Faculté des bioingénieurs

Modeling agricultural systems and policies to advance sustainability: a review

Author: Timothée Lefebvre

Promoter: Prof. Philippe Baret

Readers: Prof. Goedele Van den Broeck, Hubert Bedoret

Advisors: Océane Duluins, Anton Riera

Academic year 2023-2024

Master's thesis for the diploma of Bioengineer in agricultural science: Sustainability engineering

ABSTRACT

Agriculture significantly impacts global sustainability challenges, necessitating effective policymaking to steer agricultural practices towards greater sustainability. Given the complexity of the agricultural system, mathematical models represent a powerful tool for supporting agricultural policymaking. This master's thesis provides a comprehensive overview of policy-oriented macro-level models, identifying their characteristics, effectiveness at integrating sustainability themes, and the actors involved in their development and funding. After a PRISMA-based systematized review of 1064 articles from the Scopus database and prominent institutional websites, this study analyzes 75 macro-level models. These models are analyzed for their ability to incorporate sustainability across different dimensions—environmental, economic, social, and governance, based on the Planetary Boundaries and SAFA frameworks.

The findings reveal significant diversity among the models, with *integrated bio-economic models*, *structural simulation models* and *calibrating optimization models* demonstrating superior performance in integrating sustainability themes. In contrast, computable general equilibrium (CGE), econometric, and spatial equilibrium models exhibit lower integration capabilities. This disparity is influenced by both technical factors, such as data availability and the complexity of modeling processes, and agenda-driven priorities that may focus attention toward specific themes.

The development of these models is driven by actors from public research institutions, independent centers, and universities. Notable contributors are institutions like the ERS of the USDA, INRAE of France, and the JRC of the EU. Funding is primarily sourced from public institutions. Both model development and funding predominantly originates from OECD countries.

This Master's thesis highlights the need for strategic advancements in policy-oriented macro-level models to enhance the integration of sustainability themes. Recommendations include addressing data limitations, enhancing model connectivity, and fostering international collaborations to improve model interoperability and stakeholder engagement. The study advocates focusing on high-performing model classes to inspire broader improvements across all models, ultimately supporting more effective and sustainable agricultural policymaking.

ACKNOWLEDGEMENTS

I would like to express my gratitude to the many people who have made the completion of this Master's thesis possible.

First of all, I would like to thank Prof. Philippe Baret, my promoter and professor at UCLouvain, for providing me with the opportunity and freedom to explore this fascinating topic. The 'Sytra spirit' and your high expectations presented a significant challenge, which I am proud to have met. This accomplishment would not have been possible without your encouragement, insightful perspectives, and valuable feedback.

Next, I would like to thank Océane Duluins and Anton Riera, respectively PhD student and researcher under Prof. Philippe Baret. Your extraordinary support, patience, and always relevant feedback have inspired me to produce the best work possible. I have learned a lot from our discussions and by observing your exemplary approaches to research.

To my dearest Victoire, your incredible support and belief in my abilities have kept me motivated throughout this journey.

I am also thankful to my friends Oriane, Charles, Cloé, Sophie and Félix. Going through this journey by your side has been a daily source of joy. Additionally, I want to thank Antoine, Martin, and Loïc for the enriching conversations and the inspiration I draw from their own work.

I would like to express my deepest gratitude to my parents. Your support and advice for every project I undertake, and your unconditional love, have given me a solid foundation on which to build. My sister and brother also play an important role in this caring atmosphere, thank you.

Finally, I'd like to thank you, the reader, for your interest in this subject. I sincerely hope that you that you will find this reading enlightening and informative.

Timothée Lefebvre

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

LIST OF ABBREVIATIONS

AFOLU	Agriculture, forestry, and other land uses
AgMIP	Agriculture Model Intercomparison and Improvement Project
BEFM	Bio-Economic Farm Models
CGE	Computable general equilibrium
CGIAR	Consultative Group on International Agricultural Research
CR	Criterion
ERS	Economic Research Service
EU	European Union
FAO	Food and Agriculture Organization of the United Nations
GHG	Greenhouse gas
INRAE	National Institute of Agricultural, Food and Environmental Research
IPCC	Intergovernmental Panel on Climate Change
JRC	Joint Research Center
LP	Linear programming
MP	Mathematical programming
NLP	Non-linear programming
PB	Planetary Boundaries
PE	Partial equilibrium
PMP	Positive mathematical programming
PRISMA	Preferred Reporting Items for Systematic reviews and Meta-Analyses
SAFA	Sustainability Assessment of Food and Agriculture systems
SD	System dynamics
SDG	Sustainable Development Goals
UN	United Nations
USDA	United States Department of Agriculture
WUR	Wageningen University & Research

INTRODUCTION

As a major contributor to current sustainability issues, agriculture is facing many challenges. Agricultural policies are a major way for humankind to guide the agricultural system towards sustainability. Given the complexity of the agricultural system, mathematical models represent a powerful tool for supporting agricultural policymaking.

However, previous research has never drawn a full overview of the models operating at a macro level to support policymaking. The present master's thesis therefore focuses on ***policy-oriented macro-level models*** of the agricultural system.

The first objective of this work is to review policy-oriented macro-level models and to provide an overview of their main characteristics. This is done by performing a systematized literature review of the Scopus database. The second objective consists of analyzing the inclusion of sustainability themes in the selected models. The SAFA and Planetary Boundaries frameworks are used as references to define sustainability. The third objective is to identify the actors of the development and funding of policy-oriented macro-level models.

This work is divided into five parts. First, the "State of the Art" is organized in four chapters. The first chapter sets the context of the sustainability challenge and the role of agriculture. Next, modeling tools are presented, starting by a broad view of agricultural models to end with a definition and description of *policy-oriented macro-level models*. The third chapter outlines the policy process and the role of models in this process. Finally, the sustainability frameworks used in this work – SAFA and the Planetary Boundaries – are presented in the fourth chapter of the State of the Art.

The second part, the "Objectives", explicitly defines the general aim of this dissertation, which is subdivided into three objectives, on which the methodology is based.

The third part, "Methods", details the approach taken to perform the systematized review and the analysis.

The fourth part, "Results", presents the results obtained for each of the three objectives. The results are analyzed by model class, and by sustainability themes.

The fifth part, "Discussion", discusses and interprets the results. The most insightful findings are highlighted, and the results are compared with results of previous studies with a similar methodology. Finally, the discussion is concluded by a critique of the methodology follows and by recommendations for further research.

1 STATE OF THE ART

1.1 CONTEXT: THE SUSTAINABILITY CHALLENGE AND AGRICULTURE

Since 1950, many earth systems and socioeconomic trends have experienced unprecedented growth, a phenomenon termed the *Great Acceleration* (Steffen, Broadgate, et al., 2015). The year 1950 is considered a potential marker for the start of the *Anthropocene* (Zalasiewicz et al., 2015). On one hand, numerous socioeconomic indicators reflect significant improvements in human well-being, such as reduced poverty, higher education levels, and improved health care access. Conversely, the period is also marked by severe negative impacts, including climate change and biodiversity loss, which threaten the perennity of these advancements (Rockström et al., 2009). This dichotomy has given rise to the concept of sustainable development, defined in the *Brundtland Report* as “development that meets the needs of the present generation without compromising the ability of future generations to meet their own needs” (WCED, 1987). The challenge of sustainable development, or *sustainability challenge*, results from contrasting increasing demand on the one hand and diminishing resources and carrying capacity of the Earth system on the other hand (Dorph et al., 2016). More than thirty years after the Brundtland report, the discourse around sustainable development and sustainability has evolved and faced critique (Purvis et al., 2019; Swain, 2018). The current successor of the Brundtland Report is the Sustainable Development Goals (SDG) framework, adopted in 2015 by the United Nations (UN)(Swain, 2018).

Sustainability is commonly represented through three *pillars* or *dimensions*: environmental, economic and social (Purvis et al., 2019; WCED, 1987). However, the efforts to achieve sustainability goals can reveal synergies or require trade-offs, which necessitates setting priorities and making choices (Kanter et al., 2018; Nerini et al., 2017). This has led to the differentiation between "weak" sustainability, which treats all dimensions equally, and "strong" sustainability, which hierarchizes the dimensions, prioritizing the environmental dimension, followed by the social and finally the economic dimension (Bosselmann, 2010).

Each **sustainability *dimension*** (or pillar) can be subdivided into **sustainability *themes*,** which focus on a precise process. Each theme can be measured by one or several *indicators*. For example, climate change is a *theme* of the environmental *dimension*, and can be measured by the greenhouse gas emissions *indicator* (FAO, 2014).

1.1.1 Sustainability and agriculture

Among all sectors of activity, food systems and agriculture make a major contribution to several environmental and socio-economic impacts (Campbell et al., 2017). Several SDGs are associated with food systems and agriculture, as indicated by various authors who reference as few as 6 (Streimikis & Baležentis, 2020) and as many as 12 (Chaudhary et al., 2018) of the 17 SDGs. Regarding environmental impacts, agriculture, forestry, and other land uses (AFOLU) accounted for approximately 24% of global anthropogenic GHG emissions between 2007 and 2016, the most significant sources being enteric fermentation in ruminants (39%), nitrous oxide emissions from soil management practices (28%), manure management (10%), rice cultivation (9%), and agricultural energy use and other emissions (14%) (IPCC, 2014). Furthermore, agricultural activities are the largest driver of biodiversity loss through habitat fragmentation and deforestation, are responsible for >70% of freshwater use, occupy 40% of the earth's surface, and eutrophy and acidify natural terrestrial and aquatic ecosystems with agrochemicals (Clark & Tilman, 2017; Dudley & Alexander, 2017). These impacts will likely intensify with population growth and changes in dietary habits towards more meat-based diets (Tilman & Clark, 2014). Finally, agriculture depends on non-renewable resources such as fossil fuels (as a source of energy and raw material for agrochemicals) and phosphate rock (Kirschenmann, 2010; March et al., 2016; Murphy & Hall, 2011).

The food system also faces socio-economic challenges. Despite recent gains in productivity, around 820 million people in the world still suffer from hunger, and not only in poor countries (Gomez y Paloma et al., 2020). Moreover, many agriculture-dominated rural communities are suffering from social problems such as poverty, or declining employment opportunities (X. Zhang et al., 2021).

1.1.2 Current approaches towards sustainable agriculture

It is important to note that in the context of food and agriculture systems, there are two prevalent perspectives on the notion of "sustainability" (Schader et al., 2014): the **farm perspective** of sustainability describes whether the production activities are able to sustain themselves for an extended period of time. To that end, the agricultural production system must use its natural, social, and economic resources without depleting them, and be resilient enough to survive future changes. The **societal perspective**, as defined in the Our Common Future report (WCED, 1987), assesses whether a production system contributes to a sustainable development of society. This means that the impacts of the production system on the economic, social, and environmental resources of society are on average positive (Schader et al., 2014).

The urgent need to make the agricultural system more sustainable has given rise to several responses. These responses can be divided into *approaches* and *practices* (Muhie, 2022; Oberč & Arroyo Schnell, 2020). **Approaches** are ways of making agriculture more sustainable, defined by a set of principles (goals, philosophy, angle taken) and practices (practical implementation of the approach). Oberč & Arroyo Schnell (2020) provide an exhaustive list of these approaches, which include *agroecology*, *organic farming, permaculture*, *conservation agriculture*, *climate-smart agriculture*, *carbon farming*, *sustainable intensification*, among others. The authors conclude that many of these approaches share common practices. The most shared **practices** are crop rotation, cover and companion crops, mixed crop and intercropping, reduction of synthetic pesticide and mineral fertilizer use, reduction of tillage, and lower livestock densities. Other often-mentioned practices are diversification, nutrient management, and inclusion of landscape elements. In another attempt to overcome the debate by focusing on commonalities between approaches, Foley et al. (2011) propose four key strategies to make agriculture sustainable: (1) stop expanding agriculture, (2) close yield gaps, (3) increase agricultural resource efficiency, and (4) increase food delivery by shifting diets and reducing waste.

Although approaches to sustainable agriculture share common practices, they also share common challenges, which are cost, productivity and profitability, scalability and uptake, knowledge, and environmental sustainability (which is not guaranteed) (Oberč & Arroyo Schnell, 2020).

1.1.3 Policymaking to advance agricultural sustainability

Oberč & Arroyo Schnell (2020) conclude from their review that many of the great challenges of agricultural sustainability approaches find their solution partly in policy decisions. They argue that the solutions to knowledge-building and uptake can be policy-driven, and the issues of cost and profitability could be reevaluated if the societal costs of negative externalities are considered (Oberč & Arroyo Schnell, 2020). Consequently, the challenge for policymaking is to establish a market and regulatory environment that encourages farmers to follow the societally desirable path, adapted to every local context (Oberč & Arroyo Schnell, 2020). There is thus a need for tools able to predict which policies will best encourage the transition of agriculture to greater sustainability.

In this first chapter, we discovered the sustainability challenge and the need for policymaking to face it. In chapter 2, modeling tools to advance sustainability in agriculture are presented. Finally, in chapter 3, the link between modeling and agricultural policy is outlined (**Figure 1**).

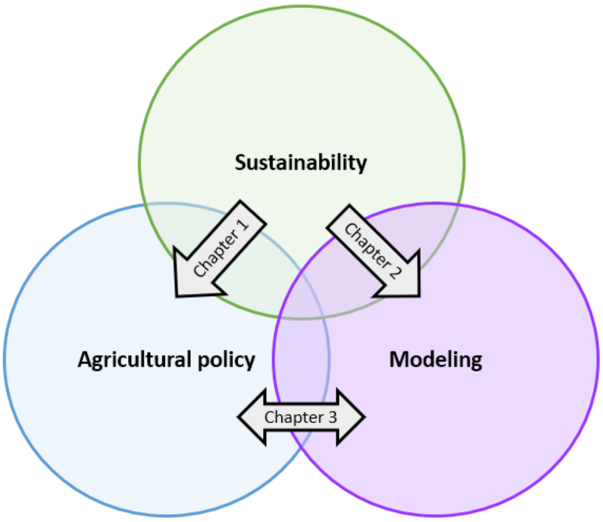

Figure 1: *Structure of the state of the art. The first three chapters will each present the intersection of two elements among sustainability, agricultural policies, and modeling*

1.2 AGRICULTURAL MODELING TO ADVANCE AGRICULTURAL SUSTAINABILITY

Advancing in solving the sustainability challenge with agricultural policies is a very complex task due to the multidimensional aspect of the sustainability challenge, the interactions between the sustainability goals (synergies and trade-offs) and the complexity of the global food system (Jones et al., 2017a; Kanter et al., 2018; Loring & Sanyal, 2021). Therefore, complex tools as mathematical models can prove instrumental to make progress on these topics. Mathematical models are a powerful tool for representing a complex system quantitatively and simulating its behavior, which is crucial to understanding how the system works and to guiding human decision-making (Jones et al., 2017a; Loring & Sanyal, 2021).

In this section, an overview of the field of agricultural modeling is provided. First, we detail the general characteristics of agricultural models. Second, we present a classification of agricultural models and a brief history of their development. Third, we delve deeper into the models operating at macro-level.

1.2.1 Agricultural models

A model is a simplified representation of reality used to understand, describe, and predict the behavior of complex systems. Models can be either **a mathematical or physical representation** of a system or theory that accounts for all or some known properties (EEA, 2024).

Recent decades have seen the emergence of a wide variety of agricultural models (see Box 1). Jones et al. (2017a) and Jones et al. (2017b) provide a history and classification of agricultural models, respectively. These models vary in scale, scope, and complexity, addressing aspects from individual crop growth to global trade dynamics and integrating agronomic, environmental, and economic factors.

Box 1

Agricultural model: definitions

As defined in the context of this work, an **agricultural model** or **agricultural system model** refers to a mathematical representation (or mathematical model) that simulates parts or the entirety of an agricultural system (as in Jones et al. (2017a)).

This definition is distinct from terms like **'agriculture model'** or **'agricultural model'**, which are sometimes used to describe overarching production systems, such as organic or conventional (Therond et al., 2017).

1.2.2 General characteristics of agricultural models

To understand the landscape of agricultural models, it is important to know which characteristics distinguish the different agricultural models. Several reviews and comparisons of models have been based on some of these characteristics (e.g. Heckelei et al., 2012; Schader et al., 2008). As main characteristics, we could mention the geographical scale, the treatment of time, and the coverage of agricultural sectors and other themes, the aim of the model…

The geographical characteristics of a model are not a single attribute: the *geographical level* (or *scale*) is the size (national, global,…) of the area covered by the model, called the *geographical scope*. Agricultural models range from narrow levels, such as the field level, to large levels as the global level. The different levels (or scales) and the corresponding users and relevant decisions are illustrated by **Figure 2** (Jones et al., 2017a).

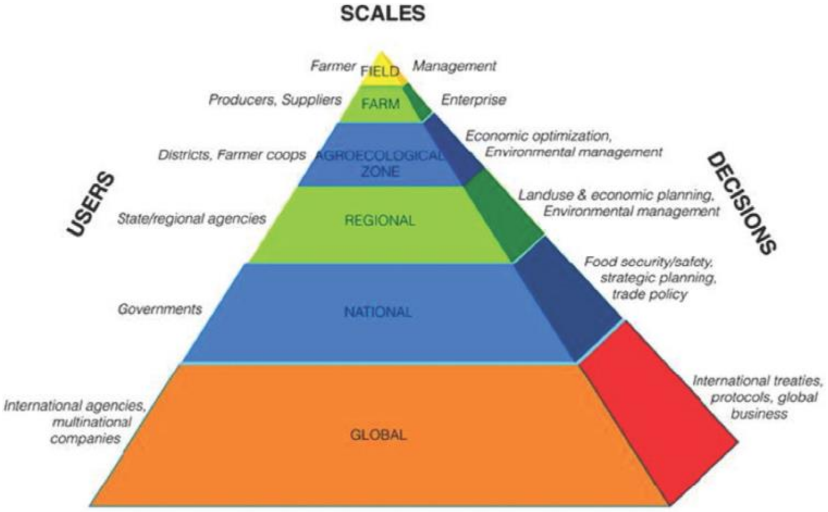

Figure 2: *Model scales, related users and decisions (Jones et al. 2017a)*

The treatment of time is another characteristic that distinguishes models. Models can either adopt a **comparative static**, or a **recursive dynamic** approach of time. Simulations with a comparative static approach are run in one single timestep and provide a single starting and ending situation as output. Recursive dynamic models work with several consecutive timesteps, which permits to track the system's evolution dynamically (Corong et al., 2017; Jayet et al., 2023).

Two motivations for model development are distinguished by Jones et al. (2017a): (1) increasing basic scientific understanding of an agricultural system, or (2) providing information to support decisions and policies.

1.2.3 A classification for agricultural models

Jones et al. (2017b) delineate seven primary classes of agricultural models: (1) cropping systems models, (2) reduced form summary crop models (3) livestock systems models, (4) pest and disease models, (5) landscape/watershed models, (6) economic models, and (7) aggregate agricultural systems models. Some of these classes are further divided in sub-classes. These classes must not be understood as perfectly separated model types; on the contrary, models can incorporate aspects of several classes and are inspired by the development of other model classes. These classes are better interpreted as directions of main research fields in agricultural modeling. **Table 1** displays the classes, of the potential sub-classes and the scale at which the models of each class operate. In the next section, each class is explained, examples of models are given and reference reviews are provided.

Table 1: *Model classification, adapted from Jones et al. (2017b)*

Class	Sub-class	Scale
1 – Cropping system and grassland models		Crop/field
2 – Reduced form summary crop models		Crop/field
3 – Livestock systems	Animal performance models	Animal
	Herd dynamics models	Animal/farm
	Integrated livestock systems models	Farm
4 – Pest & disease models	Statistical models	Individual/field
	Near-future pest & disease models	Individual/field
	Evolutionary models	Individual
5 – Landscape/watershed models: water & environmental quality		Landscape
6 – Economic models	Farm management linear programming models	Farm
	Econometric production models	Regional/national/global
	Risk behavior models	Farm
	Spatial equilibrium models	Regional or higher
	Structural simulation models	Regional or higher
	Calibrating optimization models	Regional or higher
	Computable general equilibrium (CGE) models	Regional or higher
	Integrated bio-economic models	Regional or higher
7 – Aggregate agricultural systems models		Regional and global

At the most narrow scale, some models focus on a single plant or animal individual. This is the case for models of classes 1 to 4: cropping systems models, reduced form summary crop models, livestock systems models and pest & disease models.

Cropping systems and grassland models (Class 1) were the first agricultural models to be conceived, in the 1960's. These models simulate crop growth and cropping systems in several ways. Functional-Structural Plant Models (FSPM) focus on the architecture of a single plant, while plant-soil-atmosphere models (also known as Crop Simulation Models (CSM)) include the field management practices of the farmer (plowing, fertilization) and weather data, and are able to describe physicochemical stocks and fluxes precisely (Muller & Martre, 2019).

Reduced form summary crop models (Class 2) are a simplified version of Class 1 models. They are used to be embedded in other model classes, such as economic models (Class 5), without increasing the data requirements too much.

The animal production equivalents of Classes 1&2 are **livestock systems models (Class 3)**. Jones et al. (2017b) identify three subclasses in this class: *animal performance models* at the animal level, *herd dynamics models* at the herd level, and *integrated livestock systems* that include whole livestock farms and their key components.

Pest and disease models (Class 4) are used at to predict the propagation of weeds, pests and diseases, both for plant and animal production. For this model class, it is important to make the distinction between statistical models, which predict the appearance of diseases based on correlated variables (e.g. climate, crop development stage), and mechanistic models which simulate the biological processes of the disease and the host. This field has pioneered the research on coupling models, such as disease models with crop models (Donatelli et al., 2017).

Landscape and watershed models (Class 5) are used for assessing environmental quality and water resource management in agricultural settings. Models in this category thus often have a focus on hydrology or nature and biodiversity, incorporated into a spatial framework. A key challenge in advancing these models is achieving a better integration of various scales and of multiple dimensions (crop, livestock, hydrology, ecologic and economic).

A number of **economic models (Class 6)** have been developed to predict the economic impact of policies and decisions, for various scales and purposes. Jones et al. (2017b) distinguish eight subclasses in this broad class: (1) farm management linear programming models, (2) econometric production models, (3) risk behavior models, (4) spatial equilibrium models, (5) structural simulation models, (6) calibrating optimization models, (7) computable general equilibrium models, and (8) integrated bio-economic models.

