Synthesis of model-based studies

MATS Deliverable 2.2

MATS
making agricultural trade sustainable

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Summary

The current study presents computational models used in preceding published agricultural trade-related papers. The study analyses the results of published work in regards to the models that were used to assess the relation between trade and sustainability (environmental, social, and economic dimensions). The models are described in detail and information about their characteristics, goal, type, regional coverage, time frame, and applications are presented.

A synthesis of results is depicted in tables to accumulate important information about the models investigated. This approach allows a comparison to be made between the various models not only on their basic characteristics but also on their application, their regional coverage, and the sustainability dimensions they are capable of covering. Furthermore, this study presents an assessment of how methods and models are complementary to one another. The main method of the analysis that took place in this study was a literature review of previous work focused on agricultural trade and sustainability matters, in terms of trade dynamics, agricultural production, and agricultural production output. A great number of international agricultural papers were examined with an equivalently great variety of trade and sustainability-related subjects.

The findings of the present study about the computable models used in agricultural trade studies are the following:

- Computable General Equilibrium (CGE) models. The CGE models represent an economy of many goods which are produced by many sectors and are used to analyse some policy challenges and economic "shocks" including global climate change, trade agreements, and international labour migration, among others. Able to capture characteristics and general functionalities of an economy; quantitative policy analysis tools of high significance. These models cover all three of the Sustainability Dimensions: Economy (GDP, saving and investments, government tax revenues, bio-economy, farm optimization, socio-economic factors, taxes, prices, outputs, demands, trade liberalization, trade protectionism), Environment [climate change, energy, climate-yield linkages, climatic conditions, agricultural systems, farm, landscape, greenhouse gas (GHG) emissions] and Society (socio-economic factors, securing food supply, labour). The CGE models are stronger in the Economical and Environmental dimensions rather than the Social. They are vastly used since they can forecast up to 2100 in Trade Dynamic studies

and up to 2050 in Agricultural Production Studies. They cover regional to global studies.

- Partial Equilibrium models. Partial equilibrium models confine themselves to one sector or a small group of sectors. In the case of the agricultural market, partial models consider the market as a closed system without linkages with the rest of the economy. Changes in model parameters and exogenous variables may be used to account for the effects of the rest of the economy or the world market on the agricultural system. Partial models can provide much product detail which cannot be obtained from CGE models. These models cover all three of the Sustainability Dimensions: Economy (technology, growth, GDP, yields, and prices, productivity, shocks on agricultural markets, consumption, tariffs, market, exports, imports, trade), Environment (climate change, agri-environmental policy, carbon emissions, land-use), Society (food security). Partial Equilibrium models like the CGE ones do not cover the social dimension in such depth as the other two dimensions, the economy, and the environment. They can forecast up to 2100 just like the CGE models and are equally used for regional to global studies.

- The Gravity Approach. The Gravity approach explains international or regional trade. The model uses a function to relate the trade flows between countries to the distance between the origin and destination countries and the various explanatory variables related to the characteristics of both origin and destination countries. These models cover all three of the Sustainability Dimensions: Economy (international or regional trade, trade agreements, exchange rates, income level, transportation cost), Environment (climate change), Society (human development, common official language, common colonial past). The strength of the gravity models is the economic dimension. Their forecasting horizon is relatively short and the exact length depends on the hypothesis of the study and can cover regional to global studies.

- Regression Models. The models are used to perform impact evaluation, causal analysis, and forecasting. These models cover all three of the Sustainability Dimensions: Economy (international or regional trade, income level, policy, consumption expenditure, and welfare benefits), Environment (climate change, carbon emissions), Society (human development, household welfare, living standard). The models cover in-depth the economic dimension and hence are stronger on that factor. Similar to the Gravity Approach, their forecasting horizon is relatively short and the exact length depends on the experiment and covers all regions.

- System Dynamics (SD) models. The SD modelling framework has been widely used in research related to agricultural land, soil, and water resources management, as well as in the examination of the resilience in food systems to address complex and non-linear feedback systems (Sterman, 2000). These models cover all three of the Sustainability Dimensions: Economy (international or regional trade, income, policy), Environment (climate change, agricultural land, soil, and water resources management, energy policy, innovation, strategic planning, water use), Society (food systems, population dynamics, food gap). All of the three dimensions are equally covered by the SD models with an exception of trade in the economic dimension. The forecasting ability of these models depends on the nature of the experiment as in the previous two categories and they cover regional to global studies.

