE nexus, with the aim to provide an overview of the state of the art.

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

Over the reference time interval, CGE models rank first with 19 publications. IAMs are the ones covering the most the WEF and WEFE nexus in its integrity. DSGE models focus mainly on the energy side, even though such association heavily relates to the topic of climate change, GHGs emissions, mitigation and adaption policies as well as temperature variability. ABMs also perform well at WEF level. In addition to that, they are mostly focused on ecosystems as single component.

Uncertainty is addressed differently by the models. CGE ones are combined with other physical models to study the economic effect of different future scenarios. In the IAMs such scenarios are designed to show different state of the world mostly related to the change of the climate. DSGE models have been conceived to account for random shocks and focuses mostly on a WEFE single component. ABMs incorporate uncertainty in the form of agents' incomplete information.

On the side of the WEF and WEFE nexus modelling, IAMs structure is the most suited to represent the nexus complexity, whereas DSGE models majorly focus on single components. On the other hand, DSGE models appears to be better suited to account for 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 tools, since we found some references focusing on two WEFE components at the same time, namely water and energy, but most of the DSGE models study a single WEFE component.

On the policy perspective side, CGE models and ABMs seem to be more suitable options. The most relevant strength of the first is their ability to incorporate the intrinsic characteristics of an economy as well as accounting for interlinkages across sectors and countries. On the side of ABMs, the possibility to model different agents' behaviour allows to define theoretical frameworks able to better approximate reality. On the other hand, the integrated approach characterizing the IAMs, suits more the purpose of understanding the WEFE nexus as whole, thanks to a well-defined combination of physical and economic structures. Such a modelling context, favours also the incorporation of uncertainty and the evaluation of risks.

It is therefore worth to acknowledge that further research effort must be undertaken on the side of macro modelling in the field of WEFE nexus. We have to recognize that each model type considered in this review can be a relevant tool for policy purposes on the WEFE side. Strengths, as well as weaknesses, arise with respect to the different fields of analysis. Thus, each of the models has to be used carefully in their respective specific context. Then, 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.

5. APPENDIX / ANNEXES

Online Excel file
Online BibteX file

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