Farm management linear programming models are whole-farm models and employed to optimize farm management, and guide general decision-making, be it for farmers or policymakers. Janssen & van Ittersum (2007) provide a review of what they call Bio-Economic Farm Models (BEFM), updated by Reidsma et al. (2018).

Econometric production models represent the agricultural production and market at macro level with econometric and statistical equations. They are generally poorly linked with bio-physical and agronomic and have limited capacity to extrapolate outside the estimation sample.

Risk behavior models tackle the importance of risk and farmer decision-making in the behavior of the agricultural system. Recent research has extended this approach to investigate impacts of climate change.

Spatial equilibrium models try to integrate space into economic modeling. This is done particularly in two areas: trade between regions and countries, and spatially variation of agricultural production (land use change).

Structural simulation models are complex models of the agricultural system. Based on the concept of system dynamics (Forrester, 1968), they are modeling a system of components with their behavior and relationships to describe the system behavior. In that sense, various micro-economic models are often used together to simulate the macro-economic system. The diversity of models in this subclass includes: linear and non-linear programming models, household models, agent-based models (ABM), and other bio-economic models. An advantage of this micro-to-macro approach is the possibility to link local environmental and biophysical processes and to assess their impact at macro level.

Calibrating optimization models are based on a calibration technique called Positive Mathematic Programming (PMP, Howitt, 1995). These models were originally designed to optimize the agricultural system by maximize revenue, but they now integrate biophysical models and predict environmental harm (Mérel & Howitt, 2014).

Computable general equilibrium (CGE) models are economy-wide models, as they model supply and demand in almost all economic sectors. This contrasts with *partial equilibrium models*, which focus on a single economic sector (agriculture in our case). This approach is both a strength and a weakness: CGE models are very data-intensive and, even with a lot of data, they can hardly achieve a high level of accuracy.

Integrated bio-economic models are linking biophysical and economic models to represent the agricultural system. Again, this subclass can be seen as a modeling method rather than as a precisely definer class of models.

Finally, **aggregate agricultural systems models (Class 7)** try to address the issue of coupling models operating at different scales. These models disaggregate large-scale data (e.g. climate data) at narrow scale to feed a local level model (e.g. crop model), which is then aggregated back to a large scale.

1.2.4 Definition of policy-oriented macro-level models

In this study, the models will be divided in two categories: *micro-level models* and *macro-level models*. Micro-level models operate at landscape level or lower, while macro-level models operate at a level higher than the landscape level: regional, national, international, and global models. The two classes matching these levels are Class 6 (economic models) and Class 7 (aggregate agricultural systems models). However, the focus will be kept on models that are used (or can be used) for policy support: policy analysis (ex-ante) or policy evaluation (ex-post). Since most prominent policy instruments are from economic nature (Brooks & OECD, 2010; Weerahewa & Jacque, 2022), only Economic models (Class 6) will be considered. Box 2 summarizes the definition of policy-oriented macro-level models used in this study.

Box 2

Policy-oriented macro-level model: definition

In this study, by **policy-oriented macro-level model** (or simply macro-level models), we designate an agricultural model that meets the following criteria:

(1) Being part of class 6 (economic models) of the classification of Jones et al. (2017b) (see p.15).

(2) Operating at a level higher than the landscape level, i.e. at regional, national, international or global level.

1.2.5 Macro-level models terminology

The literature employs a fuzzy terminology to describe the various macro-level models, including sector models, agro-economic models, bio-economic models, agricultural supply models, and agricultural system models (Nehrey et al., 2019; Reidsma et al., 2018; Rizojewa-Silava et al., 2018; Schader et al., 2008; Schmidt et al., 2024). The classification of these models is primarily based on (1) the economic approach and (2) the mathematical approach, and it varies from study to study. In contrast, the classification by Jones et al. (2017b) is comprehensive and clearly defines each class. To the best author's knowledge, it is the only classification of this type. This classification will therefore serve as a the foundation for the analysis conducted in this study. Six classes of the classification correspond to the definition of policy-oriented macro-level models: econometric production models, spatial equilibrium models, structural simulation models, calibrating optimization models, computable general equilibrium (CGE) models, and integrated bio-economic models. In the following paragraphs, the principal economic and mathematical approaches used as classification by the literature are presented.

The economic approach distinguishes two economic equilibrium modeling approaches: **computable general equilibrium** (CGE) models and **partial equilibrium** (PE) models. While CGE models simulate all the sectors of the economy, PE models only focus on a few sectors, such as agriculture, crop production, or livestock production. CGE models have the advantage of being more comprehensive and modeling interactions between sectors: this is for example useful for bioenergy studies, which link agriculture, land use (land markets) and energy sectors. However, CGE models require a considerable amount of data, to reach a sufficient detail level. Conversely, PE models can reach a much better level of detail with less data: spatial and commodity disaggregation, linkage with physical quantities and environmental processes (Henseler et al., 2020).

The mathematical approach determines how a model is mathematically constructed. In the field of policy-oriented macro-level models, a first distinction is made between **econometric** and **mathematical programming** models (Gomez y Paloma et al., 2013). We can also identify **agent-based models** and **system dynamics models**.

Econometric models primarily rely on existing time-dependent data. Although validation inside the calibration sample is straightforward, they have poor extrapolation validity (Gomez y Paloma et al., 2013; Jayet et al., 2023). Consequently, these models are predominantly used for ex-post evaluation (Gomez y Paloma et al., 2013).

Mathematical programming (MP), simulation or structural models represent the agricultural system in a more detailed way, based on existing relationships and causalities. A set of equality and inequality constraints is used to define the production possibilities of the system (Gomez y Paloma et al., 2013; Jones et al., 2017b). The advantage of MP models is that they can contribute to the understanding of the system and underlying mechanisms, and that they have greater transferability to new situations, new policies. They are therefore useful for ex-ante policy analysis. Different mathematical approaches exits among MP models: **linear programming** (LP), **non-linear programming** (NLP), **positive mathematical programming** (PMP). Linear programming is the historical method, but is limited for the simulation of certain processes (e.g. risk and stochasticity) and is difficult to calibrate (Y. Zhang, 2018). With the introduction of improved solving techniques in the 1980s and 1990s, non-linear programming techniques were introduced to better represent complex mechanisms (GAMS, 2024; Robinson et al., 2015). Positive Mathematical Programming (PMP) was later introduced by Howitt (1995) to improve the calibration techniques (Heckelei et al., 2012; Mérel & Howitt, 2014).

Agent-based models (ABM) represent multiple agents (generally farms), their behavior and their interactions to simulate the agricultural system (Möhring et al., 2016). By doing so, they combine the advantages of farm-level models for modeling farm-specific policies, but without missing a comprehensive representation of the system (Lobianco & Esposti, 2010).

System dynamics (SD) have been introduced by Forrester (1968) as an approach for quantitatively representing complex systems over time. The methodology aims to understand how physical processes, information flows, and management policies interact, how these relationships form the "structure" of the system, and how this system behaves over time (Elsawah et al., 2017; Saysel et al., 2002).

1.2.6 Sustainability in the agricultural models

Macro-level models do not always include many sustainability themes. However, this is crucial for improving the understanding of how agricultural policies can advance sustainability. Especially, covering a large array of sustainability themes is necessary to capture synergies and trade-offs between sustainability objectives (Kanter et al., 2018; van der Linden et al., 2020).

Few studies have been carried out so far to outline how much sustainability is modelled in macro-level models (van der Linden et al., 2020). Due to this lack of overview, modelers risk constantly reinventing the wheel, adding up to the quantitative proliferation of models without participating to their qualitative improvement (van der Linden et al., 2020). At the author's best knowledge, there exist four studies addressing the inclusion of sustainability themes in agricultural models. None of these studies is focused on macro-level models.

Van der Linden et al. (2020) carry out a review of livestock models and analyze the inclusion of sustainability themes in these models. The scope is limited to European livestock models, and the models are assessed on 19 sustainability themes that are commonly used in livestock systems literature. Among these themes, twelve themes fall under the environmental pillar of sustainability. The study finds out that social sustainability themes are underrepresented in comparison to environmental and economic themes. Also, the number of sustainability themes addressed in the studied models seems to increase. Among environmental themes, nitrogen use, land use and GHG emissions are the most represented.

The review carried out by Bastidas-Orrego et al. (2023) focuses on 37 models and assessment methods used for policy evaluation. The study first reviews articles, following the PRISMA guidelines, and then performs an analysis of the tools used for the policy evaluation and their inclusion of sustainability. However, the presence of sustainability is only assessed at the level of the three sustainability dimensions/pillars (environmental, economic, social). In consequence, the provided overview is less detailed than a theme-based approach. Moreover, the selected research string results in a review that lacks comprehensiveness.

Reidsma et al. (2018) review bio-economic farm models in a broad and systematic way. The models are analyzed on a set of characteristics as farmer decision-making, description of activities, constraints, multifunctionality and end use. Among the characteristics measured to assess multifunctionality, the study lists different sustainability themes that are addressed by models. However, the analysis remains qualitative for sustainability themes, and only provide quantitative results at the level of sustainability dimensions. Moreover, the study adopts a very broad definition of "farm model", which leads to including macro-level models such as CAPRI.

In this older study, Rossing et al. (2007) have analyzed the multifunctionality of 15 integrated modeling approaches originating from France, Germany and the Netherlands. Multifunctionality is measured by the inclusion of environmental, social and economic indicators, which can be associated with sustainability themes. However, just like the previous study, However, the analysis remains qualitative for sustainability themes, and only provide quantitative results at the level of sustainability dimensions. Furthermore, the scope is limited to three countries, and the study dates back to 2007.

1.3 THE ROLE OF MODELING APPROACHES IN SHAPING AGRICULTURAL POLICY

In chapter 1, we concluded that the sustainability challenge in agriculture needed to be addressed partially by policymaking. In chapter 2, we discovered how the agricultural model and its sustainability features could be simulated with macro-level models. In this chapter, the place of macro-level modeling in the policy process is discussed to close the loop (**Figure 3**).

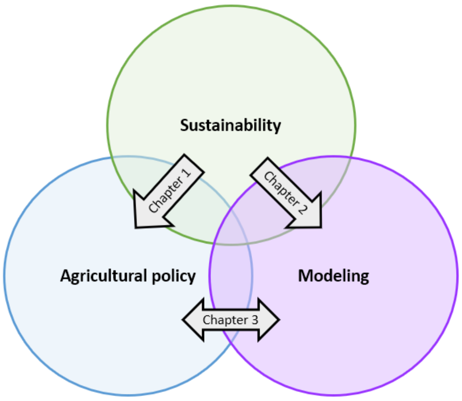

Figure 3: *Structure of the state of the art. The first three chapters will each present the intersection of two elements among sustainability, agricultural policies, and modeling*

1.3.1 Agricultural policy and the policy process

The agricultural sector is treated as a special and strategic economic sector, which needs special support from public authorities (Weerahewa & Jacque, 2022). This is described by the term of *agricultural exceptionalism* (Daugbjerg & Swinbank, 2012). Due to this special support and the challenges to face, making progress on sustainability in the agricultural sector necessitates the participation of agricultural policies (Oberč & Arroyo Schnell, 2020). In recent years, some sustainability themes have already become part of the agenda of agricultural policies (Brooks & OECD, 2010; Coderoni et al., 2021; Daugbjerg & Swinbank, 2012). However, a lot of progress still needs to be made. Tt is thus crucial to understand the policy process.

The policy process can be described through a series of stages (Weerahewa & Jacque, 2022):

(1) **Problem Identification**: Determine the root cause of a policy problem.
(2) **Policy Analysis**: Identifying possible policy options and picking the most appropriate option.
(3) **Strategy and Policy Development**: Planning how to develop, draft, and enact the policy.
(4) **Policy Enactment**: Following official procedures to get the policy authorized.
(5) **Policy Implementation**: Planning for successful policy implementation and achieving the desired outcomes.

During the *policy analysis* phase, scientific inquiry—often referred to as *policy research*—can provide the evidence base necessary for informed strategy and policy development. Effective policy analysis acts as a safeguard against policy failure in two critical ways: it informs the crafting of impactful policies through **ex-ante** policy analysis and refines active policies through **ex-post** policy evaluation, ensuring that they meet their targets and contribute positively to societal and economic objectives.

1.3.2 The role of macro-level models in the policy process

Agricultural policy research and analysis is predominantly conducted by (agricultural) economists (Weerahewa & Jacque, 2022). Indeed, economists are well-equipped with both the theoretical framework and the context-specific knowledge needed to analyze policies (mostly economic in nature) in the face of complex institutional, governance, and environmental challenges (Weerahewa & Jacque, 2022). Another reason for the predominance of economical science in policy support is the nature of agricultural policy instruments. Brooks & OECD(2010) distinguish (1) market interventions; (2) provision of public goods, (3) income transfer, and (4) changing institutions.

Economic models offer the advantage of permitting numerous simulations at varying degrees of precision for a relatively low cost. They can also capture complex system interactions and feedback loops. The downside is that they rely on many hypotheses and simplifications. However, since absolutely realistic valid models do not exist, it is enough to have a model "*whose form and content are just sufficient to solve a problem*" (Phillips, 1989, p. 108; cited in Shi & Gill, 2005).

In terms of geographical level of the model, it must be adapted to the corresponding policies. While older agricultural policies (such as taxes and price support) targeted every actor equally, the evolutions of agricultural support (since the 1990's), such as decoupled income transfers or greening measures in the EU, can be farm-specific (Anderson et al., 2014; Gomez y Paloma et al., 2013). Therefore, recent years have seen a surge in farm-level models for policy analysis, replacing the older aggregated models (Gomez y Paloma et al., 2013; Reidsma et al., 2018). However, higher level models are still required for proper understanding of the interactions between farms, the landscape, the market, and trade, especially in a globalizing food system (Lassaletta et al., 2014). Meyers et al. (2010, p. 134) point that out: "*Bigger models are better. A model that is too narrow (…) is likely to miss many issues of great importance*", however warning that "*it is not always better to expand the size and scope of a model. The bigger the model, the more time and resources it takes to build and maintain and the greater opportunity for modeling error.*"

Macro-level models, which all belong to the class of Economic models (section 1.2.3) and operate at broad level, could thus be adapted for policy analysis. And indeed, macro-level agricultural models are used for policy analysis in many studies (some prominent examples: Bastidas-Orrego et al., 2023; Britz & Mittenzwei, 2015; EC, 2024b; Jayet et al., 2023; OECD-FAO, 2022; Valera et al., 2023).

1.4 OPERATIONALIZING SUSTAINABILITY: SUSTAINABILITY FRAMEWORKS

Until now, sustainability has been used as a concept without clear definition. However, to enhance the sustainability of the agricultural system with the help of models, it is important to use common metrics to define and measure the sustainability outcomes of agricultural approaches or practices. Numerous authors have proposed methodologies and indicators to measure the sustainability of agricultural systems, for several purposes (reviewed, discussed and compared by de Olde et al., 2017; Desiderio et al., 2022; Janker & Mann, 2020; Lebacq et al., 2013; Schader et al., 2014; Van Passel & Meul, 2012). A broad overview of these *sustainability tools*, provided by the "SAFA Guidelines" report (FAO, 2014), is presented in **Table 2**. While some tools operate at a high level, for example planning tools to guide policymaking, other tools target the value chain of a product (VSS and life cycle tools), or the narrow farm-level for certain assessment tools.

Table 2: *Overview of different sustainability tools (FAO, 2014)*

Tool	Scope/purpose	Example
Planning	Policy	National sustainable development strategies, SDGs, SAFA
Reporting framework	Organizations	Global Reporting Initiative, SAFA
Directories (meta-level)	Standards, codes & frameworks	ITC Standards Map
Benchmarks	Standards, codes & frameworks	SSTI, GSCP
Voluntary Sustainable Standards (VSS)	Products	FSC, Fairtrade, Rainforest Alliance
Assessment: Life Cycle Tools	Products & production	Social-LCA, The Sustainability Consortium
Self-assessment and data sharing platforms	Production	SAI Platform, LEAF, People4Earth
Assessment & impact tools	Production	RISE, COSA, SAFA

The main challenges faced by these tools are data availability, the choice of the appropriate tool and method for a particular use, the management of potential trade-offs and synergies between different sustainability objectives (how to prioritize?), the choice of the right scope, the trade-off between scope and precision (Kanter et al., 2018; Lebacq et al., 2013; Schader et al., 2014).Two frameworks in particular are presented more in detail in the following sections: the Planetary Boundaries (PB) framework (section 1.4.1) and the Sustainability Assessment of Food and Agriculture systems (SAFA) framework (section 1.4.2). The choice of these two frameworks is explained by the topic of this work, i.e. using sustainability tools to evaluate the inclusion of sustainability themes in policy-oriented macro-level models (see section 1.2.6).

In this regard, these frameworks have several advantages regarding the other sustainability tools. First, they both have a prominent place in the sustainability literature, but also have a large reputation outside the scientific world. This is important since our analysis occurs in the context of the science-policy interface. Secondly, both frameworks have a large and versatile approach to sustainability, while remaining precise in the definition of sustainability. SAFA also has the advantage of having been used for a similar purpose by Schader et al. (2014). Moreover, SAFA is one of the rare tools adding a fourth dimension to sustainability, "governance" (Nadaraja et al., 2021). Finally, both frameworks show a good complementarity (see section 1.4.3).

1.4.1 Planetary boundaries

The Planetary Boundaries (PB) framework is a reference framework of sustainability. The PBs have been coined by Rockström et al. (2009) and subsequently updated by Steffen et al. (2015) and Richardson et al. (2023). The authors have identified nine critical environmental processes of the Earth system. For each process, they propose a boundary (threshold level) that must not be exceeded in order to keep the Earth system in what they call the safe operating space (SOS) for humanity, a Holocene-like stable state of the Earth system permitting human development.

The nine Planetary Boundaries (PBs) are (1) climate change, (2) change in biosphere integrity, (3) stratospheric ozone depletion, (4) ocean acidification, (5), biogeochemical flows: P and N cycles, (6) land system change, (7) freshwater change, (8) atmospheric aerosol loading, (9) novel entities (**Figure 4**, Richardson et al., 2023). The detailed control variables and boundaries can be found in Annex 1 (p. 70).

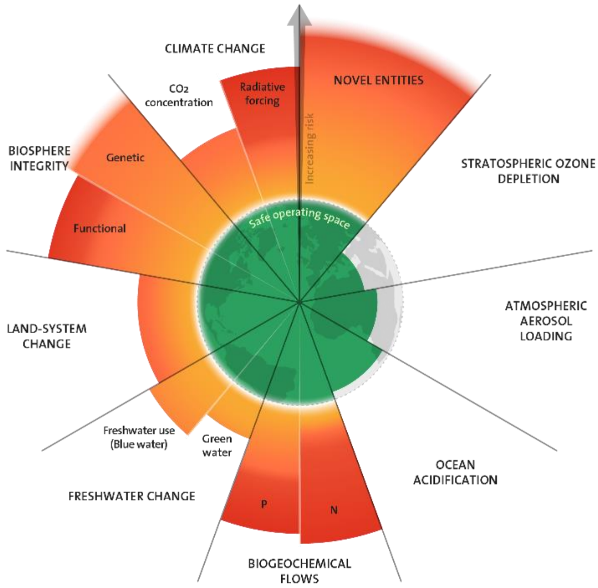

Figure 4: *Representation of the nine Planetary Boundaries. The green zone represents the Safe Operating Space (SOS) while a crossed boundary is represented in red (Richardson et al., 2023).*

The PBs and SOS concepts have been widely cited (>3500 times) and used by both academia, industry and government (Downing et al., 2019; Ryberg et al., 2020). Further research on interactions between PBs have identified climate change and biosphere integrity as a "core PB", which have the greatest interactions with all other boundaries (Lade et al., 2020). The PBs have also been criticized: the concept and realization of the framework have been questioned, but above all the applications of the PBs by other authors (e.g. downscaling) have been heavily criticized (see Biermann & Kim, 2020 for a review of the critics).

However, the PBs have remained a reference regarding environmental harm of human activities. Due to their reputation and scientific approach, they are used in this study as a standard for sustainability next to the SAFA framework.

1.4.2 Sustainability Assessment of Food and Agricultural systems (SAFA)

The Sustainability Assessment of Food and Agriculture systems (SAFA) framework has been published by the Food and Agriculture Organization of the United Nations (FAO) in 2014 (FAO, 2014). The goals of SAFA are threefold (FAO, 2011):

1. Define a **sustainability framework** to define sustainability in a practical context
2. Provide international **guidelines** on sustainability assessment (*SAFA Guidelines*)
3. Based on the Guidelines, develop a **tool** for the use of food businesses to assess and improve their sustainability (*SAFA Tool*)

The SAFA Framework divides sustainability into four pillars (environmental integrity, social well-being, economic resilience & good governance), 21 themes, 58 sub-themes, and 116 indicators (**Figure 5**, FAO, 2014). The complete list of themes and subthemes can be found in Annex 2 (p. 71).

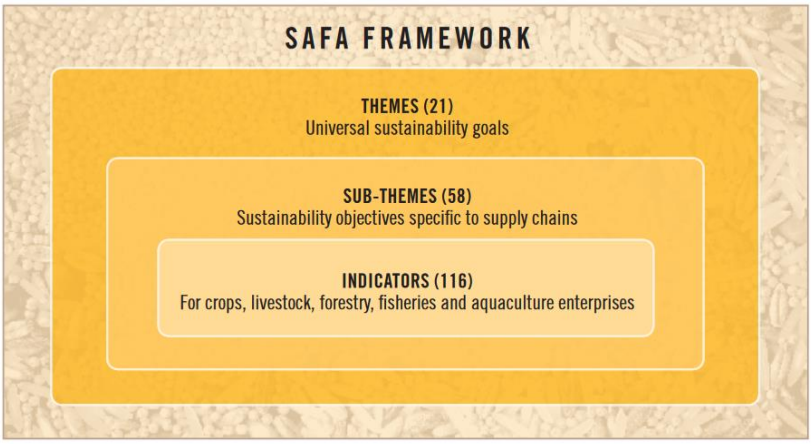

Figure 5: *Different levels of the SAFA framework, and application scopes*

The 116 indicators specified in the SAFA Guidelines (FAO, 2014) are categorized into three types: Target-based (T), Practice-based (R) and Performance-based (P), in increasing order of relevance. While the 116 default indicators offer a robust starting point, the SAFA methodology is adaptable to include other relevant indicators.