- Integrated Assessment Models (IAMs). IAMs designed to examine issues related to the future development of environmental and sustainability topics. Such models have examined the interactions between human activities (such as energy use and agriculture) and environmental factors such as land cover and climate systems. These models cover all three of the Sustainability Dimensions: Economy (production), Environment (climate change, sustainability, environmental factors, land-cover, climate systems, energy systems, biomass, ecosystem, water use, and biodiversity), Society (food systems, food security). IAMs cover more in-depth the Environment dimension. They can forecast up to 2100 like the CGE and Partial Equilibrium models and they cover national, regional, and global studies.

- Optimal Crop Allocation models. Optimal Crop Allocation models are utilized to solve diverse types of optimization matters. These models cover only two of the Sustainability Dimensions: Economy (production planning, profit, risk management, yield, market prices) and Environment (land, planting, agro-metrological phenomena). These models do not cover the social dimension which can be characterized as a weakness. Their forecasting horizon depends on the hypothesis of the experiment and can cover up to global studies.

- Calibrated programming models. These models are empirical analysis tools that allow the use of all available information. These models cover only two of the Sustainability Dimensions: Economy (agricultural production, management, policy) and Environment (water use, agronomic, hydrologic, and other biophysical models). These models do not cover the social dimension which can be characterized as a weakness. Their forecasts depend on the hypothesis of the experiment and can cover regional to global studies.

- Spatial models. Spatial models such as InVEST can utilize map and value key ecosystem services to answer inquiries on a local, regional or global level. These models cover only two of the Sustainability Dimensions: Economy (trade flows, agricultural production) and environment (ecosystem services, landscape, carbon sequestration, water yield, pollinator abundance, sediment and nutrient retention, crop yield, and nutrient value for a fixed set of crops, and habitat quality). These models do not cover the social dimension which can be characterized as a weakness. Their forecasts depend on the hypothesis of the experiment and can cover regional to global studies.

- Sustainability Assessment Models. Sustainability assessment models evaluate dimensions and subjects with respect to farm management strategies. These models cover all three of the Sustainability dimensions: Economy (agricultural policies, sustainable economy, growth, and production), Environment (ecosystem services, climate, biophysical conditions, and environmental impact), and Society (food, food security, nutrition, food labels, nutritional impact). All the dimensions are covered equally and hence the models do not appear to have a particular strength on just one dimension. These models are used for farm-level studies.

- Agricultural Production Growth Models. They examine the relationship between agricultural production and important inputs of production such as physical capital stock, labour, and land. These models cover all three of the Sustainability Dimensions: Economy (agricultural production, capital stock), Environment (land), and Society (labour, gender). The strength of such models is the economic dimension. Their forecasting horizon is relatively small and depends on the hypothesis of the experiment and can cover from regional to global studies.

- Economic and Financial Analysis. Economic and financial models can be developed to analyse investments in the agriculture sector. These models cover only two of the Sustainability Dimensions: Economy [cash flows, Cost-Benefit Analysis, investment performance, financing, expected return on equity investment, Net Present Value (NPV), Internal Rate of Return (IRR), expected income] and Environment (climate-smart agriculture practices). Such models lack a social dimension coverage which can be characterized as a weakness. Their forecasting ability is relatively short and can cover from regional to national studies.

Models that have been reviewed in this report have also been used in studies for analysing issues that are puzzling the Global South. The range of studies analysed in the Global South includes papers from African countries, like Nigeria, to Latin America's Brazil, and Asia's Pakistan. These studies have utilized the capabilities of CGE models, SD models, GTAP models, DCGE (Dynamic CGE) models, or Gravity models in their attempt to examine vital sustainability matters in agriculture such as gender gap in productivity, agricultural production, and employment, impact assessments on agriculture goods exports, livestock productivity, trade, etc. Moreover, investigations on a plethora of agricultural sustainability issues were conducted by scientists using not only the well-known before mentioned models but other more specialised modelling frameworks like the National Water–Food (NWF), InVest, or extensions of those models.