Figure 6 details the four dimensions (or pillars) and 21 themes of the SAFA framework.

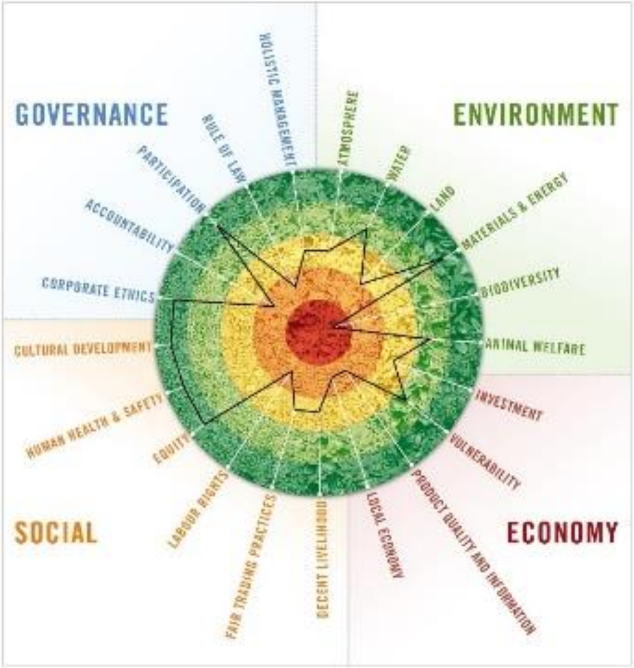

Figure 6: *Four dimensions and 21 themes of the SAFA Framework*

1.4.3 Comparative analysis of SAFA and PB: Assessing similarities and divergences

The SAFA and PB frameworks are complementary in evaluating sustainability in agricultural models. Indeed, the PB framework has an environmental focus and a quantitative approach, while the SAFA framework covers the three dimensions of sustainability and is more qualitative. While the SAFA framework has been designed specifically for agriculture and food systems and therefore addresses sustainability through the agricultural point of view, the PBs are centered on the Earth systems and its disturbance by human activities. The PBs have however also applied to agriculture by several studies (e.g. Campbell et al., 2017). The approach of the frameworks could, therefore, be linked to the two perspectives of sustainability in agriculture: the SAFA framework corresponds more closely to the **farm perspective** of sustainability, while the PBs correspond to the **societal perspective** of sustainability (see section 1.1.2).

An example can be found in their approach to the "land" theme. The SAFA sub-themes for land are (1) soil quality and (2) land degradation (through soil degradation and desertification), two processes that primarily affect the farmer's ability to maintain production in the long term. Conversely, the PB approach for "land" is the process of land use change. This process may not have unsustainable consequences at the local level, but it becomes a threat to sustainability at the societal level because of the disruption to the Earth's system.

2 OBJECTIVES

The primary aim of this Master's thesis is to shed light on the current use of macro-level agricultural mathematical models in the context of policy analysis while evaluating their incorporation of sustainability dimensions. This endeavor aligns with the recommendations by Reidsma et al. (2018) for thorough and consistent evaluations and comparisons of models.

To achieve this goal, three objectives have been defined:

Objective 1

Offer a comprehensive survey of macro-level agricultural mathematical models currently employed in policy analysis, detailing their mathematical and economic approach, geographical scope and treatment of time, and applications.

Objective 2

Evaluate how these models integrate various dimensions and themes of sustainability and identify the reasons and challenges associated with this integration.

Objective 3

Identify the designers and funders of these models, detailing their roles and contributions in the development of the models.

3 METHODS

This section introduces the methods that are used to answer the research questions. The research is conducted in three phases. **Phase 1** is a systematized review of the mathematical models that are the subject of this research, i.e. policy-related macro-level agricultural models (defined in Section 1.2.4). In **Phase 2**, these models are classified according to the classification of Jones et al. (2017b) (see **Table 3**) to provide an overview of the existing models. Finally, **Phase 3** is an in-depth analysis of these models: their main characteristics, their inclusion of sustainability themes and the main actors of their development are extracted from the reference documentation of the models. The whole process is summarized by **Table 3**, and will be outlined in the following sections.

Table 3: *Overview of the methodology of this study.*
For each phase, goal, data type (input), inclusion criteria, data treatment and output

Phase title	**Phase 1:** Screening and inclusion	**Phase 2:** Classification	**Phase 3:** Analysis
Goal	Collect the literature about policy-oriented macro-level agricultural models	Provide a classification of the models and the frequency of named models' appearance	Assess the inclusion of sustainability themes in the named models and provide insights of the role of models in the science-policy interface
Data type/input	Articles from Scopus search	Eligible articles (title + abstract + full text if necessary)	Macro-level models with a name
Inclusion criteria	Research string	Criteria 1 to 4 (Table 4)	Criteria 1 to 5 (Table 4)
Data treatment	Screening and assessment for eligibility: Criteria 1 to 4 (Table 4)	1. Classification into classes (see Table 5) 2. Identify models' names: Criterion 5 (Table 4)	1. Searching for reference documentation of each model 2. Extracting models' main characteristics and inclusion of sustainability themes
Output	Eligible articles	Macro-level models with a name	Analysis results for each model

3.1 PHASE 1: SYSTEMATIZED REVIEW OF THE MODELS

The first phase is a *systematized review* of policy-related macro-level agricultural mathematical models. A systematized review is a streamlined approach that provides a structured synthesis of existing literature, similar to a systematic review, but without the exhaustive breadth and comprehensive scope typically associated with systematic methods (Grant & Booth, 2009). The methodology is, therefore, inspired by the *PRISMA guidelines for updated systematic reviews* (Page et al., 2021). Like systematic reviews, the review process is transparently reported, and efforts are made to ensure comprehensiveness. However, unlike a systematic review, this systematized review does not claim to be systematic, lacks bias analysis, and is not registered in any review database. It is also based on a single database, Scopus.

The review process consists of three steps: (1) the *identification* papers from a database, (2) the *screening* to assess eligibility, and (3) the *inclusion* of eligible papers for further analysis.

3.1.1 Identification

In the identification phase, we employ a double approach, utilizing two distinct sources to identify the models.

Database search

The Scopus database (www.scopus.com) is used to identify any study that uses policy-oriented macro-level models. To that end, the following research string is used:

Agricultur AND ("agricultural policy" OR "policy support" OR "policy advice" OR "policy analysis" OR "policy assessment" OR "policy evaluation") AND (sector OR system) AND ("mathematical model" OR "mathematical programming" OR modeling OR simulation)*

The string is designed to:

- Capture the broad agricultural context.
- Focus on studies that engage with policy using targeted keywords to filter out tangential mentions of 'policy'.
- Define the "macro" scope of the model as either sectoral or systemic.
- Ensure the inclusion of mathematical and simulation models, excluding non-relevant uses of the term 'model'.

Additional sources

In addition to the Scopus search, we scrutinize the websites and publications of key organizations known for their involvement in policy decision-making. While Scopus is expected to yield a comprehensive list of models, this step serves as a precautionary measure to capture any prominent models that might have been missed, thereby reinforcing the thoroughness of our search.

The following organizations are chosen, based on Pandey (2014):

- the European Commission (e.g. MIDAS (EC, 2024b)),
- the US Department of Agriculture (USDA),
- the UN Food and Agriculture Organization (FAO),
- the research centers of the CGIAR (e.g.: IFPRI, IRRI, CIMMYT,…),
- the AgMIP (Agriculture Model Intercomparison and Improvement Project).

3.1.2 Screening & inclusion

Once the studies are identified, they are screened to assess their eligibility for inclusion in the next phase. To do this, the outcome of the *identification* step is extracted in an Excel database. Each study's abstract is then reviewed against predefined eligibility criteria, specifically criteria CR1 to CR4 as outlined in **Table 4**. Criterion CR5, which pertains to a more advanced level of selection, is reserved for application during Phase 2 of the screening process. At this stage, no criterion is added on the policy orientation of the model, since assessing this from the model's title and abstract is a difficult task. Instead, the research string is considered to ensure a link, or the intention of a link, with policy-making.

Table 4: *Eligibility criteria. Criteria CR1 to CR4 enable studies to move from phase 1 to phase 2, and criterion CR5 allows models to move to phase 3.*

Phase		Criteria	Inclusion	Exclusion
From Phase 1 to Phase 2	CR1	Language	English language	Other languages
	CR2	Theme	Focus on terrestrial agriculture	Other sectors (bioenergy, environment) or aquatic cultures
	CR3	Topic	Review, discussion, comparison or implementation of one or more models	Models are not main topic of article
	CR4	Level	Macro-level	Farm, field or crop level
From Phase 2 to Phase 3	CR5	Name	Model has a name	Model has no name

3.2 PHASE 2: CLASSIFICATION AND NAMING

After their selection, the included studies undergo a thorough examination to catalogue the mathematical models employed within. Each model is recorded by its given name and is categorized into a specified model class, which encompasses similar models that share certain methodological approaches or are designed to address similar problems within the agricultural domain. The classes are based on the classification established by Jones et al. (2017b), as detailed in **Table 5** and presented in section 1.2.3.

Table 5: *Classification of macro-level models, adapted from Jones et al. (2017b)*

Class	Scale
Econometric production models	Regional/national/global
Spatial equilibrium models	Regional or higher
Structural simulation models	Regional or higher
Calibrating optimization models	Regional or higher
Computable general equilibrium (CGE) models	Regional or higher
Integrated bio-economic models	Regional or higher

The outcome of this stage is a structured inventory of models that offers insights into the prevalence of each model class and the naming conventions employed.

3.3 PHASE 3: DETAILED ANALYSIS OF MODELS

In Phase 3, a limited number of models are selected for further analysis. This analysis aims to identify (1) the main characteristics of each model, (2) the model's inclusion of PB and SAFA frameworks' themes, and (3) the main actors of the model's development and use.

From the models included in Phase 2, we only keep the models with a name (criterion CR5, **Table 4**). Indeed, the designation of a name to a model is a key factor in its potential for reuse by the research community (Reidsma et al., 2018). Models lacking a distinct name tend to be custom solutions, crafted for specific, one-time research applications, whereas named models generally signify a broader, more sustained research initiative and are crafted for longer-term applicability and recognition. This criterion is common amongst model reviews in scientific literature (Heckelei et al., 2012; Moulogianni, 2022; Nehrey et al., 2019; Reidsma et al., 2018; Schader et al., 2008; Schmitz et al., 2014; Wiborg, 2000).

To start the analysis, the reference documentation of each model is sought out by reviewing citations from the papers selected after Phase 2. This documentation typically provides the most comprehensive description of the model and is often authored by the model's creators.

For models with multiple versions, only the documentation corresponding to the most recent version is selected, to ensure up-to-date analysis and relevance.

Next, the reference documentation is studied to fill in the database. **Table 6** details the first segment of the database, which outlines model characteristics such as name, class, reference publication, and various model attributes, including mathematical type, spatial coverage, and sectoral focus, along with the coverage of key variables such as water, climate, and market dynamics.

***Table 6:** First part of the database: model characteristics, possible values and explanation*

Characteristic	**Possible values**	**Explanation**
Model name	[model name]	/
Model class	[model class]	Following Jones et al. (2017b) classification (section 1.2.3)
Reference documentation	[citations]	Citation of the reference documentation
Economic approach	CGE/PE/blank	See section 1.2.5
Mathematical approach	ABM, PMP, LP, econometric model…	See section 1.2.5
Geographical level	Global/international/national/regional	/
Geographical scope	[e.g.: global/EU28, Germany,…]	Which geographical unit precisely
Used database	[names of database]	Main prominent data sources
User interface	YES/NO	Does the model have a dedicated user interface ?
Program or programming language	[name of program/programming language]	All programs or languages used to implement the model

Subsequently, the database is augmented by evaluating the inclusion of SAFA and PB themes, as specified in **Table 7** (FAO, 2014; Richardson et al., 2023). We investigate whether each model incorporates indicators—or plausible proxies—pertinent to the sub-themes of PB and SAFA. For example, mineral fertilizer use can serve as a proxy for N cycle disruption (P5). This process entails a keyword search within the model's reference documentation to identify if any variables or parameters correspond with those keywords. The detailed lists of PB and SAFA indicators are available in Annex 1 and Annex 2.

***Table 7:** Second part of the database: inclusion of SAFA and PB themes. Each sustainability theme has its identification code, where the first letter stands for: P – PB themes; E – environmental SAFA themes; G – governance SAFA themes; C – economic SAFA themes; S – social SAFA themes*

Code	**Sustainability theme**	**Explanation**
P1&E1	Climate change	Caused by greenhouse gas (GHG) emissions
P2&E4	Change in biosphere integrity	Or biodiversity loss
P3	Stratospheric ozone depletion	Ozone layer depletion, for agriculture mainly due to N_2O emissions
P4	Ocean acidification	Is due to the higher concentration in atmospheric CO_2
P5	Biogeochemical flows: P & N cycle	Inputs and outputs of production; great impact of fertilizers
P6	Land system change	Also called land use and land use change (LULUC)
P7&E2	Water use & quality	Freshwater change: blue & green water
P8&E1	Atmospheric aerosol loading	Aerosols from agriculture mainly originate in burning culture residues
P9	Novel entities	Introduction of novel entities (plastic, pesticides) in the environment
E3	Land	Soil quality and land degradation

E5	Materials and Energy	Material use, Energy use, Waste reduction & disposal
E6	Animal Welfare	Animal health, Freedom from stress
G1	Corporate Ethics	Mission Statement, Due diligence
G2	Accountability	Audits, Responsibility, Transparency
G3	Participation	Stakeholder dialogue, Grievance procedures, Conflict resolution
G4	Rule of Law	Legitimacy, Remedy, restoration, prevention, Civic responsibility, Resource appropriation
G5	Holistic Management	Sustainability management plan, Full-cost accounting
C1	Investment	Internal investment, Community investment, Long-ranging investment, Profitability
C2	Vulnerability	Stability of production, Stability of supply, Stability of market, Liquidity, Risk management
C3	Product Quality and Information	Food safety, Food quality, Product information
C4	Local Economy	Value creation, Local procurement
S1	Decent Livelihoods	Quality of life, Capacity development, Fair access to means of production
S2	Fair Trading Practices	Responsible buyers, Rights of suppliers
S3	Labor Rights	Employment relations, forced labor, child labor, freedom of association, right to bargaining
S4	Equity	Non discrimination, Gender equality, Support to vulnerable people
S5	Human Health and Safety	Workplace safety and health provisions, Public health
S6	Cultural Diversity	Indigenous knowledge, Food sovereignty

Not all SAFA and PB themes are assessed individually. Indeed, E1 (atmosphere) would duplicate P1 (climate change) and P8 (atmospheric aerosol loading). Therefore, E1 is merged with P1 and with P8. Furthermore, the E2 and P7 themes (water) are merged, as well as the E4 and P2 themes (biodiversity) (**Table 7**).

Finally, the institutions which are actors of the model development and funding are collected to collect the database. For the model development, all public institutions and research groups are collected, but only the two first universities (following the order of the authors). Additionally, funding sources are collected separately. Finally, if the model is at the center of a research project or modeling network, the latter is reported too.

4 RESULTS

In this chapter, we describe the results of the systematized review and of the further analysis. Section 4.1 provides an overview of the review process (Phase 1 & Phase 2). Section 4.2 presents the characteristics of the analyzed models (Objective 1). Section 4.3 details the inclusion of sustainability themes in the models (Objective 2). Finally, section 4.4 discusses the actors of macro-level modeling (Objective 3).

4.1 OVERVIEW OF THE REVIEW PROCESS

4.1.1 Phase 1: Systematized review: identification, screening & inclusion

In the identification stage, the first stage of the systematized literature review, the research string yielded 1064 records on Scopus. The screening for eligibility excluded 532 papers for the following reasons: 39 were not in English (criterion CR1), 119 were not focusing on agriculture (criterion CR2), 62 were not discussing a mathematical model (criterion CR3), and 305 were discussing a model at a level other than the macro level (criterion CR4). Three other records did not have an abstract, and four records were a duplicate of another records. The remaining 532 records were included in Phase 2. The whole process is documented in the Supplementary Material.

Additionally, the screening trough the websites and reports of prominent institutions (see section 3.1.1) yielded ten relevant models which were not yet present in the review. From these ten models, six corresponded to the eligibility criteria to be included in Phase 2. **Figure 7** shows the PRISMA flow diagram providing an overview of the review process and subsequent phases.

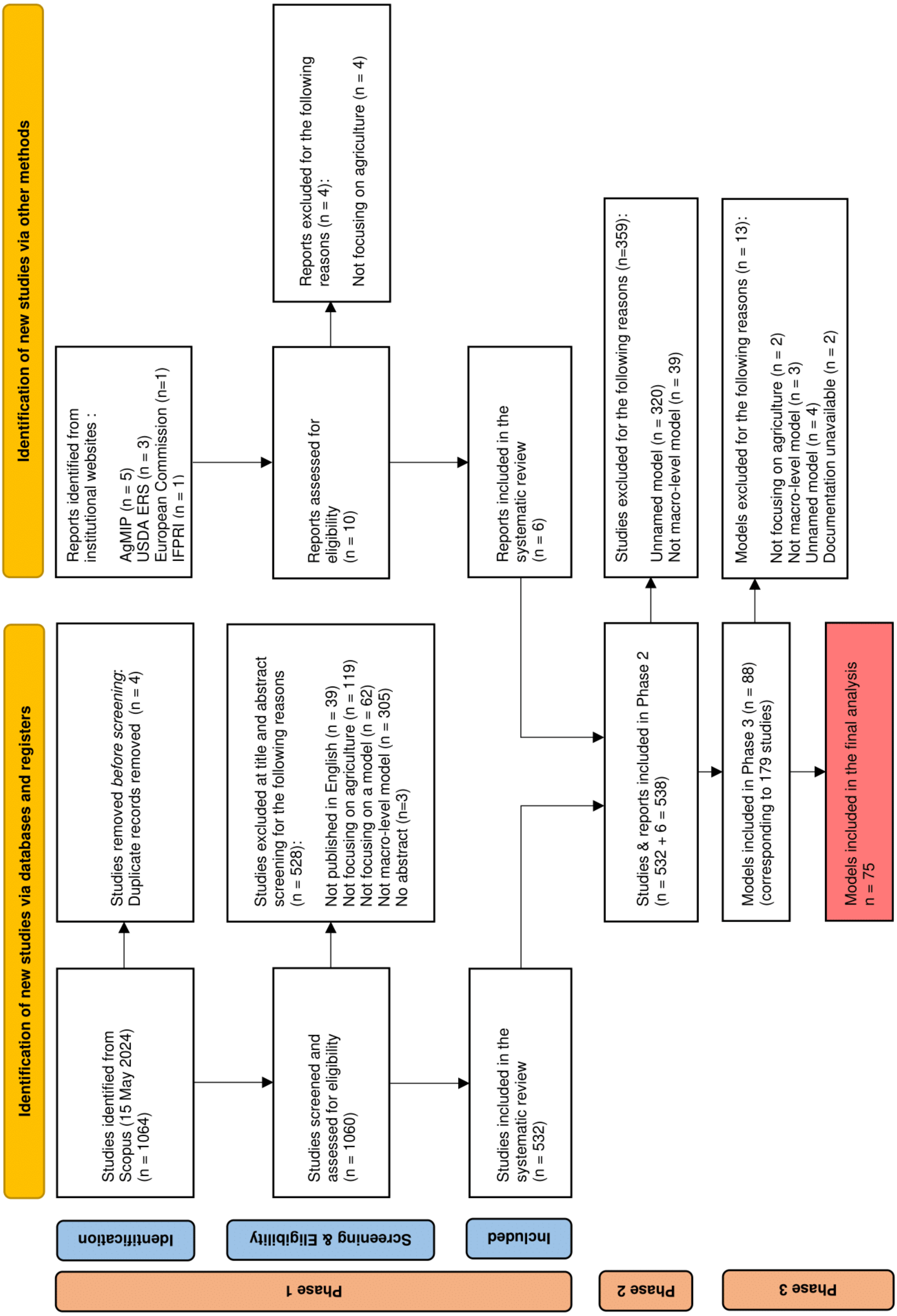

Figure 7: *PRISMA flow diagram. Adapted from Page et al. (2021)*

Figure 8 shows the number of included and excluded studies for each year. A strong increase can be observed in the middle of the 2000-2010 decade.

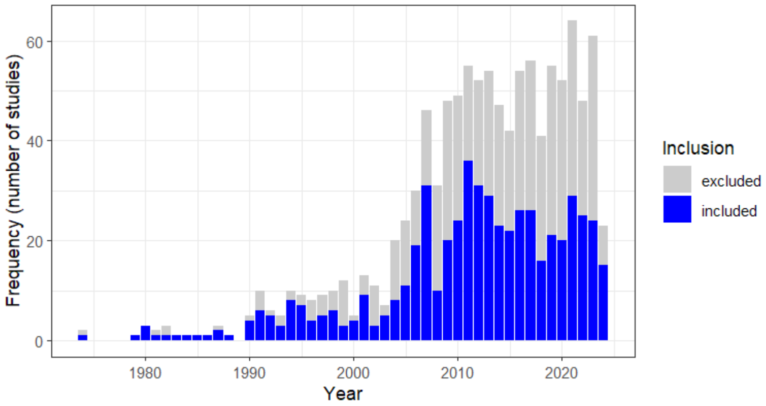

Figure 8: *Number of included and excluded studies per year*

4.1.2 Phase 2: Classification and naming

From the 538 articles analyzed in Phase 2, 320 articles were discussing a model without a name. Moreover, 39 models did not correspond to the definition of a macro-level model (see section 1.2.4, p. 18).

The remaining 179 articles were discussing at least one macro-level model with a name. Since models can be present in several articles, removing the duplicates resulted in 88 models that could go on to Phase 3.

4.1.3 Phase 3: Model analysis

In Phase 3, we analyzed the 88 models resulting from the selection of Phase 2. During this stage, an additional 13 models were excluded for various reasons: two models were not focused on agriculture (eligibility criterion CR2), three models did not correspond to the macro-level definition (criterion CR4, see section 1.2.4, p.18), and four models lacked a name (criterion CR5). Regarding the latter, the names identified in Phase 2 were actually associated with projects encompassing several models, not with individual models. These instances were mistakenly identified as named models during phase 2, but the more detailed analysis in Phase 3 revealed that these names did not refer to models. Finally, the documentation of two models was impossible to access, and two models were an older version of a more recent model.

In the end, the final analysis of Phase 3 was applied to 75 models (**Figure 7**). The results of this analysis are presented in the following sections.

4.2 CHARACTERISTICS OF REVIEWED MACRO-LEVEL MODELS (OBJECTIVE 1)

This section outlines the general characteristics of the 75 models analyzed in Phase 3 of the present study. The full results presented in the next section are summarized in Annex 3 (**Table 9**, p. 72).

4.2.1 Name, class, type, and mathematical approach

Among the 75 models, CAPRI was the most cited with almost 30 citations (**Figure 9**). The AGMEMOD, GTAP and RAUMIS models follow without around ten citations.

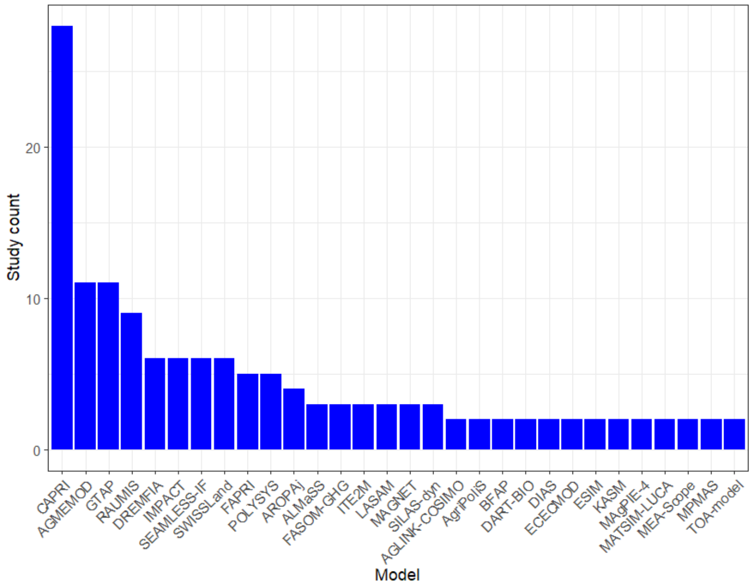

Figure 9: *Frequency of model citation in studies. Models cited in just one study are excluded from the graph*

The classes of the 75 models (based on the classification of Jones et al. (2017b)) are represented in different orders of magnitude. 32% of the models are structural simulation models, 24% spatial equilibrium models, 15 % integrated bioeconomic models, 12% econometric production models, 9% Computable General Equilibrium (CGE) models, and 8% calibrating optimization models (**Figure 10**). These frequencies are relatively similar to the frequencies of all models in phase 2, including unnamed models. **Figure 10** shows the proportion of the model classes in Phase 2 and Phase 3. *Structural simulation models* and *spatial equilibrium models* are proportionally more frequent among the 75 named models of Phase 3 than among the 538 studies of Phase 2.

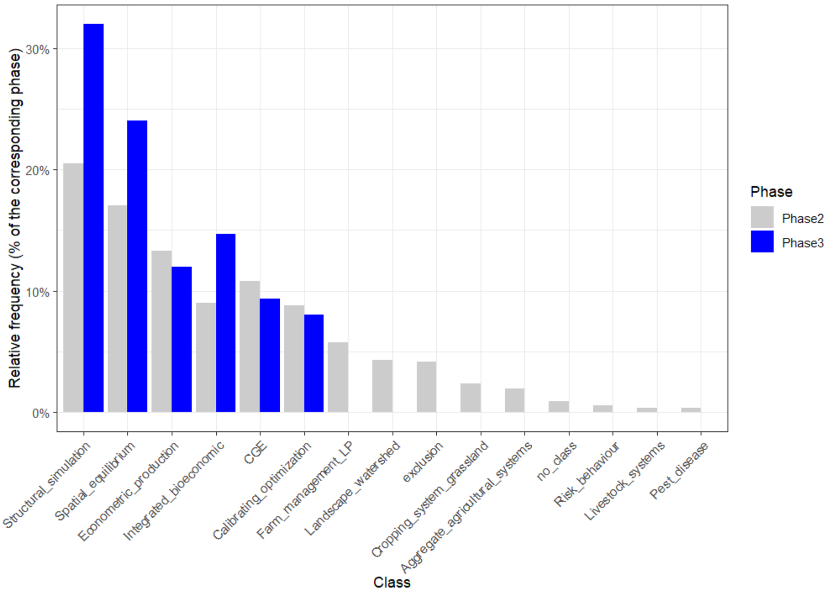

Figure 10: *Relative frequency of model classes in phase 2 and phase 3. Only 6 classes (in blue) are eligible for phase 3*

Figure 11 displays the mathematical and economic approaches defined in section 1.5.3. In terms of mathematical approach, econometric models are the most frequent, while the other approaches (agent-based models (ABM), mathematical programming (MP), non-linear programming (NLP), positive mathematical programming (PMP)) have similar frequencies. Only linear programming (LP) models are slightly under-represented. Finally, 15 models did not specify a mathematical approach.

Regarding economic approaches, partial equilibrium (PE) models dominate with 25 models, while 7 models use the computable general equilibrium (CGE) approach. Furthermore, 43 models did not use a particular economic approach.

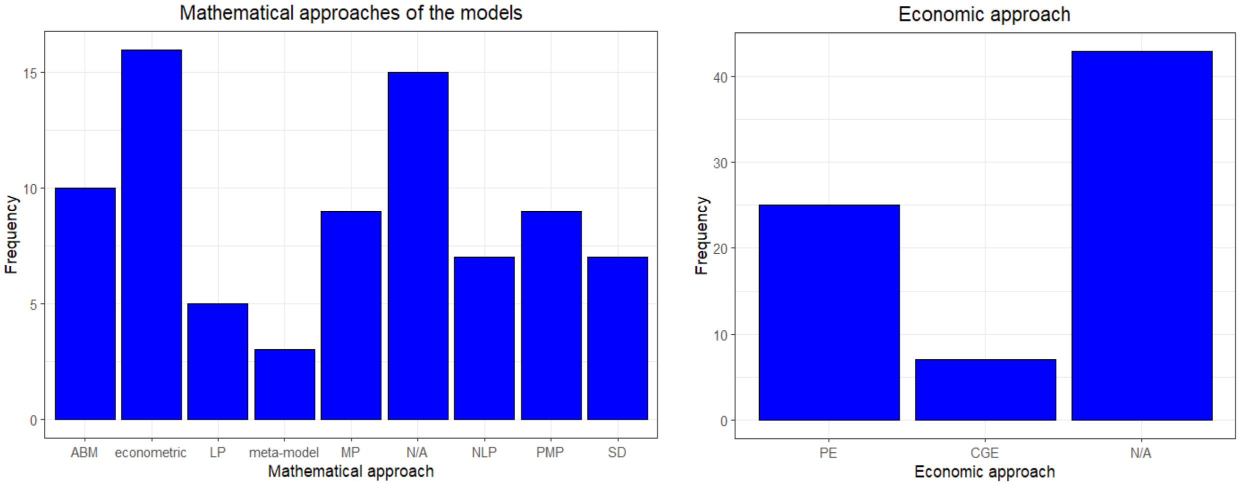

Figure 11: *Mathematical approach (left) and economic approach (right) of the models*

4.2.2 Geographical scope, geographical origin and treatment of time

In terms of geographical scope, diverse levels are represented: global (whole world), international (multiple countries), national, and regional. Figure 12 displays the proportion of models at each level. Global models represent 23% of the models (n=17), while international models account for 11% (n=8). The latter primarily include models of the EU (5 out of 8). The other international models consist of respectively one model of West-Africa, one of seven major OECD regions, and one of 159 major countries worldwide. The national level is the most represented, accounting for 39% of the models (n=29). Seven models simulate the United States, and two models each depict Canada, Norway, and Switzerland. The remaining 16 national models each represent a different country: seven countries from the Europe five from Asia, three from Africa, and one from Oceania. Finally, the regional models account for 28% (n=21) and correspond to regions in the following areas: Europe (8 models), China (4), United States (2), Norway (1), the Philippines (1), Turkey (1), and regions of the Mediterranean area (1). Three regional models are versatile and have not been developed for a specific location.

With regard to the treatment of time, both static-comparative and dynamic-recursive approaches are widely used (defined in section 1.3.2: static models only compare the initial and final situations, while dynamic models trace the evolution over time). Static and dynamic models account for 33% (n=25) and 60% (n=45) of the total, respectively. Additionally, four models (5%) – MEA-Scope, ENVISAGE, MAGNET, and FAPSIM – employ both approaches. They use them either simultaneously in different submodules of the model, or as two alternative operational modes. The treatment of time of one model (1%) was impossible to determine from the available documentation.

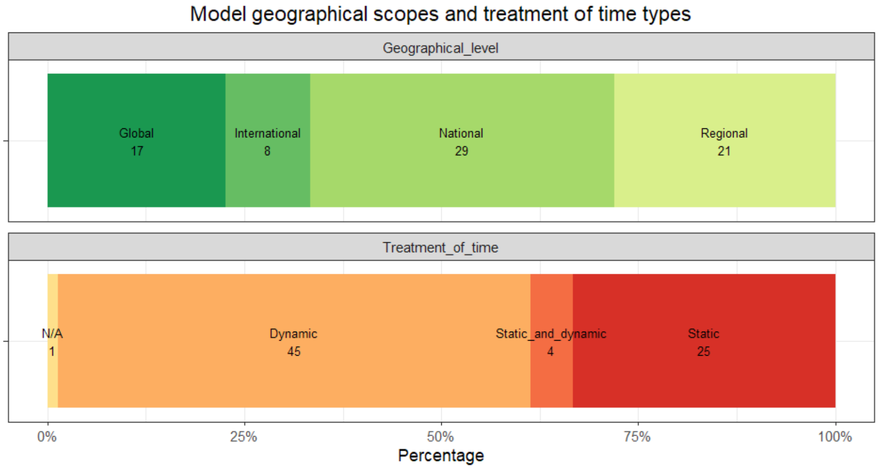

Figure 12: *Geographical level and treatment of time of the analyzed models*

4.2.3 Implementation: mathematical language and user interface

The models are implemented with various programs and programming languages. The most popular is GAMS, used by 19 models. Next, C++ is used by six models, FORTRAN and Excel by four models each, and GEMPACK, R, GEONAMICA and STELLA by three models each. The 14 other cited programs or languages are each used by a single model. The complete list is available in Annex 3 (**Table 9**, p. 72).

These programs and programming languages have different specializations and are used for different purposes. The General Algebraic Modeling System (GAMS) is a modeling system for mathematical programming and optimization, consisting of a language compiler and several associated solvers (GAMS, 2024). It is widely used to solve linear and non-linear optimization problems. C++ is a general-purpose programming language. Due to its good performances and compatibility with the C language, it has been widely adopted for various uses, including software and model development (Stroustrup, 1996). Excel is a spreadsheet editor from Microsoft that allows to easily store and handle data, and make simple computations (Harvey, 2011). The FORTRAN (standing for Formula Translation) programming language has been designed for computationally intensive applications in science and engineering (Fortran Community, 2024). GEMPACK (General Equilibrium Modelling PACKage) is a modeling system for CGE modeling developed by the Center of Policy Studies (CoPS) in Australia and used by many prominent CGE models (Harrison & Pearson, 1996). GEONAMICA is software environment to create end-user ready decision support systems (DSS) integrating spatial data. It has been developed by RIKS (see Annex 4) to support impact assessment of policy options (RIKS, 2014). R is an open-source programming language focused on statistics and data analysis (The R Foundation, 2024). Finally, the Systems Thinking, Experimental Learning Laboratory with Animation (STELLA) is a visual programming language specialized in system dynamics (ISEE Systems, 2024).

From the 75 analyzed models, 30 models (40%) have a dedicated user interface (UI), facilitating the use of the model for non-specialized users.

4.3 SUSTAINABILITY IN MACRO-LEVEL MODELS (OBJECTIVE 2)

In this section, the results of Objective 2 are presented. The inclusion of sustainability themes of the PB and SAFA frameworks (**Table 7**) has been assessed for the 75 models. First, the results of all models are presented, followed by results by theme, by class and by model.

The presence or absence of each sustainability theme (PB and SAFA themes) in each model is illustrated by Figure 13. Eight themes (G1-G4, C3, S2, S3 and S6) are not included in any model.

__Figure 13:__ Results of inclusion of SAFA and PB themes in the models. The rows represent models and the columns represent sustainability themes

By adding up the proportion of included sustainability themes for each model, we observe that the IMPACT 3, MOWASIA , SEAMLESS-IF, ASFF, and AISEEM models include highest cumulated proportion of themes (Figure 14). Conversely, the models CRAM, AGMEMOD, FAPRI, Jordmod II, ESIM, PEATSim, SWOPSIM and IFPSIM include the least sustainability themes. Especially, IFPSIM does not include any sustainability theme.

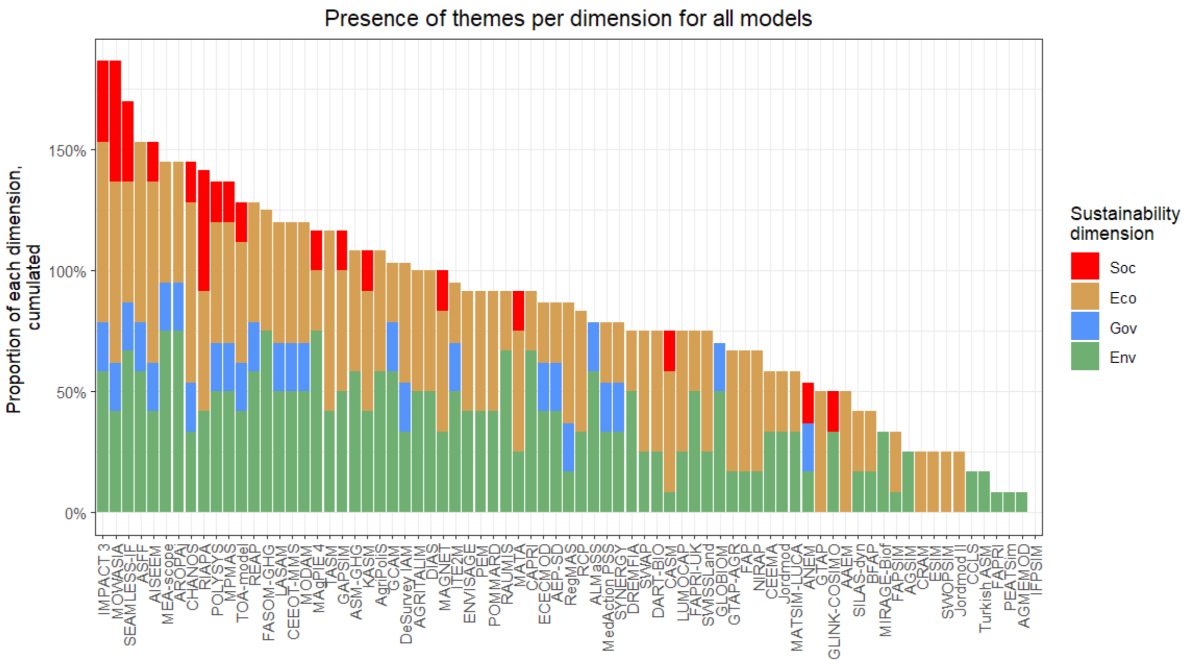

***Figure 14:** Proportion of included sustainability themes per dimension for each model. The proportion for all dimensions are cumulated, giving a possible total value higher than 100%*

Due to the equal weight given to all dimensions, dimensions with few themes and/or high proportions of included themes are more important in determining the "best scoring" models. A model must also score well where other models do not to stand out. This explains why all higher score models have a good score in the social dimension. The environmental dimension also seems to be a factor of overall good score, while it is less the case for the economic and governance dimensions.

4.3.1 Presence of individual sustainability themes

The presence of sustainability themes in the models is presented in Figure 15.

The environmental sustainability themes are the 9 Planetary Boundaries and the 6 themes from the *Environmental integrity* Pillar of the SAFA. The most included themes are E5 Materials and energy (72%), P6 Land use and land use change (71%) and P5 P&N cycle (63%). Conversely, E6 animal welfare (0%), P4 ocean acidification (0%), E1/P8 aerosol emission (7%), P3 ozon layer integrity (17%) and E4/P2 biodiversity erosion (19%) are the less represented themes. Finally, E1/P1 greenhouse gas emissions (40%), E2/P7 water use (51%), E3 soil and land quality (49%) and P9 novel entities (40%) are represented in approximately half of the models.

The presence of economic themes is heterogenous. C1 Investment & Profitability is included in 79% of the models, which variables such as *income*, *revenue* or *margin*. C4 Local economy is included in 53% of the models, mainly under the form of labor force variables linked to a geographic area. C2 – Vulnerability, which can be the sensibility to supply and demand prices or risk and insurance behavior, is present in 16% of the models. Finally, C3 – Product quality information is not included in any model (0%).

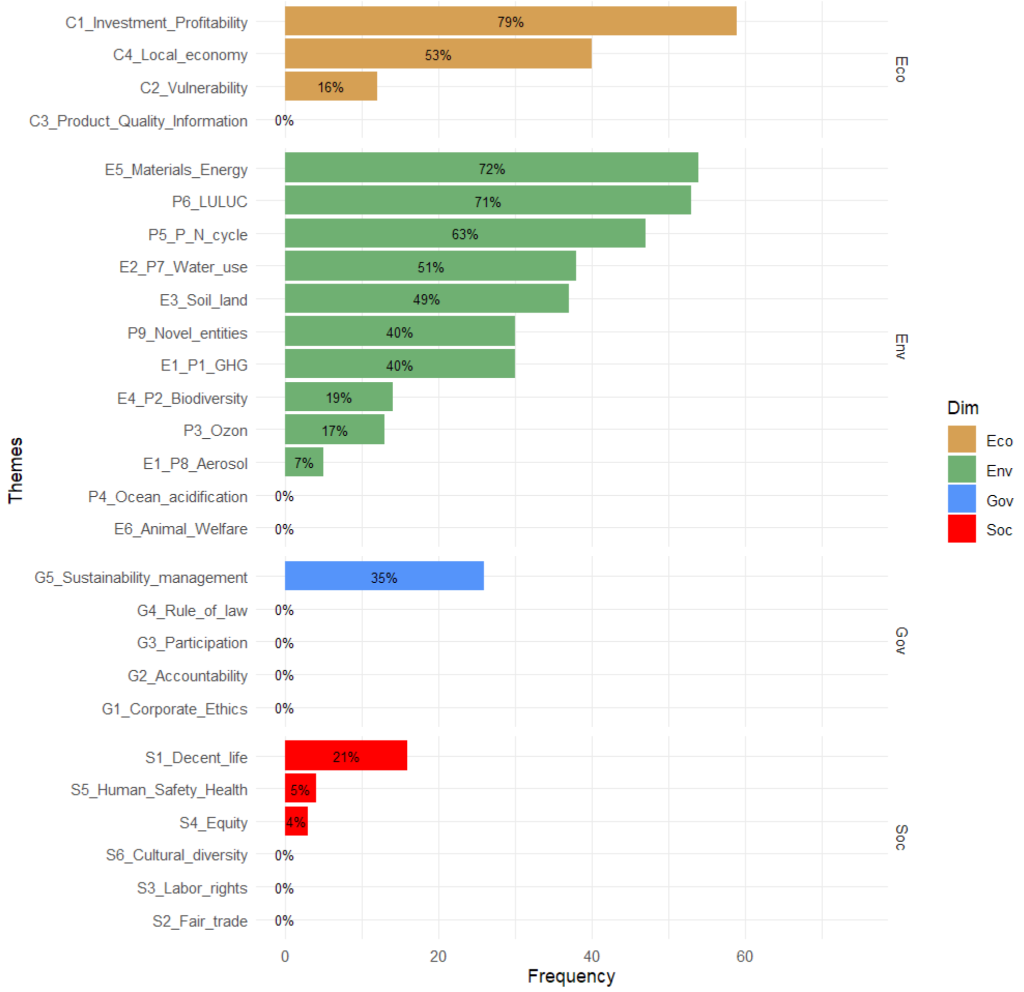

Figure 15: *Presence of SAFA and PB themes in the models*

Governance themes are hardly ever present in models, with no model (0%) including the themes of G1 – Corporate ethics, G2 – Accountability, G3 – Participation and G4 – Rule of law. Only G5 – Sustainable management is included in 35% of the models. These models contain variables regarding farmer's management choices and practices (for example distinguishing organic and conventional agriculture practices).

The social themes are poorly represented in the models, with 3 themes not represented in any model (S2 – Fair trade, S3 – Labor rights, S6 – Cultural diversity). S4 – Equity and S5 – Human Safety and Health are respectively included in 4% and 5% of the models. Two models include both S4 and S5: RIAPA from IFPRI, a CGE model simulating 30 African and Asian countries and MOWASIA, a multi-scale integrated model simulating West-Africa. In addition, S4 – Equity was present in the SEAMLESS integrated framework (SEAMLESS-IF), and S5 – Human Safety and Health was present in the IMPACT 3 partial equilibrium model from IFPRI. Finally, the S1 – Decent life theme is included in 21% of the models: as detailed in Annex 2, the Decent life SAFA theme encompasses variables related to poverty, education and nutrition quality and quantity.

4.3.2 Performance of classes in the inclusion of sustainability themes

Here, results are analyzed by class. Figure 16 summarizes graphically how different classes integrate the sustainability pillars into the variables and parameters of the models.