After a thorough review of the presented models it is notable to indicate that although most models address a wide variety of sustainability dimension issues, several models provide modelling frameworks that are technically more flexible than the others. Such models are mostly the Sustainability Assessment models, the IAM models, and the System Dynamic models. To exemplify, a state of the art modelling framework that is currently being used, to address economic, environmental as well as societal issues is the System Dynamics (SD) modelling approach. In comparison to other models, the respective framework introduces the element of non-linearity in terms of developing efficient Decision Support Tools (DST). Thus, the corresponding framework provides additional complexity to the calculation in relation to most of the participatory, deterministic, and probabilistic approaches (Vannier et al., 2022). However, it can be linked or coupled to those different approaches, to improve the emphasis regarding the complexity of issues connected to natural, as well as agricultural resources. Moreover, the SD modelling approach is adequately designed for policy prospection and scenario testing at a regional, national and global scale and it allows multi-method and multi-disciplinary integration. Although a main difficulty in the SD modelling is validation, the respective approach is appropriate for the reproduction of agricultural systems' organisation, as well as for designing and experimenting with new strategies and management/policy scenarios respectively (Turner et al., 2016).

However, the thorough investigation regarding the available modelling approaches considering the synthesis of model-based studies indicated the lack of an important feature that is not being addressed, at a volume that corresponds to its magnitude. That is, regarding the sustainability dimension of the models, not a lot of them address the partition referring to the social aspect of the sustainability dimension. Cases such as unemployment, human development, household welfare, living standard, population dynamics, food gap, gender productivity gap, and labour market refer to issues of vital importance for the society that although some computational models address, future research could focus more on their analysis. That is, the implementation of social experiments by using computational models addressing the overall sustainability dimension and aiming towards the identification of key points regarding changes in agricultural trade policy that foster the positive and reduce the negative impacts of trade on human rights and sustainable development.

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Contents

List of Abbreviations

AEZ	Agro-Ecological Zone
AGMEMOD	Agricultural Member State Modelling
AgMIP	Agricultural Model Intercomparison and Improvement Project
AIDADS	An Implicit, Directly Additive Demand System
APSIM	Agricultural Production Systems sIMulator
ARDL	Autoregressive Distributed Lag
ARIMA	Autoregressive Integrated Moving Average
A-WEAI	Abbreviated Women's Empowerment in Agriculture Index
BCR	Benefit to Cost Ratio
CAP	Common Agricultural Policy
CAPRI	Common Agricultural Policy Regionalized Impact
CARD	Centre for Agricultural and Rural Development
CBA	Cost-Benefit Analysis
CES	Constant Elasticity of Substitution
CET	Constant Elasticity of Transformation
CGE	Computable General Equilibrium
CICES	Common International Classification of Ecosystem Services
CLD	Causal Loop Diagrams
CSIRO	Commonwealth Scientific and Industrial Research Organization
DCGE	Dynamic Computable General Equilibrium Model
DLG	German Agricultural Society
DST	Decision Support Tools
DYNARDL	Dynamic Autoregressive Distributed Lag
EAA	Economic Accounts for Agriculture
EU	European Union
EUR	Euro
FAO	Food and Agriculture Organization
FAOSTAT	Food and Agriculture Organization Corporate Statistical Database
FAPRI	Food and Agricultural Policy Research Institute
FEW	Food-Energy-Water
FPA	Flower Pollinated Algorithm
FPU	Food Production Unit
GAINS	Greenhouse Gas and Air Pollution Information and Simulation
GAMS	General Algebraic Modelling System
GDP	Gross Domestic Product
GEM	Green Economy Model
GEM-E3	General Equilibrium Model for Economy, Energy, and Environment
GEMPACK	General Equilibrium Modelling Package
GHG	Greenhouse Gas
GIZ	German Agency for International Cooperation
GLOBIOM	Global Biosphere Management Model
GTAP	Global Trade Analysis Project
GTEM-C	Global Trade and Environment Model