Figure 16: *Heatmap of average inclusion of sustainability themes, by class and by dimension. The columns represent the six classes, while each sustainability dimension corresponds to a line (plus the "total" line). The percentages represent the average proportion of included themes from a certain dimension and for a particular class.*

As indicated on the "Total" line, integrated bioeconomic models and structural simulation models perform better at incorporating sustainability themes overall, followed by calibration optimization models and CGE models. This outcome results from uniformly weighing all four dimensions in the 'Total' score calculation. Nonetheless, the environmental and economic pillars are more influential as performances in these areas are generally superior to those in the social and governance pillars. Thus, it is not surprising that the classes excelling overall also perform well in the environmental pillar, with the exception of CGE models, which show stronger performance in the economic theme.

In the economic pillar, most classes have similar scores, except for spatial equilibrium models, which fall behind. For governance themes, integrated bioeconomic models and structural simulation models have higher scores. Finally, computable general equilibrium (CGE) models stand out in the social pillar.

4.4 ACTORS OF MACRO-LEVEL MODELING (OBJECTIVE 3)

For the third objective, the present analysis has established an overview of the principal actors of the field of policy-oriented macro-level modeling. The political institutions, research groups and universities that were involved in the model *development* and *funding* have been collected (see section 3.3 for the detailed methodology).

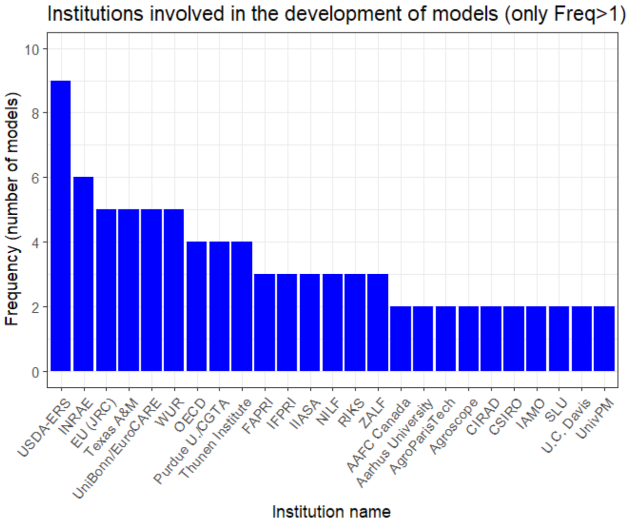

Figure 17: *Institutions involved in the development of models. Institutions involved in the development of only one model are not shown here (n=66). The full list is available in the Supplementary Material.*

Figure 17 displays the number of models for which each institution was involved in the *development*. Since models are frequently developed by several institutions, the total amount of times where an institution was involved in the development of a model is 151, which comes to approximately 2 institutions by model. Three public research centers are the most involved, the Economic Research Center (ERS) of the US Department of Agriculture (USDA), involved in nine models, the National Institute of Agricultural, Food and Environmental Research (INRAE) of France (six models), and the Joint Research Center (JRC) of the European Union (five models). Three universities are also involved in five models, Texas A&M, the University of Bonn with the linked EuroCARE research center, and Wageningen University & Research (WUR). While 25 institutions have participated in the development of at least two models (for a total of 85 participations), 66 institutions are involved in a single model of our analysis (the latter are not shown on Figure 17). Among these institutions, 57% are universities, 23% are public research institutions, and 20% are other types of research institutions (private or independent research centers).

The analysis also captured the geographical origin of involved institutions. This is represented by Figure 18. Note that this origin does not mean any link with public institutions of the country/region. The United States are by far the most prominent country, with US institutions involved 41 times in the development of a model, followed by Germany (22 times) and France

14 times). Except for China, Ghana, Peru, South Africa and Taiwan, all countries are OECD members.

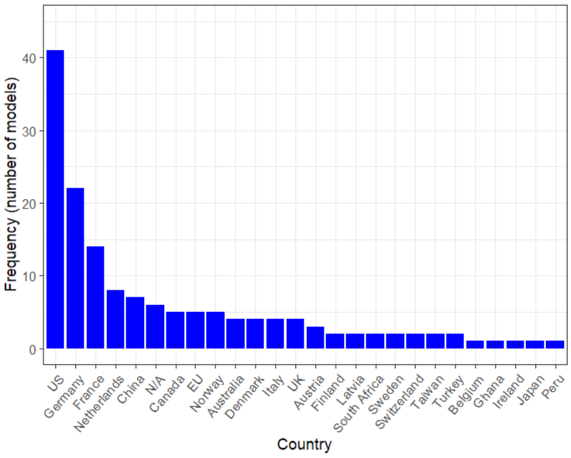

Figure 18: *Origin of institutions involved in model development.*

Several modeling networks have been developed to permit collaboration on the development and use of macro-level models. The present analysis has identified the following modeling projects or networks: AGMEMOD network, CAPRI network, DeSurvey Project, GENEDEC project, GTAP Consortium, LUMOCAP project, MAGNET Consortium, PERD project, SEAMLESS integrated project, SIM4NEXUS, SURE project, SUSAGFU project, TOP-MARD project.

Figure 19 displays the sources of funding of the models. Only 44 models specified their funding sources, and some models had multiple funding sources, which comes to a total of 55 model funding occurrences. In addition to the sources represented on Figure 19, the sources of funding of 31 models were either unspecified or non-existent. Most funding sources are public institutions. The EU is the first funding source with 14 models. Again, the US, Germany and France play a prominent role too. In addition to public sources, the Consultative Group for International Agricultural Research (CGIAR), the Alabama Farmers Federation (ALFA), and the Bill & Melinda Gates Foundation also participate to the funding of model development.

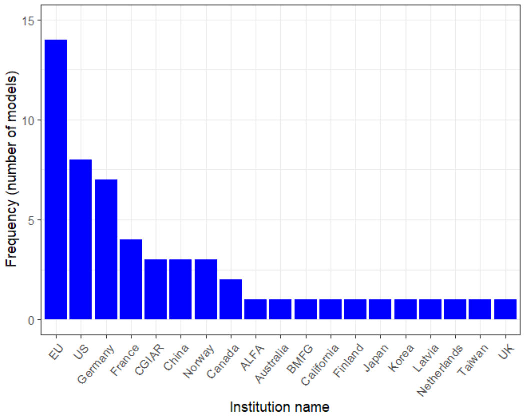

Figure 19: *Institutions involved in the funding of models.*

5 DISCUSSION

This section discusses the research results in light of the research objectives and the previous literature review. Objective 1 aims at offering an overview of the macro-level models and their characteristics. Objective 2 seeks to evaluate how these models integrate various dimensions and themes of sustainability and to identify the reasons and challenges behind this integration. Objective 3 is to identify the designers and funding sources of these models, detailing their roles and contributions in the development and application of the models.

The discussion will be divided into three parts, corresponding to the three objectives.

5.1 CHARACTERISTICS OF REVIEWED MACRO-LEVEL MODELS (OBJECTIVE 1)

This study provides the first overview of policy-oriented macro-level models, i.e. models operating at regional, national, international or global level (defined in section 1.2.4, p.18). Due to the abundant literature on the topic, the choice was made to restrict the analysis to models with a name. Indeed, providing a name for a model facilitates its identification and enhances the possibility of re-use of the model (Reidsma et al., 2018).

The different classes are represented in varying quantities in the review (see section 4.2), and they vary in their performance regarding the integration of sustainability themes (Figure 16).

Integrated bio-economic models (GLOBIOM, ECECMOD, GCAM, MATA, CEEOT-MMS, LUMOCAP, MODAM, SEAMLESS-IF, DeSurvey IAM, ITE2M, MEA-scope) are linking biophysical and economic models to represent the agricultural system. From the 11 models, two are global, two are international, two are national, and five are regional in geographical level. Many of the integrated bioeconomic models are almost closer to a model framework, integrating multiple specialized "submodels", than to a single model (e.g. SEAMLESS-IF and MEA-Scope). Therefore, physical variables can be represented in a detailed, process-based and disaggregated way. Weather and agronomic variables serve as detailed inputs and parameters of the models. Unsurprisingly, integrated bio-economic models are the best at simulating environmental variables (48% of the themes on average). Almost all models include the N&P cycle, water use, and soil properties or land use. Almost half of the models (5 out of 11) simulate biodiversity, and the same amount include GHG emissions. This class also has the best representation of governance themes, although it remains quite low with an average of 16% of the themes included. This is mainly due to the *G5 Sustainability Management* theme, present in nine models out of eleven.

Structural simulation models are the biggest class in number of models (24 models). They represent the agricultural system by modeling its structure, which is close to a process-based approach. This permits to integrate many processes, and therefore to include physical and agronomic variables. It is therefore not surprising that structural simulation models are scoring third highest on the inclusion of environmental sustainability themes, and highest on economic themes. The two dominant mathematical approaches of this class are *agent-based models* (ABM) with ten models (AAEM, AEP-SD, AgriPoliS, ALMaSS, ANEM, CHANOS, MOWASIA, MPMAS, RegMAS, SWISSLand) and *system dynamics* (SD) models with six models (AISEEM, GAPSIM, KASM, MAgPIE 4, MedAction PSS, POMMARD). The remaining eight models use various mathematical programming and econometric approaches (AROPAj, ASFF, NIRAP 2, RCP, REAP, SYNERGY, TASM, Turkish ASM).

Agent-based models (ABMs) simulate agricultural systems by representing the behavior multiple agents (typically farms). This approach combines the precision of farm-level modeling with a holistic system perspective (Möhring et al., 2016). Unsurprisingly, ABMs demonstrate a high integration of governance sustainability themes, as their approach is particularly well-suited to including farm decision-making and sustainable management practices. ABMs also perform well on social and economic themes, leveraging the agent-based approach for themes as labor and poverty. However, their performance in environmental themes is average.

System dynamics (SD) models quantitatively represent complex agricultural systems by modeling components and their interactions, focusing on how physical processes, information flows, and management policies converge to form system structures and determine behavior over time (Elsawah et al., 2017). SD models performing well in including social themes, but they have average results on the other dimensions.

The other *structural simulation models*, which are neither ABMs nor SD models, have performances ranging from low (2 themes in the Turkish ASM) to high (12 themes in AROPAj).

The six **calibrating optimization models** (AGRITALIM, DREMFIA, FASOM-GHG, RAUMIS, SILAS-dyn, SWAP) all use a mathematical programming approach to optimize an objective function (see section 1.2.5, p.20). Merel and Howitt (2014) state that the objective function has historically been focused on revenue and profit, but now integrates risk and environmental variables more often. This is partly confirmed by the analysis of Phase 3, since the most recent models (FASOM-GHG, AGRITALIM and the recent version of RAUMIS) integrate the most sustainability themes, and with the most detailed/disaggregated methodologies. In particular, AGRITALIM include a disaggregated process-based IPCC (Intergovernmental Panel on Climate Change) methodology for GHG emissions. Also, RAUMIS is the only model of this class that includes biodiversity. Although Calibrating Optimization models are the third best class for environmental themes, they are the worse for governance and social themes, with an average of zero included themes for both pillars.

There are seven analyzed **computable general equilibrium models** (DART-BIO, ENVISAGE, GTAP, GTAP-AGR, MAGNET, MIRAGE-Biof, RIAPA). CGE models, have the advantage of comprehensively simulating the interactions of the economy by taking all economic sectors into account, which is crucial for studying sectors such as bioenergy (Henseler et al., 2020). CGE models rank among the least effective in integrating environmental themes, a finding that aligns with observations made by Henseler et al. (2020) and Jones et al. (2017b). According to these authors, the extensive sector coverage of CGE models complicates the simulation of detailed processes, particularly biophysical ones, due to the high demands on data and computational resources. While Figure 16 might suggest that CGE models are the best-performing class for integrating social themes, the class average is in fact pulled up by two high-performing models (RIAPA and MAGNET), while all others fail to integrate any social themes at all.

Econometric production models (AGSIM, BFAP, CASM, CEEMA, CRAM, DIAS, FAPSIM, LASAM, POLYSYS) employ a statistical approach to predict macroeconomic market variables. They all operate at national level, except POLYSYS whose level is regional. Moreover, this class includes some of the oldest models in our analysis, representing one of the historical approaches to macro-level modeling. Econometric production models are the second worse class at representing environmental sustainability themes, which is in line with the description of Jones et al. (2017b). The representation of the other pillars (governance, social and economic) is also quite low. This result is probably due to the fact that econometric models do not aim to represent sustainability in detail. However, the coupling of the POLYSYS model with the EPIC (Environmental Policy Integrated Climate) cropping systems model demonstrates the potential to enhance the simulation of physical and environmental variables in econometric production models (De La Torre Ugarte & Ray, 2000).

Spatial equilibrium models are mostly used to simulate trade, but also land use change. They are mostly partial equilibrium models, which means only specific sectors of the economy are modelled. Global, international and national levels are well represented, while there is only one regional model. Their performance on sustainability themes is similar to that of *econometric production models*. Indeed, both model classes mainly operate with economic data, and poorly integrate biophysical/agronomic variables. However, the two classes differ on their geographical scope: while econometric production models were all national or regional, spatial equilibrium models are mainly international or global. Although the class is performing low on average on inclusion of sustainability, the IMPACT 3 spatial equilibrium model is the best performing model of the whole study, with 13 sustainability themes. This model from the International Food Policy Research Institute (IFPRI) is a multimarket model and is linked to several submodels such as a crop model, a land-use model, a CGE model, and nutrition and health models (Robinson et al., 2015). However, the central module of IMPACT 3 is focused on trade of commodities, which justifies its place in the *spatial equilibrium models* class.

In conclusion, this class-based analysis reveals significant disparities in the performance of different model classes on integrating sustainability themes. In general, model classes adopting a more process-based/structural approach (such as ABM, SD, model integration) perform better at integrating sustainability themes in general. Two classes stand out: integrated bioeconomic models and structural simulation models. This is mainly due to their high performance on environmental and economic themes, and comparatively good performance on governance themes. Calibrating optimization models also perform well on environmental and economic themes, but never integrate social and governance themes. Furthermore, a more process-based/structural approach also allows better predictions outside the validation sample than econometric/statistical approaches, which is crucial for ex-ante policy analysis in a context of global changes (e.g. climate change) (Jayet et al., 2023).

Not all model types have been designed to analyze sustainability outcomes of policies. CGE models, econometric models and spatial equilibrium models focus on (macro)economic changes and trade rather than on sustainability (Jones et al., 2017b). While it makes sense to develop different model types for different uses, the author argues that the urgent need to address sustainability issues does not permit to omit these considerations from agricultural policy analysis. This idea is supported by Coderoni et al. (2021) which identifies nine key policy objectives for ex-ante assessment of agricultural and rural policies, among which three are environmental sustainability objectives, and three others are respectively one social, one economic and one governance sustainability objective.

Among the 75 analyzed models, many models can approximately do the same things, which could seem a waste of time and resources. A solution to that is to combine forces of many modeling themes with the help of modeling networks (see section 4.4 and 5.3). However, it is also important to compare the performances of different models to improve the overall skills of the research field. This is the aim of the AgMIP (Agricultural Model Intercomparison and Improvement Project) (Antle et al., 2015; von Lampe et al., 2014). An interesting result of such a model intercomparison is that the median of multiple models can be a better predictor of future outcomes than any single model (Jones et al., 2017a). Therefore, a diversity of models can be seen as a strength, but it is crucial to harmonize their parametrization and outputs to allow the comparison of their results (von Lampe et al., 2014). This study participates to this intercomparison effort, with a focus on sustainability.

5.2 INCLUSION OF SUSTAINABILITY THEMES IN THE MODELS (OBJECTIVE 2)

There are consequent gaps in the inclusion of the 27 sustainability themes, with some themes being present in almost 80% of the models, and 10 themes being absent from all models. This can be explained by many reasons, and can differ from theme to theme. Figure 15 illustrates the inclusion of each theme in the models.

5.2.1 Comparison with the literature

Four studies have assessed the integration of sustainability in models, using a similar methodology for other model types (see section 1.2.6). Three studies evaluate the inclusion of sustainability *dimensions* or *pillars* (Bastidas-Orrego et al., 2023; Reidsma et al., 2018; Rossing et al., 2007), while one other study provides a more detailed analysis by assessing the inclusion of sustainability *themes* (van der Linden et al., 2020).

In the broad picture, the results of inclusion of sustainability dimensions in the present study are moderately similar to the results of previous studies. First of all, the governance is not analyzed by any of the four previous studies. Next, all four previous studies and the present study find the lowest inclusion levels for the social sustainability dimension (Figure 20). However, the precise themes that are considered from the social dimension differ greatly. From the four themes of van der Linden et al. (2020), two belong to another dimension in the SAFA framework: *labor requirements* is a SAFA economic theme and *animal health and welfare* is a SAFA environmental theme. Apart from these two themes, no other theme is represented a lot in the van der Linden et al. (2020) study, and only *decent life* (S1) is shared as a theme by the present study. The relatively high representation of social themes in Reidsma et al. (2018) is probably due to the fact that the study assessed bio-economic farm models, which are closer to social realities due to their level.

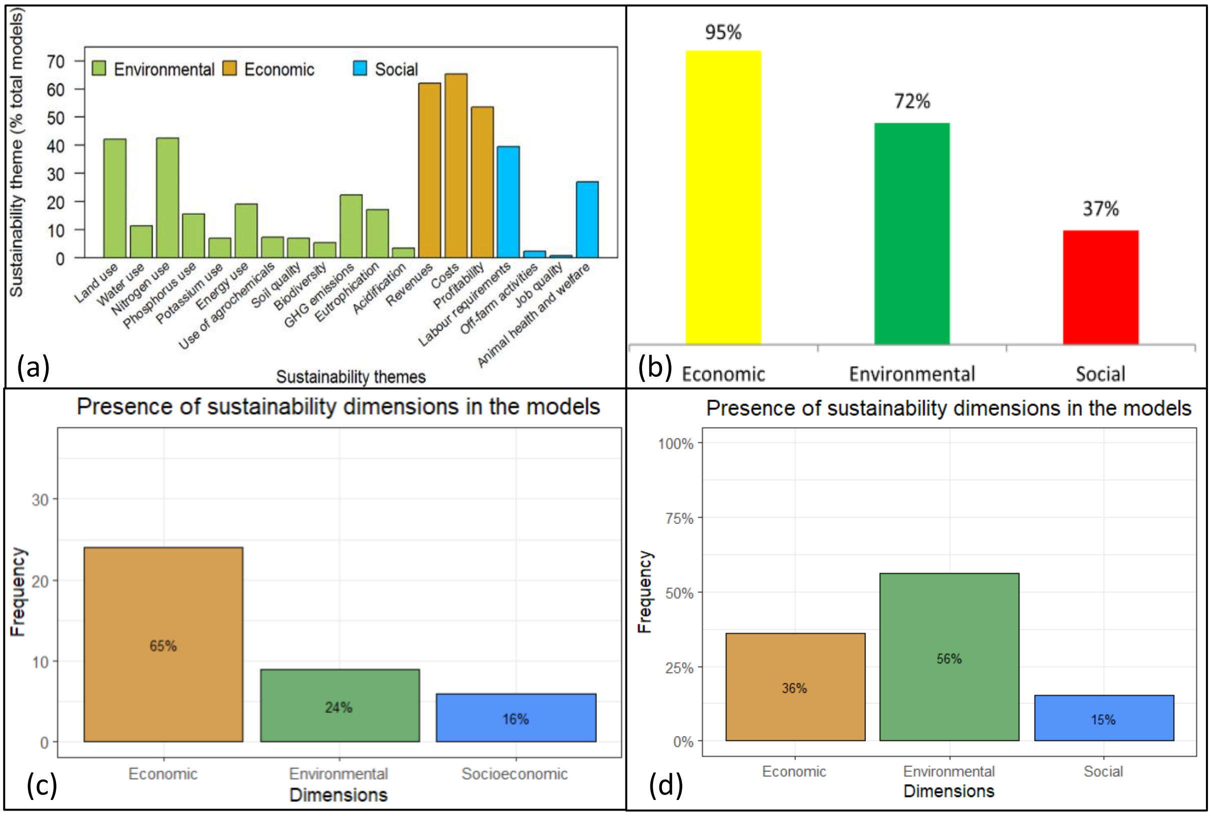

***Figure 20:** Results of inclusion of sustainability themes and dimensions in existing reviews. (a) van der Linden et al. (2020), (b) Reidsma et al. (2018), (c) Bastidas-Orrego et al. (2023) (own construction from the study's data), (d) Rossing et al. (2007) (own construction from the study's data).*

For the environmental and economic dimensions, results differ. While the economic dimension dominates the environmental dimension in the studies from van der Linden (a), Reidsma (b) and Bastidas-Orrego (c) (Figure 20), it is the opposite for the study of Rossing (d). For the present study, it is difficult to draw a conclusion, since the data is provided by theme and not by dimension. There are more environmental themes than economic ones, but the proportions of inclusion have similar levels. This situation contrasts with the literature on sustainability assessments at farm level, where the environmental dimension is considered to receive more attention (Riera et al., 2023; Schader et al., 2014).

The methodology probably plays a role in this dominance of the economic themes in three studies. Indeed, when analyzing sustainability by dimension, the presence of a single economic theme, which is quite frequent, is enough to consider the whole dimension as present. However, the presence of a single theme does not mean that the economic dimension is included completely. It is therefore difficult to understand how much the economic and environmental dimensions really are included with a dimension-based analysis. Indeed while the methodologies of studies from Reidsma (b), Bastidas-Orrego (c) and Rossing (d) do provide a list of themes corresponding to each dimension, they do not precise which themes are included in each model to consider the dimension as included.

Regarding the study of van der Linden (a), the measured themes are cost, revenue and profitability, which are captured as a single theme by the SAFA framework used for this study (C1 Investment & Profitability). In this study, this theme also dominates all other themes. However, three other themes are considered here: Vulnerability (C2), Product Quality & Information (C3), and Local Economy (C4). The two first ones are not represented at all in the four previous studies. However, Local Economy (C4) encompasses local labor requirements, which belongs to the social themes of the study of van der Linden et al. (2020). The frequencies around 40% to 50% are comparable in the present study and the van der Linden study.

Regarding the environmental dimension, contrasts between themes and between studies are high. Reidsma et al. (2018) and Bastidas-Orrego et al. (2023) respectively measured inclusion in 72% and 24% of the models. The results of van der Linden et al. (2020) and the present study can't be aggregated at the dimension level like that, but the maxima of a single theme are around 40% and 72%, respectively. The scores of the themes of van der Linden et al. (2020) confirm the intuition developed with the present study: themes are more often modelled when they are closer to the agronomic production reality. In both studies, nitrogen use, land use, energy use and eutrophication (water use & quality (E2/P7) in this study) are the most included. Also, biodiversity and acidification are amongst the less represented. However, divergences can also be observed: soil quality (E3) is far more included in this study, while water use is poorly represented in the other study. In both studies, GHG emissions occupy a middle-range position, showing an interest of modelers for what is considered a "core Planetary Boundary" (see section 1.4.1).

In conclusion of this section, the comparison of the present study with previous literature provides contrasting results. While the social sustainability dimension is the less represented in all studies, the environmental and economic dimensions are approximately equally included in the present study, while three other studies show a higher inclusion of the economic dimension, and one other study shows the opposite. The themes of each dimension are also different. This study, based on the SAFA and PB framework, uses more and more diversified themes, especially for the economic dimension. Finally, the most represented themes of the environmental dimensions are roughly the same in this study and in the study of van der Linden et al. (2020), which is methodologically the closest.

5.2.2 Reasons for the presence or absence of sustainability themes

Many factors can explain the presence or absence of sustainability themes in the models. Based on the work carried out for this review, these factors seem to fall into two categories: technical factors and agenda-setting factors.

The main technical factors include the lack of data and the absence of methods to simulate certain processes, particularly for social and environmental themes (Desiderio et al., 2022; Reidsma et al., 2018; Riera et al., 2023; van der Linden et al., 2020). Data limitations can be addressed by initiatives like GODAN, and linking different model classes can also help bridge certain data gaps – for example, linking a crop model with an economic model (GODAN, 2024; Jones et al., 2017b). Transdisciplinary research can further advance the understanding of these processes, essential for developing assessment and modeling methods (Jones et al., 2017a). To that end, consistent model evaluation and comparison are crucial, which depend on improved interoperability of models and standardized documentation (Reidsma et al., 2018; van der Linden et al., 2020).

Agenda-setting factors involve the motivations behind why modelers or funding sources might want to include specific sustainability themes in a model. According to Jones et al. (2017a), two primary motivations for model development are: (1) increasing basic scientific understanding of an agricultural system, or (2) providing information to support decisions and policies. The inclusion of a theme can thus be influenced by researchers as well as political agendas, which are driven by policy objectives identified by various studies (Brooks & OECD, 2010; Coderoni et al., 2021). However, the methodology of the present study does not permit a deeper exploration of these factors.

5.3 ACTORS AND USERS OF MACRO-LEVEL MODELS (OBJECTIVE 3)

The last objective of this study is to provide a view of the actors implied in the development, funding and use of policy-oriented macro-level models.

The three institutions most involved in model development are all public institutions (USDA ERS, EU JRC, INRAE, see section 4.4). While the JRC and INRAE mostly participate to the model development in collaboration with other actors, the Economic Research Center of the USDA has developed four models internally and collaborated on five models. This shows a different approach between European and American institutions. Different modeling capacities probably also play a role in this different approach. Indeed, while all 285 staff members of the ERS are focused on economic research for agriculture, the JRC has 2600 members for 33 different research areas (energy, economy, agriculture…), which comes to approximately 78 members for agriculture (members per department are not publicly available)(EC, 2024a; USDA ERS, 2022). At INRAE, approximately 464 members are in the modeling and policy departments (INRAE, 2024), which suggests that modeling capacity is not the only factor. The more collaborative approach of the JRC and INRAE could also be due to the general public funding of universities and some research groups, while American universities receive less public support.

Since the JRC has a more collaborative approach of modeling, it is not surprising that the EU funds the most models, since they are not developed internally. However, as for model development, the US, Germany and France are leading actors too. Most other actors originate from OECD countries. China is the most involved non-OECD country: Chinese actors are involved in development of seven models, and China has funded directly three models. This dominant participation of high and middle income countries can participate to explain other results: the small inclusion of social sustainability themes such as *decent life* (poverty, nutrition), *fair trade*, *cultural diversity*. Indeed, the two models with highest scores the social dimension (RIAPA and MOWASIA) both operate for low-income countries (Belem & Saqalli, 2017; Diao & Thurlow, 2012). Also, highly included environmental themes such as N&P cycle, water quality and pesticide use are probably included because they are key policy issues of high-income countries, while they are less central in low-income countries (Brooks & OECD, 2010; Coderoni et al., 2021).

Modeling projects and networks play a crucial role in the development, maintenance and use of models. 13 models are at the center of a modeling project or network, among which the three most cited models (CAPRI, AGMEMOD and GTAP, see section 4.2.1). Modeling networks are decisive not only for the model development but even more so for their use and diffusion. Broader knowledge sharing is essential for the longevity and maintenance of models. Additionally, networks can serve as interfaces with policymakers, with some networks or projects even being initiated by the policy sector, such as the SUPREMA and GENEDEC projects (Blanco et al., 2019; GENEDEC et al., 2008)

Assessing the users of the models is a difficult task and would have needed a more comprehensive search with a different methodology. This could therefore be the purpose of a further study.

5.4 LIMITATIONS & RECOMMENDATIONS

This section shows the limitations of the methodology and results of this study. Next, recommendations for further research are proposed.

5.4.1 Limitations

A first considerable limitation of this study is the systematized review. This study has followed the PRISMA methodology as closely as possible, but does not claim to be systematic for the following reasons: more databases could have been used for the identification stage, there is no bias analysis, and the study is not registered in any review database.

The choice of using a single database (Scopus) and reviewing the websites of prominent institutions can be an explanation for the domination of OECD countries in the results. Indeed, the study of Bastidas-Orrego et al. (2023) uses seven databases and has results originating from more non-OECD countries. The limitation to papers written in English and to publications of peer-reviewed scientific journals may also have contributed to this bias. Leydesdorff & Wagner (2009) have indeed shown a dominance of the USA and the EU in the scientific publications. Finally, the reviewed institutions are all based in OECD countries.

The choice of the SAFA and PB framework is an arbitrary way to define sustainability. While these frameworks have been chosen for the comprehensiveness, complementarity and prominent place in the sustainability literature, they may not be the best suited for the analysis carried out in this study. Especially, some SAFA themes such as several governance themes (G1-4), fair trade (S2), labor rights (S3), and product quality (C3) may be more relevant at the farm level than at the macro-level, which could explain why they are never included in the analyzed models.

Furthermore, since every model documentation is different, assessing the presence of the themes can be a hard task. Efforts have been made to standardize the process, by following the indicators of the SAFA and PB frameworks as closely as possible.

5.4.2 Recommendations

The results of this study lead to recommendations for further research and evolutions on the development and use of policy-oriented macro-level models.

First, it is essential to continue efforts to integrate sustainability themes into macro-level models. Several challenges, discussed in sections 5.1 and 5.2, must be addressed. Key priorities include overcoming data limitations, increasing model linking, improving interoperability and standardization to facilitate consistent evaluation and comparison, developing modeling networks and international collaboration, and deepening the understanding of complex processes related to underrepresented sustainability themes (Antle et al., 2015; Jones et al., 2017b, 2017b; Reidsma et al., 2018; van der Linden et al., 2020).

Second, closer stakeholder interaction and more user-driven model development are crucial for translating modeling efforts into policymaking that promotes sustainability (Jones et al., 2017a; Reidsma et al., 2018). Collaborations between independent and public research centers, projects founded by public institutions, and an increased implementation of user interfaces of models are ways of making progress in this direction.

Finally, a main conclusion of this study to focus the research efforts on better-performing model classes – integrated bio-economic models, structural simulation models (particularly ABM and SD models) and calibrating optimization models – and on models that adopt a rather mechanistic/process-based approach. However, their strengths could also inspire improvements in models from other classes.

6 CONCLUSION

Policy-oriented macro-level models are a powerful tool for supporting policymaking aimed at enhancing the sustainability of agricultural systems. These models effectively represent the many actors and processes of the agricultural system, making them ideal for capturing its complex behavior. This is a major asset for predicting the outcome of agricultural policies before their implementation (ex-ante) and assessing their impact afterwards (ex-post).

This study has conducted a PRISMA-based systematized review of 1064 articles from Scopus and screened the websites of prominent institutions, to provide a comprehensive list of 75 policy-oriented macro-level models. These models were analyzed in detail on three aspects: main characteristics, integration of sustainability themes, and actors involved in their development and funding.

A first result of the overview of macro-level models are that we observe a high model diversity. Studies suggest that the median of the results of multiple models can be a better predictor than any single model. Therefore, diversifying the models used can be crucial for guiding policymaking. However, it is essential to harmonize the parametrization and outputs of different models to enable their intercomparison.

Integrating sustainability themes into macro-level models is crucial for supporting policymaking in making agriculture more sustainable. Three model classes proved better at integrating sustainability: *integrated bio-economic models* and *structural simulation models* (especially ABM and SD models) had the best overall results and where good in all four dimensions of sustainability, while *calibrating optimization models* particularly performed well in the environmental and economic dimensions. In contrast, computable general equilibrium (CGE) models, econometric models and spatial equilibrium models have shown a much lower integration of sustainability themes. Even though it is not their primary purpose, we argue that the urgent need to address sustainability issues does not permit to omit these considerations from agricultural policy analysis.

Sustainability themes are not equally represented across the models studied. The economic and environmental dimensions are more frequently included than the governance and social dimensions. Furthermore, significant disparities exist within these dimensions. The themes that are most represented tend to align closely with the practical realities of agricultural production, indicating that the inclusion of themes is not necessarily driven by the societal importance of their sustainability impacts. The unequal integration of sustainability themes is also influenced by *technical* factors, such as data availability and the difficulty to model complex processes, as well as *agenda-driven* factors, where scientists or policymakers may prioritize certain themes for modeling over others.

Finally, the actors involved in the development of the models consist of public research institutions, independent research centers and universities. The institutions involved in the most models are the ERS of the USDA, the INRAE of France and the JRC of the EU. Following these are Texas A&M, UniBonn/EuroCARE, and WUR, three universities. The modeling institutions predominantly originate from the USA, Germany, France, the Netherlands, and China, with the vast majority of modeling teams coming from OECD countries.

Regarding the funding of models, it is primarily sourced from public institutions, except for five models. These funding sources follow the same geographical distribution as the model development institutions.

This study recommends several strategic advancements for policy-oriented macro-level models to enhance sustainability integration. Key actions include addressing data limitations, enhancing model connections, and standardizing model interoperability to support consistent evaluation and comparison. Developing international modeling networks and deepening the understanding of complex sustainability themes are also crucial. Furthermore, fostering closer stakeholder interactions and promoting user-driven development will help translate modeling efforts into effective policymaking. It's also advised to concentrate research on high-performing model classes, such as integrated bio-economic, agent-based, and system dynamics models. These models' strengths could inspire enhancements across various model categories, leading to broader improvements in sustainability modeling.

7 REFERENCES

Anderson, K., Rausser, G., & Swinnen, J. (2014). Agricultural Policy : A Global View. In N. K. Van Alfen (Éd.), *Encyclopedia of Agriculture and Food Systems* (p. 179-194). Academic Press. https://doi.org/10.1016/B978-0-444-52512-3.00120-0

Antle, J. M., Valdivia, R. O., Boote, K. J., Janssen, S., Jones, J. W., Porter, C. H., Rosenzweig, C., Ruane, A. C., & Thorburn, P. J. (2015). AgMIP's transdisciplinary agricultural systems approach to regional integrated assessment of climate impacts, vulnerability, and adaptation. *Handbook of climate change and agroecosystems*, 27-44.

Bastidas-Orrego, L. M., Jaramillo, N., Castillo-Grisales, J. A., & Ceballos, Y. F. (2023). A systematic review of the evaluation of agricultural policies : Using prisma. *Heliyon*, *9*(10). https://www.cell.com/heliyon/pdf/S2405-8440(23)07500-X.pdf

Belem, M., & Saqalli, M. (2017). Development of an integrated generic model for multi-scale assessment of the impacts of agro-ecosystems on major ecosystem services in West Africa. *Journal of Environmental Management*, *202*, 117-125. https://doi.org/10.1016/j.jenvman.2017.07.018

Biermann, F., & Kim, R. (2020). The Boundaries of the Planetary Boundary Framework : A Critical Appraisal of Approaches to Define a "Safe Operating Space" for Humanity. *Annual Review of Environment and Resources*, *45*, 497-521. https://doi.org/10.1146/annurev-environ-012320-080337

Blanco, M., Martinez, P., Witzke, P., van Leeuwen, M., Jongeneel, R., Salamon, P., Frank, S., Havlík, P., Barreiro-Hurlé, J., Rau, M. L., van Meijl, H., Tabeau, A., & Lesschen, J. P. (2019). *D1.5 : Documentation of the SUPREMA model tools*. SUPREMA Project.

Bosselmann, K. (2010). Losing the Forest for the Trees : Environmental Reductionism in the Law. *Sustainability*, *2*(8), Article 8. https://doi.org/10.3390/su2082424

Britz, W., & Mittenzwei, K. (2015). The JORDMOD II market model. In G. Stokstad & S. Eiter (Éds.), *AGRISPACE: background, concepts and frameworks* (p. 72). https://core.ac.uk/download/pdf/285987286.pdf#page=78

Brooks, J. & OECD. (2010). Agricultural policy choices in developing countries : A synthesis. *Global Forum on Agriculture, OECD. Paris*, 29-30. https://www.researchgate.net/profile/Anoop-Srivastava/post/What_should_be_the_strategy_so_that_small_and_marginal_farms_sustainably_contribute_for_high_yields_incomes_and_livelihood/attachment/59d63dc579197b807799a80f/AS%3A421342013870080%401477467172488/download/46340461.pdf

Campbell, B., Beare, D., Bennett, E., Hall-Spencer, J., Ingram, J., Jaramillo, F., Ortiz, R., Ramankutty, N., Sayer, J., & Shindell, D. (2017). Agriculture production as a major driver of the Earth system exceeding planetary boundaries. *Ecology and Society*, *22*(4). https://doi.org/10.5751/ES-09595-220408

Chaudhary, A., Gustafson, D., & Mathys, A. (2018). Multi-indicator sustainability assessment of global food systems. *Nature Communications*, *9*(1). https://doi.org/10.1038/s41467-018-03308-7

Clark, M., & Tilman, D. (2017). Comparative analysis of environmental impacts of agricultural production systems, agricultural input efficiency, and food choice. *Environmental Research Letters*, *12*(6), 064016. https://doi.org/10.1088/1748-9326/aa6cd5

Coderoni, S., Helming, J., Pérez-Soba, M., Sckokai, P., & Varacca, A. (2021). Key policy questions for ex-ante impact assessment of European agricultural and rural policies. *Environmental Research Letters*, *16*(9), 094044. https://doi.org/10.1088/1748-9326/ac1f45

Corong, E. L., Hertel, T. W., McDougall, R., Tsigas, M. E., & Mensbrugghe, D. van der. (2017). The Standard GTAP Model, Version 7. *Journal of Global Economic Analysis*, *2*(1), Article 1. https://doi.org/10.21642/JGEA.020101AF

Daugbjerg, C., & Swinbank, A. (2012). An introduction to the ‘new’ politics of agriculture and food. *Policy and Society*, *31*(4), 259-270. https://doi.org/10.1016/j.polsoc.2012.10.002

De La Torre Ugarte, D. G., & Ray, D. E. (2000). Biomass and bioenergy applications of the POLYSYS modeling framework. *Biomass and Bioenergy*, *18*(4), 291-308. https://doi.org/10.1016/S0961-9534(99)00095-1

de Olde, E. M., Bokkers, E. A. M., & de Boer, I. J. M. (2017). The Choice of the Sustainability Assessment Tool Matters : Differences in Thematic Scope and Assessment Results. *Ecological Economics*, *136*, 77-85. https://doi.org/10.1016/j.ecolecon.2017.02.015

Desiderio, E., García-Herrero, L., Hall, D., Segrè, A., & Vittuari, M. (2022). Social sustainability tools and indicators for the food supply chain : A systematic literature review. *Sustainable Production and Consumption*, *30*, 527-540. https://doi.org/10.1016/j.spc.2021.12.015

Diao, X., & Thurlow, J. (2012). A recursive dynamic computable general equilibrium model. In *Strategies and priorities for African agriculture : Economywide perspectives from country studies* (Vol. 2, p. 17-50). Washington DC: International Food Policy Research Institute. https://books.google.be/books?hl=fr&lr=&id=YiRC5v9XzEYC&oi=fnd&pg=PA17&dq=A+recursive+dynamic+computable+general+equilibrium+model&ots=u_8qlPeKHS&sig=28toFPYIvw_xklWkictZc_GI06o

Donatelli, M., Magarey, R. D., Bregaglio, S., Willocquet, L., Whish, J. P., & Savary, S. (2017). Modelling the impacts of pests and diseases on agricultural systems. *Agricultural systems*, *155*, 213-224.

Dorph, J. R., Harvey, N., & Ploeg, P. (2016). *Planetary Boundaries and Sustainability Principles : An integrated approach in the context of agriculture.* https://urn.kb.se/resolve?urn=urn:nbn:se:bth-12367

Downing, A. S., Bhowmik, A., Collste, D., Cornell, S. E., Donges, J., Fetzer, I., Häyhä, T., Hinton, J., Lade, S., & Mooij, W. M. (2019). Matching scope, purpose and uses of planetary boundaries science. *Environmental Research Letters*, *14*(7), 073005. https://doi.org/10.1088/1748-9326/ab22c9

Dudley, N., & Alexander, S. (2017). Agriculture and biodiversity : A review. *Biodiversity*, *18*(2-3), 45-49. https://doi.org/10.1080/14888386.2017.1351892

EC. (2024a). *JRC sites across Europe*. https://joint-research-centre.ec.europa.eu/jrc-sites-across-europe_en

EC. (2024b). *Modelling Inventory and Knowledge Management System of the European Commission (MIDAS)*. European Commission. https://web.jrc.ec.europa.eu/policy-model-inventory/

EEA. (2024). *EEA Glossary* [Glossary]. European Environment Agency. https://www.eea.europa.eu/help/glossary/eea-glossary

Elsawah, S., Pierce, S. A., Hamilton, S. H., van Delden, H., Haase, D., Elmahdi, A., & Jakeman, A. J. (2017). An overview of the system dynamics process for integrated modelling of socio-ecological systems : Lessons on good modelling practice from five case studies. *Environmental Modelling & Software*, *93*, 127-145. https://doi.org/10.1016/j.envsoft.2017.03.001

FAO. (2011). *Sustainability Assessment of Food and Agriculture systems (SAFA) : Background Document for the E-Forum held in February-March 2011*.

FAO. (2014). *SAFA Guidelines*. https://www.fao.org/nr/sustainability/sustainability-assessments-safa

Foley, J. A., Ramankutty, N., Brauman, K. A., Cassidy, E. S., Gerber, J. S., Johnston, M., Mueller, N. D., O’Connell, C., Ray, D. K., West, P. C., Balzer, C., Bennett, E. M., Carpenter, S. R., Hill, J., Monfreda, C., Polasky, S., Rockström, J., Sheehan, J., Siebert, S., … Zaks, D. P. M. (2011). Solutions for a cultivated planet. *Nature*, *478*(7369), 337-342. https://doi.org/10.1038/nature10452

Forrester, J. W. (1968). *Principles of systems*. http://www.mtas.ru/search/search_results.php?publication_id=20097

Fortran Community. (2024). *The Fortran Programming Language—Fortran Programming Language*. https://fortran-lang.org/index

GAMS. (2024). *About GAMS*. GAMS. https://www.gams.com/about/company/

GENEDEC, Marette, S., & Jayet, P.-A. (2008). *GENEDEC Website*. http://www.grignon.inra.fr/economie-publique/genedec/eng/index.htm

GODAN. (2024). *GODAN 2.0*. https://www.godan.info/

Gomez y Paloma, S., Ciaian, P., Cristoiu, A., & Sammeth, F. (2013). The future of agriculture. Prospective scenarios and modelling approaches for policy analysis. *Land Use Policy*, *31*, 102-113. https://doi.org/10.1016/j.landusepol.2011.12.005

Gomez y Paloma, S., Riesgo, L., & Louhichi, K. (2020). *The role of smallholder farms in food and nutrition security*. Springer Nature. https://library.oapen.org/handle/20.500.12657/39585

Grant, M. J., & Booth, A. (2009). A typology of reviews : An analysis of 14 review types and associated methodologies. *Health Information & Libraries Journal*, *26*(2), 91-108. https://doi.org/10.1111/j.1471-1842.2009.00848.x

Harrison, W. J., & Pearson, K. R. (1996). Computing solutions for large general equilibrium models using GEMPACK. *Computational Economics*, *9*, 83-127.

Harvey, G. (2011). *Excel 2007 For Dummies*. John Wiley & Sons.

Heckelei, T., Britz, W., & Zhang, Y. (Éds.). (2012). Positive Mathematical Programming Approaches – Recent Developments in Literature and Applied Modelling. *Bio-Based and Applied Economics Journal*. https://doi.org/10.22004/ag.econ.125722

Henseler, M., Delzeit, R., Adenäuer, M., Baum, S., & Kreins, P. (2020). Nitrogen Tax and Set-Aside as Greenhouse Gas Abatement Policies Under Global Change Scenarios : A Case Study for Germany. *Environmental and Resource Economics*, *76*(2), 299-329. https://doi.org/10.1007/s10640-020-00425-0

Howitt, R. E. (1995). Positive Mathematical Programming. *American Journal of Agricultural Economics*, *77*(2), 329-342. https://doi.org/10.2307/1243543

INRAE. (2024). *Liste des départements INRAE*. https://www.inrae.fr/departements

IPCC. (2014). *Climate Change 2014 : Mitigation of Climate Change. Contribution of Working Group III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*. Intergovernmental Panel on Climate Change. https://www.ipcc.ch/report/ar5/wg3/

ISEE Systems. (2024). *Stella Architect*. https://www.iseesystems.com/store/products/stella-architect.aspx

Janker, J., & Mann, S. (2020). Understanding the social dimension of sustainability in agriculture : A critical review of sustainability assessment tools. *Environment, Development and Sustainability*, *22*(3), 1671-1691. https://doi.org/10.1007/s10668-018-0282-0

Janssen, S., & van Ittersum, M. K. (2007). Assessing farm innovations and responses to policies : A review of bio-economic farm models. *Agricultural Systems*, *94*(3), 622-636. https://doi.org/10.1016/j.agsy.2007.03.001

Jayet, P.-A., Petsakos, A., Chakir, R., Lungarska, A., De Cara, S., Petel, E., Humblot, P., Godard, C., Leclère, D., & Cantelaube, P. (2023). *The European agro-economic model AROPAj*. https://hal.inrae.fr/hal-04109872

Jones, J. W., Antle, J. M., Basso, B., Boote, K. J., Conant, R. T., Foster, I., Godfray, H. C. J., Herrero, M., Howitt, R. E., Janssen, S., Keating, B. A., Munoz-Carpena, R., Porter, C. H., Rosenzweig, C., & Wheeler, T. R. (2017a). Brief history of agricultural systems modeling. *Agricultural Systems*, *155*, 240-254. https://doi.org/10.1016/j.agsy.2016.05.014

Jones, J. W., Antle, J. M., Basso, B., Boote, K. J., Conant, R. T., Foster, I., Godfray, H. C. J., Herrero, M., Howitt, R. E., Janssen, S., Keating, B. A., Munoz-Carpena, R., Porter, C. H., Rosenzweig, C., & Wheeler, T. R. (2017b). Toward a new generation of agricultural system data, models, and knowledge products : State of agricultural systems science. *Agricultural Systems*, *155*, 269-288. https://doi.org/10.1016/j.agsy.2016.09.021

Kanter, D. R., Musumba, M., Wood, S. L. R., Palm, C., Antle, J., Balvanera, P., Dale, V. H., Havlik, P., Kline, K. L., Scholes, R. J., Thornton, P., Tittonell, P., & Andelman, S. (2018). Evaluating agricultural trade-offs in the age of sustainable development. *Agricultural Systems*, *163*, 73-88. https://doi.org/10.1016/j.agsy.2016.09.010

Kirschenmann, F. (2010). Alternative agriculture in an energy- and resource-depleting future. *Renewable Agriculture and Food Systems*, *25*(2), 85-89. https://doi.org/10.1017/S1742170510000141

Lade, S. J., Steffen, W., de Vries, W., Carpenter, S. R., Donges, J. F., Gerten, D., Hoff, H., Newbold, T., Richardson, K., & Rockström, J. (2020). Human impacts on planetary boundaries amplified by Earth system interactions. *Nature Sustainability*, *3*(2), Article 2. https://doi.org/10.1038/s41893-019-0454-4

Lassaletta, L., Billen, G., Grizzetti, B., Garnier, J., Leach, A. M., & Galloway, J. N. (2014). Food and feed trade as a driver in the global nitrogen cycle : 50-year trends. *Biogeochemistry*, *118*(1), 225-241. https://doi.org/10.1007/s10533-013-9923-4

Lebacq, T., Baret, P. V., & Stilmant, D. (2013). Sustainability indicators for livestock farming. A review. *Agronomy for Sustainable Development*, *33*(2), 311-327. https://doi.org/10.1007/s13593-012-0121-x

Leydesdorff, L., & Wagner, C. (2009). Is the United States losing ground in science? A global perspective on the world science system. *Scientometrics*, *78*(1), 23-36. https://doi.org/10.1007/s11192-008-1830-4

Lobianco, A., & Esposti, R. (2010). The Regional Multi-Agent Simulator (RegMAS) : An open-source spatially explicit model to assess the impact of agricultural policies. *Computers and Electronics in Agriculture*, *72*(1), 14-26.

Loring, P. A., & Sanyal, P. (2021). Indicators of Complexity and Over-Complexification in Global Food Systems. *Frontiers in Sustainable Food Systems*, *5*. https://doi.org/10.3389/fsufs.2021.683100

March, M. D., Toma, L., Stott, A. W., & Roberts, D. J. (2016). Modelling phosphorus efficiency within diverse dairy farming systems − pollutant and non-renewable resource? *Ecological Indicators*, *69*, 667-676. https://doi.org/10.1016/j.ecolind.2016.05.022

Mérel, P., & Howitt, R. (2014). Theory and Application of Positive Mathematical Programming in Agriculture and the Environment. *Annual Review of Resource Economics*, *6*(Volume 6, 2014), 451-470. https://doi.org/10.1146/annurev-resource-100913-012447

Meyers, W. H., Westhoff, P., Fabiosa, J. F., & DJ, H. (2010). The FAPRI global modelling system and outlook process. In *Journal of international agricultural trade and development* (Vol. 6, p. 1-19). https://www.krei.re.kr/portlet-repositories/v_dept_emp/files/1421637006689.pdf#page=7

Möhring, A., Mack, G., Zimmermann, A., Ferjani, A., Schmidt, A., & Mann, S. (2016). Agent-Based Modeling on a National Scale – Experiences from SWISSland. *Agroscope Science*, *30*, 1-56.

Moulogianni, C. (2022). Comparison of Selected Mathematical Programming Models Used for Sustainable Land and Farm Management. *Land*, *11*(8), Article 8. https://doi.org/10.3390/land11081293

Muhie, S. H. (2022). Novel approaches and practices to sustainable agriculture. *Journal of Agriculture and Food Research*, *10*, 100446. https://doi.org/10.1016/j.jafr.2022.100446

Muller, B., & Martre, P. (2019). Plant and crop simulation models : Powerful tools to link physiology, genetics, and phenomics. *Journal of Experimental Botany*, *70*(9), 2339-2344. https://doi.org/10.1093/jxb/erz175

Murphy, D. J., & Hall, C. A. S. (2011). Energy return on investment, peak oil, and the end of economic growth. *Annals of the New York Academy of Sciences*, *1219*(1), 52-72. https://doi.org/10.1111/j.1749-6632.2010.05940.x

Nadaraja, D., Lu, C., & Islam, M. M. (2021). The Sustainability Assessment of Plantation Agriculture—A Systematic Review of Sustainability Indicators. *Sustainable Production and Consumption*, *26*, 892-910. https://doi.org/10.1016/j.spc.2020.12.042

Nehrey, M., Kaminskyi, A., & Komar, M. (2019). Agro-economic models : A review and directions for research. *Periodicals of Engineering and Natural Sciences*, *7*(2), Article 2. https://doi.org/10.21533/pen.v7i2.579

Nerini, F., Tomei, J., To, L., Bisaga, I., Parikh, P., Black, M., Borrion, A., Spataru, C., Broto, V., Anandarajah, G., Milligan, B., & Mulugetta, Y. (2017). Mapping synergies and trade-offs between energy and the Sustainable Development Goals. *Nature Energy*, *3*, 10-15. https://doi.org/10.1038/s41560-017-0036-5

Oberč, B. P., & Arroyo Schnell, A. (2020). *Approaches to sustainable agriculture*. IUCN EURO. https://doi.org/10.2305/IUCN.CH.2020.07.en

OECD-FAO. (2022). *Aglink-Cosimo Model—A partial equilibrium model of world agricultural markets*. FAO. https://www.fao.org/markets-and-trade/publications/detail/en/c/1603651/

Page, M. J., McKenzie, J. E., Bossuyt, P. M., Boutron, I., Hoffmann, T. C., Mulrow, C. D., Shamseer, L., Tetzlaff, J. M., Akl, E. A., Brennan, S. E., Chou, R., Glanville, J., Grimshaw, J. M., Hróbjartsson, A., Lalu, M. M., Li, T., Loder, E. W., Mayo-Wilson, E., McDonald, S., … Moher, D. (2021). The PRISMA 2020 statement : An updated guideline for reporting systematic reviews. *BMJ*, *372*, n71. https://doi.org/10.1136/bmj.n71

Pandey, S. (2014). International and Regional Institutions and Instruments for Agricultural Policy, Research, and Development. In N. K. Van Alfen (Éd.), *Encyclopedia of Agriculture and Food Systems* (p. 44-48). Academic Press. https://doi.org/10.1016/B978-0-444-52512-3.00041-3

Phillips, L. D. (1989). Requisite Decision Modelling for Technological Projects. In C. Vlek & G. Cvetkovich (Éds.), *Social Decision Methodology for Technological Projects* (p. 95-110). Springer Netherlands. https://doi.org/10.1007/978-94-009-2425-3_6

Purvis, B., Mao, Y., & Robinson, D. (2019). Three pillars of sustainability : In search of conceptual origins. *Sustainability Science*, *14*(3), 681-695. https://doi.org/10.1007/s11625-018-0627-5

Reidsma, P., Janssen, S., Jansen, J., & van Ittersum, M. K. (2018). On the development and use of farm models for policy impact assessment in the European Union – A review. *Agricultural Systems*, *159*, 111-125. https://doi.org/10.1016/j.agsy.2017.10.012

Richardson, K., Steffen, W., Lucht, W., Bendtsen, J., Cornell, S. E., Donges, J. F., Drüke, M., Fetzer, I., Bala, G., von Bloh, W., Feulner, G., Fiedler, S., Gerten, D., Gleeson, T., Hofmann, M., Huiskamp, W., Kummu, M., Mohan, C., Nogués-Bravo, D., … Rockström, J. (2023). Earth beyond six of nine planetary boundaries. *Science Advances*, *9*(37), eadh2458. https://doi.org/10.1126/sciadv.adh2458

Riera, A., Duluins, O., Schuster, M., & Baret, P. V. (2023). Accounting for diversity while assessing sustainability : Insights from the Walloon bovine sectors. *Agronomy for Sustainable Development*, *43*(2), 30. https://doi.org/10.1007/s13593-023-00882-z

RIKS. (2014). *RIKS - Geonamica*. http://www.riks.nl/products/Geonamica

Rizojewa-Silava, A., Pilvere, I., & Zeverte-Rivza, S. (2018). Agriculture modelling in the European Union. *Proceedings of the International Scientific Conference « Economic Sciences for Agribusiness and Rural Economy »*, *2*, Article 2. https://js.wne.sggw.pl/index.php/esare/article/view/1493

Robinson, S., Mason-D'Croz, D., Sulser, T., Islam, S., Robertson, R., Zhu, T., Gueneau, A., Pitois, G., & Rosegrant, M. W. (2015). *The international model for policy analysis of agricultural commodities and trade (IMPACT) : Model description for version 3*. https://papers.ssrn.com/sol3/papers.cfm?abstract_id=2741234

Rockström, J., Steffen, W., Noone, K., Persson, Å., Chapin, F. S., Lambin, E. F., Lenton, T. M., Scheffer, M., Folke, C., Schellnhuber, H. J., Nykvist, B., de Wit, C. A., Hughes, T., van der Leeuw, S., Rodhe, H., Sörlin, S., Snyder, P. K., Costanza, R., Svedin, U., … Foley, J. A. (2009). A safe operating space for humanity. *Nature*, *461*(7263), Article 7263. https://doi.org/10.1038/461472a

Rossing, W. A. H., Zander, P., Josien, E., Groot, J. C. J., Meyer, B. C., & Knierim, A. (2007). Integrative modelling approaches for analysis of impact of multifunctional agriculture : A review for France, Germany and The Netherlands. *Agriculture, Ecosystems & Environment*, *120*(1), 41-57. https://doi.org/10.1016/j.agee.2006.05.031

Ryberg, M. W., Andersen, M. M., Owsianiak, M., & Hauschild, M. Z. (2020). Downscaling the planetary boundaries in absolute environmental sustainability assessments – A review. *Journal of Cleaner Production*, *276*, 123287. https://doi.org/10.1016/j.jclepro.2020.123287

Saysel, A. K., Barlas, Y., & Yenigün, O. (2002). Environmental sustainability in an agricultural development project : A system dynamics approach. *Journal of Environmental Management*, *64*(3), 247-260. https://doi.org/10.1006/jema.2001.0488

Schader, C., Grenz, J., Meier, M., & Stolze, M. (2014). Scope and precision of sustainability assessment approaches to food systems. *Ecology and Society*, *19*(3). https://doi.org/10.5751/ES-06866-190342

Schader, C., Sanders, J., Offermann, F., Lampkin, N. H., & Stolze, M. (2008). *Cost-Effectiveness Evaluation of Swiss Agri-Environmental Measures on Sector Level* [Report]. Research Institute of Organic Agriculture (FiBL), von-Thünen-Institut, Aberystwyth University. https://orgprints.org/id/eprint/20332/

Schmidt, A., Appel, F., Argueyrolles, R., Baldi, L., Filatova, T., Finger, R., Ge, J., Grujić, N., Heckelei, T., Huber, R., Koc, A. A., Li, C., Mack, G., Müller, B., Stepanyan, D., Will, M., & Delzeit, R. (2024). *Linking Economic Equilibrium Models with Agent-Based Models* (SSRN Scholarly Paper 4863569). https://doi.org/10.2139/ssrn.4863569

Schmitz, C., van Meijl, H., Kyle, P., Nelson, G. C., Fujimori, S., Gurgel, A., Havlik, P., Heyhoe, E., d'Croz, D. M., Popp, A., Sands, R., Tabeau, A., van der Mensbrugghe, D., von Lampe, M., Wise, M., Blanc, E., Hasegawa, T., Kavallari, A., & Valin, H. (2014). Land-use change trajectories up to 2050 : Insights from a global agro-economic model comparison. *Agricultural Economics*, *45*(1), 69-84. https://doi.org/10.1111/agec.12090

Shi, T., & Gill, R. (2005). Developing effective policies for the sustainable development of ecological agriculture in China : The case study of Jinshan County with a systems dynamics model. *Ecological Economics*, *53*(2), 223-246. https://doi.org/10.1016/j.ecolecon.2004.08.006

Steffen, W., Broadgate, W., Deutsch, L., Gaffney, O., & Ludwig, C. (2015). The trajectory of the Anthropocene : The Great Acceleration. *The Anthropocene Review*, *2*(1), 81-98. https://doi.org/10.1177/2053019614564785

Steffen, W., Richardson, K., Rockström, J., Cornell, S. E., Fetzer, I., Bennett, E. M., Biggs, R., Carpenter, S. R., de Vries, W., de Wit, C. A., Folke, C., Gerten, D., Heinke, J., Mace, G. M., Persson, L. M., Ramanathan, V., Reyers, B., & Sörlin, S. (2015). Planetary boundaries : Guiding human development on a changing planet. *Science*, *347*(6223), 1259855. https://doi.org/10.1126/science.1259855

Streimikis, J., & Baležentis, T. (2020). Agricultural sustainability assessment framework integrating sustainable development goals and interlinked priorities of environmental, climate and agriculture policies. *Sustainable Development*, *28*(6), 1702-1712. https://doi.org/10.1002/sd.2118

Stroustrup, B. (1996). A history of C++ : 1979--1991. In *History of programming languages—II* (p. 699-769). Association for Computing Machinery. https://doi.org/10.1145/234286.1057836

Swain, R. B. (2018). A Critical Analysis of the Sustainable Development Goals. In W. Leal Filho (Éd.), *Handbook of Sustainability Science and Research* (p. 341-355). Springer International Publishing. https://doi.org/10.1007/978-3-319-63007-6_20

The R Foundation. (2024). *R: What is R?* https://www.r-project.org/about.html

Therond, O., Duru, M., Roger-Estrade, J., & Richard, G. (2017). A new analytical framework of farming system and agriculture model diversities. A review. *Agronomy for Sustainable Development*, *37*(3), 21. https://doi.org/10.1007/s13593-017-0429-7

Tilman, D., & Clark, M. (2014). Global diets link environmental sustainability and human health. *Nature*, *515*(7528), 518-522. https://doi.org/10.1038/nature13959

USDA ERS. (2022). *ERS Annual Report, FY 2022*. https://www.ers.usda.gov/about-ers/plans-and-accomplishments/ers-annual-report-fy-2022/

Valera, H. G. A., Gopalakrishnan, B. N., Chakravarthy, S., Bharathi, S., Balié, J., & Pede, V. O. (2023). The impacts of reforming agricultural policy support on cereal prices : A CGE modeling approach. *Journal of Economic Studies*, *51*(1), 202-221. https://doi.org/10.1108/JES-06-2022-0362

van der Linden, A., de Olde, E. M., Mostert, P. F., & de Boer, I. J. M. (2020). A review of European models to assess the sustainability performance of livestock production systems. *Agricultural Systems*, *182*, 102842. https://doi.org/10.1016/j.agsy.2020.102842

Van Passel, S., & Meul, M. (2012). Multilevel and multi-user sustainability assessment of farming systems. *Environmental Impact Assessment Review*, *32*(1), 170-180. https://doi.org/10.1016/j.eiar.2011.08.005

von Lampe, M., Willenbockel, D., Ahammad, H., Blanc, E., Cai, Y., Calvin, K., Fujimori, S., Hasegawa, T., Havlik, P., Heyhoe, E., Kyle, P., Lotze-Campen, H., Mason d'Croz, D., Nelson, G. C., Sands, R. D., Schmitz, C., Tabeau, A., Valin, H., van der Mensbrugghe, D., & van Meijl, H. (2014). Why do global long-term scenarios for agriculture differ? An overview of the AgMIP Global Economic Model Intercomparison. *Agricultural Economics*, *45*(1), 3-20. https://doi.org/10.1111/agec.12086

WCED, S. W. S. (1987). World commission on environment and development. *Our common future*, *17*(1), 1-91.

Weerahewa, J., & Jacque, A. (2022). *Agricultural Policy Analysis : Concepts and Tools for Emerging Economies*. Springer Singapore. https://link.springer.com/book/10.1007/978-981-16-3284-6

Wiborg, T. (2000). *A Comparison of Agricultural Sector Models : CRAM, DRAM, SASM and the KVL Model* (Institut for Fødevare-og Ressourceøkonomi, Københavns Universitet).

Zalasiewicz, J., Waters, C. N., Williams, M., Barnosky, A. D., Cearreta, A., Crutzen, P., Ellis, E., Ellis, M. A., Fairchild, I. J., Grinevald, J., Haff, P. K., Hajdas, I., Leinfelder, R., McNeill, J., Odada, E. O., Poirier, C., Richter, D., Steffen, W., Summerhayes, C., … Oreskes, N. (2015). When did the Anthropocene begin? A mid-twentieth century boundary level is stratigraphically optimal. *Quaternary International*, *383*, 196-203. https://doi.org/10.1016/j.quaint.2014.11.045

Zhang, X., Yao, G., Vishwakarma, S., Dalin, C., Komarek, A. M., Kanter, D. R., Davis, K. F., Pfeifer, K., Zhao, J., Zou, T., D'Odorico, P., Folberth, C., Rodriguez, F. G., Fanzo, J., Rosa, L., Dennison, W., Musumba, M., Heyman, A., & Davidson, E. A. (2021). Quantitative assessment of agricultural sustainability reveals divergent priorities among nations. *One Earth*, *4*(9), 1262-1277. https://doi.org/10.1016/j.oneear.2021.08.015

Zhang, Y. (2018). *Conceptualising and estimating rationalised agricultural optimisation models* [Thesis, Universitäts- und Landesbibliothek Bonn]. https://bonndoc.ulb.uni-bonn.de/xmlui/handle/20.500.11811/7353

8 ANNEX

8.1 ANNEX 1: FULL LIST OF PLANETARY BOUNDARIES AND INDICATORS (RICHARDSON ET AL., 2023)

Earth system process	**Control variable(s) in Richardson et al. (2023)**	**Threshold levels**
1 – Climate change	Atmospheric CO_2 concentration (ppm CO_2) Total anthropogenic radiative forcing at top-of-atmosphere (W m^{-2})	350 ppm CO_2 +1.0W m^{-2}
2 – Change in biosphere integrity	Genetic diversity: E/MSY Functional integrity: measured as energy available to ecosystems (NPP)(%HANPP)	<10 E/MSY but with an aspirational goal of ca.1E/ MSY (assumed background rate of extinction loss) HANPP (in billion tonnes of C $year^{-1}$) <10% of preindustrial Holocene NPP
3 – Stratospheric ozone depletion	Stratospheric O3 concentration,(global average)(DU)	<5%reduction from preindustrial level assessed by latitude (~276 DU)
4 – Ocean acidification	Carbonate ion concentration, average global surface ocean saturation state with respect to aragonite (Ω_{arag})	≥80% Ω_{arag} of mean preindustrial aragonite saturation state of surface ocean, including natural diel and seasonal variability
5 – Biogeochemical flows: P and N cycles	Phosphate *global*: P flow from fresh water systems into the ocean; *regional*: P flow from fertilizers to erodible soils (Tg of P $year^{-1}$)	Phosphate *global:* 11 Tg of P $year^{-1}$; *regional:* 6.2 Tg of P $year^{-1}$ mined and applied to erodible (agricultural) soils. Boundary is a global average, but regional distribution is critical for impacts.
	Nitrogen *global:* industrial and intentional fixation of N (Tg of N $year^{-1}$)	Nitrogen *global:* 62 Tg of N $year^{-1}$. Boundary is a global average. Anthropogenic biological N fixation on agriculture areas highly uncertain but estimates in range of ~30 to 70 Tg of N $year^{-1}$. Boundary acts as a global "valve" limiting introduction of new reactive N to Earth system, but regional distribution of fertilizer N is critical for impacts.
6 – Land system change	*Global*: area of forested land as the percentage of original forest cover; *biome*: area of forested land as the percentage of potential forest (% area remaining)	*Global: 75%* values are a weighted average of the three individual biome boundaries; *biomes*: tropical, 85%; temperate, 50%; boreal: 85%
7 – Freshwater change	Blue water: human induced disturbance of blue water flow	Upper limit (95th percentile) of global land area with deviations greater than during preindustrial, Blue water: 10.2%
	Green water: human induced disturbance of water available to plants (% land area with deviations from preindustrial variability)	Green water: 11.1%
8 – Atmospheric aerosol loading	Interhemispheric difference in AOD	0.1 (mean annual interhemispheric difference)
9 – Novel entities	Percentage of synthetic chemicals released to the environment without adequate safety testing	0

8.2 ANNEX 2: FULL LIST OF SAFA THEMES AND INDICATORS (FAO, 2014)

***Table 8:** Pillars, themes and subthemes of the SAFA Framework*

Pillar	Code	Theme	Subtheme
Good governance	G1	Corporate Ethics	Mission Statement Due diligence
	G2	Accountability	Audits Responsibility Transparency
	G3	Participation	Stakeholder dialogue Grievance procedures Conflict resolution
	G4	Rule of Law	Legitimacy Remedy, restoration, prevention Civic responsibility Resource appropriation
	G5	Holistic Management	Sustainability management plan Full-cost accounting
Environmental integrity	E1	Atmosphere	Greenhouse gases Air quality
	E2	Water	Water withdrawal Water quality
	E3	Land	Soil quality Land degradation
	E4	Biodiversity	Ecosystem diversity Species diversity Genetic diversity
	E5	Materials and Energy	Material use Energy use Waste reduction & disposal
	E6	Animal Welfare	Animal health Freedom from stress
Economic resilience	C1	Investment	Internal investment Community investment Long-ranging investment Profitability
	C2	Vulnerability	Stability of production Stability of supply Stability of market Liquidity Risk management
	C3	Product Quality and Information	Food safety Food quality Product information
	C4	Local Economy	Value creation Local procurement
Social well-being	S1	Decent Livelihoods	Quality of life Capacity development Fair access to means of production
	S2	Fair Trading Practices	Responsible buyers Rights of suppliers
	S3	Labor Rights	Employment relations Forced labour Child labour Freedom of association and right to bargaining
	S4	Equity	Non discrimination Gender equality Support to vulnerable people
	S5	Human Health and Safety	Workplace safety and health provisions Public health
	S6	Cultural Diversity	Indigenous knowledge Food sovereignty

8.3 ANNEX 3: FULL RESULTS

Table 9: *Main results of the analysis. The columns Env, Gov, Eco and Soc contain the total number of sustainability themes included in the model for the Environmental, Governance, Economic and Social sustainability dimensions. The detailed results of the inclusion of each theme are represented by* ***Figure 13*** *(p.42)*

Model name	Reference documentation	Class	Geographical level	Geographical scope	Treatment of time	Mathematical approach	Economic approach	Program/ programming language	User Interface	Env	Gov	Eco	Soc	Developing institution	Funding institution	Network or project
RAUMIS	Henrichsmeyer 1996, Julius 2003, Thunen Institute 2024	Calibrating optimization	National	Germany	Static	MP		FORTRAN	NO	8	0	1	0	UniBonn/EuroCARE, Thunen Institute	Germany	
DREMFIA	Lehtonen 2001, Lehtonen 2005	Calibrating optimization	National	Finland	Dynamic	PMP		GAMS	NO	6	0	1	0	Helsinki University of Technology, MTT Agrifood Research	Finland	SUSAGFU project
FASOM-GHG	Beach 2010	Calibrating optimization	National	USA	Dynamic	NLP		GAMS	NO	9	0	2	0	RTI International, Oregon State University, Texas A&M, Duke University	US (US EPA)	
SILAS-dyn	Malitius 2001, Zimmerman 2008	Calibrating optimization	National	Switzerland	Dynamic	LP		LPL	YES	2	0	1	0	Agroscope (Switzerland)		
AGRITALIM	Cortignani 2022, Cortignani and Coderoni 2022	Calibrating optimization	National	Italy	Dynamic	PMP			NO	6	0	2	0	University of Tuscia (Italy)		
SWAP California	Draper 2003, Howitt 2012	Calibrating optimization	Regional	California, USA	NA	PMP		GAMS	NO	3	0	2	0	U.C. Davis	California (Dep. of Water Resources)	
ENVISAGE	van der Mensbrugghe 2017	CGE	Global	World	Both		CGE	GAMS	NO	5	0	2	0	World Bank, OECD, CGTA - Purdue U.		
GTAP	Corong 2017, Hertel 1997	CGE	Global	World	Static	NLP	CGE	GEMPACK	YES	0	0	2	0	CGTA - Purdue University		GTAP Consortium
GTAP-AGR	Keeney 2005	CGE	Global	World	Static	NLP	CGE	GEMPACK	YES	2	0	2	0	CGTA - Purdue University		GTAP Consortium
MIRAGE-Biof	Laborde 2012	CGE	Global	World	Dynamic		CGE		NO	4	0	0	0	CEPII, IFPRI, IIASA, INRAE, AgroParisTech	EU	
DART-BIO	Calzadilla 2016, Henseler 2020	CGE	Global	World	Dynamic		CGE		NO	3	0	2	0	Kiel Institute for the World Economy, UCL London, OECD, Thunen Institute	Germany (BMBF)	
MAGNET	Woltjer 2014, Philippidis 2018, Blanco 2019, MAGNET 2024	CGE	Global	World	Both	NLP	CGE	GEMPACK	NO	4	0	2	1	EU (JRC), WUR		MAGNET Consortium
RIAPA	Diao & Thurlow 2012, IFPRI 2024	CGE	National	30 countries, mostly in Africa & Asia	Dynamic		CGE	0	NO	5	0	2	3	IFPRI	US (USAID), Bill & Melinda Gates Foundation, CGIAR	
AGSIM	Taylor 1994, Taylor 1989	Econometric production	National	US	Dynamic	econometric			NO	3	0	0	0	Texas A&M, Auburn University	USDA, ALFA	

Table 9 (continued)

Model name	Reference documentation	Class	Geographical level	Geographical scope	Treatment of time	Mathematical approach	Economic approach	Program/ programming language	User Interface	Env total	Gov total	Eco total	Soc total	Developing institution	Funding institution	Network or project
CASM	Yi 2018	Econometric production	National	China	Dynamic	PMP	PE	GAMS	NO	1	0	2	1	Nainjing Agricultural University, Texas A&M	China	
BFAP	Strauss 2010, Gebrehiwet 2011	Econometric production	National	South Africa	Dynamic	econometric	PE		NO	2	0	1	0	SABMiller, BFAP		
LASAM	Pilvere 2022, Nipers 2017, Nipers 2019	Econometric production	National	Latvia	Dynamic	econometric		R; Rstudio	YES	6	1	2	0	Latvia University of Life Sciences and Technologies	Latvia	
CEEMA	Liu 2014	Econometric production	National	Canada	Static	MP, econometric	PE		NO	4	0	1	0	Beijing University of Technology, AAFC Canada, Natural Resources Canada	Agriculture and Agri-Food Canada	PERD project
CRAM	Wiborg 2000	Econometric production	National	Canada	Static	PMP, econometric	PE		NO	0	0	1	0	University of British Columbia, AAFC Canada, Iowa SU, U.C. Davis	Agriculture and Agri-Food Canada	
DIAS	Wier 2001	Econometric production	National	Denmark	Static	econometric	PE		NO	6	0	2	0	Institute of Local Government Studies, Aarhus University		
FAPSIM	Salathe 1982, Gadson 1982	Econometric production	National	USA	Both	econometric			NO	1	0	1	0	USDA (ERS)		
POLYSYS	De La Torre Ugarte 2000	Econometric production	Regional	Multiple (US)	Dynamic	LP, econometric		FORTRAN	YES	6	1	2	1	USDA (ERS), University of Tennessee, Oklahoma State University		
GCAM	JGCRI 2023, Kyle 2011	Integrated bioeconomic	Global	World	Dynamic		PE	C++	YES	7	1	1	0	PNNL, University of Maryland	US (USDE)	
GLOBIOM	IBF-IIASA 2023, globiom.org	Integrated bioeconomic	Global	World	Dynamic	LP	PE	GAMS	YES	6	1	0	0	IIASA		
SEAMLESS-IF	van Ittersum 2008, CORDIS EC 2013a	Integrated bioeconomic	International	EU	Static	meta-model		SEAMLESS-IF-GUI, MODCOM, GAMS	YES	8	1	2	2	WUR, UniBonn/EuroCARE, CIRAD, INRAE	EU (FP6)	SEAMLESS integrated project
LUMOCAP	Van Delden 2010	Integrated bioeconomic	International	EU	Dynamic	econometric		GEONAMICA	YES	3	0	2	0	RIKS, EU (JRC)	EU	LUMOCAP project
MATA	Deybe 1998	Integrated bioeconomic	National	Burkina-Faso or other	Static		PE		NO	3	0	2	1	CIRAD		
CEEOT-MMS	Osei 2008	Integrated bioeconomic	National	USA	Dynamic	LP		GAMS	YES	6	1	2	0	TIAER	US (US EPA)	
DeSurvey IAM	Van Delden 2009	Integrated bioeconomic	Regional	Multiple (arid regions)	Dynamic	SD		GEONAMICA	YES	4	1	2	0	RIKS	EU (FP6)	DeSurvey Project
ITE2M	Reiher 2006	Integrated bioeconomic	Regional	Multiple (EU)	Static	meta-model			NO	6	1	1	0	Justus-Liebig-University	Germany (DFG)	
ECECMOD	Vatn 1999, Vatn 2006	Integrated bioeconomic	Regional	Norway	Dynamic	NLP		Powersim	NO	5	1	1	0	Norwegian University of Life Sciences	Norway	
MEA-scope	Zander 2009, CORDIS EC 2013b	Integrated bioeconomic	Regional	7 European regions	Both	meta-model			YES	9	1	2	0	ZALF, IAMO	EU	
MODAM	Zander and Kachele 1999, Zander 2009	Integrated bioeconomic	Regional	Germany	Static	LP			NO	6	1	2	0	ZALF	Germany	

Table 9 (continued)

Model name	**Reference documentation**	**Class**	**Geographical level**	**Geographical scope**	**Treatment of time**	**Mathematical approach**	**Economic approach**	**Program/ programming language**	**User Interface**	**Env total**	**Gov total**	**Eco total**	**Soc total**	**Developing institution**	**Funding institution**	**Network or project**
ESIM	Banse 2005, Choi 2019, Josling 1998	Spatial equilibrium	Global	EU + Turkey, USA and ROW	Static		PE	GAMS	YES	0	0	1	0	USDA (ERS), U. of Göttingen, SLU	EU (DG AGRI), USDA	
FAPRI	Fabiosa 2010, Meyers 2010	Spatial equilibrium	Global	World	Dynamic	MP, econometric	PE	GAMS	NO	1	0	0	0	FAPRI	US	
AGLINK-COSIMO	OECD-FAO 2022	Spatial equilibrium	Global	World	Dynamic	PMP	PE, MCM	PC-TROLL, Excel, GAMS	YES	4	0	0	1	OECD, FAO		
IFPSIM	Furuya 2010	Spatial equilibrium	Global	World	Static		PE	FORTRAN 90	NO	0	0	0	0	JIRCAS, FAPRI	Japan	
SWOPSIM	Roningen 1991, Peterson 1994	Spatial equilibrium	Global	World	Static	econometric		Spreadsheet (MS Excel ?)	NO	0	0	1	0	USDA (ERS), Virginia Polytechnic Institute and State U., Purdue U.		
CCLS	Hjort 2018	Spatial equilibrium	Global	44 countries/regions	Dynamic		PE		NO	2	0	0	0	USDA (ERS)		
FAP	Fischer 1982	Spatial equilibrium	Global	World	Dynamic		PE		NO	2	0	2	0	IIASA		
PEATSim	Somwaru 2012	Spatial equilibrium	Global	27 countries/regions	Dynamic		PE		NO	1	0	0	0	USDA (ERS)		
CAPRI	CAPRI network 2022	Spatial equilibrium	International	EU + Norway + Turkey + Western Balkan; World	Static	PMP	PE	GAMS	YES	8	0	1	0	UniBonn/EuroCARE, Thunen Institute, SLU, EU (JRC)	EU	CAPRI network
IMPACT 3	Robinson 2015, Rosegrant 2012, Rosegrant 1995	Spatial equilibrium	International	159 countries	Dynamic	NLP	PE	GAMS, FORTRAN, Excel	YES	7	1	3	2	IFPRI		
AGMEMOD	van Leeuwen 2012, Esposti 2012, Hanrahan 2010	Spatial equilibrium	International	EU27 + UK + Russia + Turkey + Ukraine + FYROM	Dynamic	econometric	PE, MCM	GAMS	YES	1	0	0	0	WUR, Teagasc, Latvia SI of Agrarian Economics, Thunen Institute, UnivPM	EU	AGMEMOD network
PEM	Martini 2011, Henderson 2019, (OECD 2000)	Spatial equilibrium	International	USA, Canada, EU, Japan, Korea, Mexico, Switzerland	Static		PE		YES	5	0	2	0	OECD		
Jordmod II	Britz and Mittenzwei 2015, Britz 2018	Spatial equilibrium	National	Norway	Dynamic		PE	GAMS, CONOPT, PATH	YES	0	0	1	0	NILF, UniBonn/EuroCARE	Norway	
FAPRI-UK	Moss 2011, Moss 2010 (p. 101)	Spatial equilibrium	National	UK	Dynamic	econometric	PE	GAMS	NO	6	0	1	0	FAPRI, Agri-Food and Biosciences Institute (UK)	UK	
ASM-GHG	Schneider 2000, Schneider 2007, Shakhramanyan 2013	Spatial equilibrium	National	US + World	Static	MP	PE		NO	7	0	2	0	Hamburg University, Texas A&M, University of Luneburg	EU (FP7)	
MATSIM-LUCA	Forslund 2013, Salou et al 2019	Spatial equilibrium	National	France + World	Static		PE		NO	4	0	1	0	ADEME, INRAE	France (ADEME, INRAE)	

Table 9 (continued)

Model name	Reference documentation	Class	Geographical level	Geographical scope	Treatment of time	Mathematical approach	Economic approach	Program/ programming language	User Interface	Env total	Gov total	Eco total	Soc total	Developing institution	Funding institution	Network or project
Jordmod	Brunstad 2005, Bullock 2016	Spatial equilibrium	National	Norway	Static	MP	PE		NO	4	0	1	0	NILF, Norwegian School of Economics and Business Administration	Norway	
TOA-model	Stoorvogel 2004, Stoorvogel 2001	Spatial equilibrium	Regional	Multiple (undefined)	Dynamic	econometric		Own software, on SAS ?	YES	5	1	2	1	Montana State University, WUR, CIP	ISNAR, US (USAID), IDRC/CGIAR	
MAgPIE 4	Dietrich 2019, Dietrich 2018	Structural simulation	Global	World	Dynamic	SD		R ; GAMS	NO	9	0	1	1	PIK, ATB	EU, Germany	SIM4NEXUS
AROPAj	Jayet 2023, Godard 2005	Structural simulation	International	EU-28	Static	MP		GNU, R, GAMS	YES	9	1	2	0	INRAE, AgroParisTech, EU (JRC)	EU, France	GENEDEC project (FP6)
MOWASIA	Belem et Saqalli 2017	Structural simulation	International	West-Africa	Dynamic	ABM		OpenMi + Mimosa platforms	NO	5	1	3	3	WASCAL, CNRS	Germany	
SWISSLand	Mohring 2016, Agroscope 2016, Mohring 2010	Structural simulation	National	Switzerland	Dynamic	ABM			YES	3	0	2	0	Agroscope (Switzerland)		
Turkish ASM	Bauer 1990	Structural simulation	National	Turkey	Static	MP		0	NO	2	0	0	0	UniBonn/EuroCARE, Middle East Technical University		
REAP	Johansson 2007	Structural simulation	National	USA	Static	NLP		GAMS	YES	7	1	2	0	USDA (ERS)		
ASFF	Turner 2011, Candy 2015	Structural simulation	National	Australia	Dynamic	tensions model			NO	7	1	3	0	CSIRO, University of Melbourne, whatIf Technologies	Australia	
KASM	Abkin 1979	Structural simulation	National	Korea	Dynamic	SD			NO	5	0	2	1	USDA, Michigan State University	Korea	
TASM	Chen 2005, Kung 2013	Structural simulation	National	Taiwan	Static	MP, econometric	PE		NO	5	0	3	0	National Chung-Hsing U., National Taiwan U., Jiangxi U. of Finance and Economics, Texas A&M	Taiwan (National Science Council)	
NIRAP 2	Webb 1981, Abkin 1981	Structural simulation	National	USA	Static	econometric			NO	2	0	2	0	USDA (ERS), University of Michigan		
RCP	Aghabeygi 2022	Structural simulation	National	Iran	Static	PMP			NO	4	0	2	0	U. degli Studi di Parma, EU (JRC), INRAE		
AgriPoliS	Kellerman 2008, Zander 2009, Happe 2004, Balmann 1997	Structural simulation	Regional	Several case study regions (Europe)	Dynamic	ABM		C++	NO	7	0	2	0	IAMO, ZALF		
ALMaSS	Topping 2003, Topping 2010, Topping 2024	Structural simulation	Regional	12 European Countries	Dynamic	ABM		C++	NO	7	1	0	0	Aarhus U., Roskilde U.		
ANEM	Zheng 2015	Structural simulation	Regional	Case study: Zhongjiang County (China)	Dynamic	ABM		MATLAB	NO	2	1	0	1	China (Ministry of Transports), Tsinghua U., WUR	China, Netherlands	SURE project

Table 9 (continued)

Model name	Reference documentation	Class	Geographical level	Geographical scope	Treatment of time	Mathematical approach	Economic approach	Program/ programming language	User Interface	Env total	Gov total	Eco total	Soc total	Developing institution	Funding institution	Network or project
AAEM	Zhang 2012	Structural simulation	Regional	China	Dynamic	ABM			YES	0	0	2	0	National U. of Defense Technology (China)		
MPMAS	Schreinemachers & Berger 2011, Berger & Schreinemachers 2012, Universität Hohenheim 2024	Structural simulation	Regional	Multiple (undefined)	Dynamic	ABM, MP		MS Office Excel + IBM OSL, C++	YES	6	1	2	1	Universitat Hohenheim	Germany	
SYNERGY	Jouan 2020	Structural simulation	Regional	France	Static	PMP			NO	4	1	1	0	INRAE	France (Brittany and Pays de Loire), EU (EAFRD)	
POMMARD	Bryden 2008, Johnson 2008	Structural simulation	Regional	Multiple (EU)	Dynamic	SD		STELLA (TM)	YES	5	0	2	0	UHI Millennium Institute, NILF, University of Missouri	EU (FP6)	TOP-MARD project
AISEEM	Shi 2005	Structural simulation	Regional	Case study: Jinshan County, China)	Dynamic	SD		STELLA (TM)	YES	5	1	3	1	CSIRO, University of New England (Australia)		
GAPSIM	Saysel 2002	Structural simulation	Regional	Southeastern Anatolia, Turkey	Dynamic	SD		STELLA (TM)	NO	6	0	2	1	Bogazici University		
AEP-SD	Li 2012	Structural simulation	Regional	Kongtong District, Gansu Provine, China	Dynamic	ABM, SD		Vensim	NO	5	1	1	0	Chinese Academy of Sciences (China)	China	
RegMAS	Lobianco 2010	Structural simulation	Regional	Multiple (case study in italy)	Dynamic	ABM		C++, GLPK	YES	2	1	2	0	Università Politecnica delle Marche		
MedAction PSS	Van Delden 2007	Structural simulation	Regional	Mediterranean regions	Dynamic	SD		GEONAMICA, C++	YES	4	1	1	0	RIKS, King's College London	EU	
CHANOS	Mialhe 2012	Structural simulation	Regional	Philippines	Dynamic	ABM		NetLogo	YES	4	1	3	1	Université Paris Diderot 7, FUNDP		

8.4 ANNEX 4: NAMES OF INSTITUTIONS

AAF Canada	Agriculture and Agri-Food Canada
CGTA	Center for Global Trade Analysis (Purdue University)
China	Chinese public institutions
CSIRO	Commonwealth Scientific and Industrial Research Organization
EC	European Commission
EU	European Union
EuroCARE	European Centre for Agricultural, Regional and Environmental Policy Research
FAO	Food and Agriculture Office of the United Nations
FAPRI	Food and Agriculture Policy Research Institute
GTAP Consortium	Global Trade Analysis Project consortium
IAMO	Leibniz Institute of Agricultural Development in Central & Eastern Europe
IFPRI	International Food Policy Research Institute
IIASA	International Institute for Applied Systems Analysis
INRAE	National Research Institute for Agriculture, Food and the Environment
NILF	Norwegian Agricultural Economics Research Institute
OECD	Organization for Economic Co-operation and Development
PIK	Potsdam Institute for Climate Impact Research
Switzerland	Swiss public institutions
Texas A&M	Texas A&M University
Thünen Institute	Thünen Institute (German Federal Ministry of Food and Agriculture)
U. of Missouri	University of Missouri
UniBonn	University of Bonn
USDA	United States Department of Agriculture
WUR	Wageningen University & Research
ZALF	Leibniz-Centre for Agricultural Landscape Research

Modeling agricultural systems and policies to advance sustainability: a review

Timothée Lefebvre

Agriculture significantly impacts global sustainability challenges, necessitating effective policymaking to steer agricultural practices towards greater sustainability. Given the complexity of the agricultural system, mathematical models represent a powerful tool for supporting agricultural policymaking. This master's thesis provides a comprehensive overview of policy-oriented macro-level models, identifying their characteristics, effectiveness at integrating sustainability themes, and the actors involved in their development and funding. After a PRISMA-based systematized review of 1064 articles from the Scopus database and prominent institutional websites, this study analyzes 75 macro-level models. These models are analyzed for their ability to incorporate sustainability across different dimensions—environmental, economic, social, and governance, based on the Planetary Boundaries and SAFA frameworks.

The findings reveal significant diversity among the models, with *integrated bio-economic models*, *structural simulation models* and *calibrating optimization models* demonstrating superior performance in integrating sustainability themes. In contrast, computable general equilibrium (CGE), econometric, and spatial equilibrium models exhibit lower integration capabilities. This disparity is influenced by both technical factors, such as data availability and the complexity of modeling processes, and agenda-driven priorities that may focus attention toward specific themes.

The development of these models is driven by actors from public research institutions, independent centers, and universities. Notable contributors are institutions like the ERS of the USDA, INRAE of France, and the JRC of the EU. Funding is primarily sourced from public institutions. Both model development and funding predominantly originates from OECD countries.

This Master's thesis highlights the need for strategic advancements in policy-oriented macro-level models to enhance the integration of sustainability themes. Recommendations include addressing data limitations, enhancing model connectivity, and fostering international collaborations to improve model interoperability and stakeholder engagement. The study advocates focusing on high-performing model classes to inspire broader improvements across all models, ultimately supporting more effective and sustainable agricultural policymaking.

UNIVERSITÉ CATHOLIQUE DE LOUVAIN
Faculté des bioingénieurs
Croix du Sud, 2 bte L7.05.01, 1348 Louvain-la-Neuve, Belgique | **www.uclouvain.be/agro**