GTM	Global Trade Model
HI	Hoover Index
IAM	Integrated Assessment Model
IFM-CAP	Individual Farm Model for Common Agricultural Policy
IFSPRI	International Food Supply Policy Research Institution
IGHM	IMPACT - Global Hydrologic Model
IMAGE	Integrated Model to Assess the Global Environment
IMPACT	International Model for Policy Analysis of Agricultural Commodities and Trade
IMPLAN	Impact Analysis for Planning
InVEST	Integrated Valuation of Ecosystem Services and Tradeoffs
IPCC	Intergovernmental Panel on Climate Change
IRR	Internal Rate of Return
iSDG	Integrated Sustainable Development Goal
IWSM	IMPACT - Water Simulation Module
KSNL	Kriteriensystem nachhaltige Landwirtschaft (in German)
LCSFM	Latent Class Stochastic Frontier Model
MaGE	Macroeconometrics of the Global Economy
MAGNET	Modular Applied GeNeral Equilibrium Tool
MAgPIE	Model of Agricultural Production and its Impact on the Environment
MATS	Making Agricultural Trade Sustainable
MIRAGE	Modelling International Relationships in Applied General Equilibrium
MODAM	Multi-Objective Decision Support Model for Agri-Ecosystem Management Model
MONICA	Model for Nitrogen and Carbon Dynamics in Agro-Ecosystems
MOTAD	Minimization of Total Absolute Deviations
MS	Member State
NDC	Nationally Determined Contributions
NPV	Net Present Value
NWF	National Water-Food
OECD	Organisation for Economic Co-operation and Development
OLS	Ordinary Least Square
PE-GE	Partial Equilibrium – General Equilibrium
PFA	Project Finance Analysis
PMP	Positive Mathematical Programming
PRIMES	Price-Induced Market Equilibrium System
RCPs	Representative Concentration Pathways
RISE	Response Inducing Sustainability Evaluation
RON	Romanian leu
SA	Sustainability Assessment
SAFA	Sustainability Assessment of Food and Agriculture systems
SAGCOT	Southern Agriculture Growth Corridor of Tanzania
SAM	Social Accounting Matrix

SAR	Spatial Autoregressive model
SD	System Dynamics model
SDG	Sustainability Development Goal
SDM	Spatial Durbin Model
SFPM	Sustainable Food Profiling Model
ST	Systems Thinking
SWAP	California Statewide Agricultural Production Model
TEEB	The Economics of Ecosystems and Biodiversity
TRIMAG	Tariff Reduction Impact Model for Agriculture
UK	United Kingdom
UKAMM	UK Agricultural Market Model
UN PAGE	United Nations Partnership for Action on Green Economy
US	United States
USAID	United States Agency for International Development
VECM	Vector Error Correction Model
WTO	World Trade Organisation

1. Introduction

The present work is part of the Making Agricultural Trade Sustainable (MATS) Project, the objective of which is to investigate the advantageous changes needed in agricultural policy to achieve sustainable outcomes. In this report, a synthesis of the results of trade-related studies that have used computational models is presented. Particular attention is paid to between-study heterogeneity and the factors that might explain differences in modelling outcomes. The main steps carried out for this analysis are:

(1) A literature review focused on:

- Relevant research topics such as water, food, and trade; livestock and trade; international markets for policy analysis of agricultural commodities; agriculture, trade, and climate change adoption; trade, trade agreements, and tariffs modelling.
- Model characteristics and assumptions such as partial versus Computational General Equilibrium (CGE) models; static, dynamic, or stochastic; regional coverage; forecasting time frame; data sources; and aggregation issues.
- Models' abilities and results: Evaluation of models' abilities in terms of Sustainability Dimensions representation, and forecasting ability across economic sectors, applications, regions, and time.

(2) Assess the complementarity of methods and models such as partial equilibrium models, CGE models, various econometric models, and System Dynamics models.

(3) Relate results with the assumptions and characteristics of the models used (e.g., degree of aggregation, perfect or imperfect competition).

(4) Synthesize results of studies that might help to propose the appropriate set of models for MATS.

Having the above in mind, it should be mentioned that the European Commission uses model-based scenarios mainly to conduct impact assessments as well as policy options analyses. An important aspect of the respective analyses is the policy analysis of economic, environmental as well as social impacts considering the effects of several scenarios. Such scenarios cover the Greenhouse Gas (GHG) emissions under policies and trends, EU and global agriculture, EU and global energy systems as well as other notable scenarios that cover agricultural, energy, and economical frameworks. The following modelling approaches are being used by the European Commission as model-based scenarios (AGMEMOD, n.d.; European Commission, n.d.): a) PRIMES (Price-Induced Market Equilibrium System), a model that simulates the energy supply and consumption system (EU energy); b) PRIMES-TREMOVE, a model that forecasts the development of demand regarding passengers and freight transport per transport mean, as well as a transport mode (EU energy); c) PRIMES Biomass Supply Model for estimating the optimal use of waste resources/biomass (EU economy); d) GAINS (Greenhouse Gas and Air Pollution Information and Simulation), a model for Greenhouse Gas (GHG) emissions, air pollutants, and their interactions (Global, EU GHG air pollution); e) GLOBIOM-G4M (Global Biosphere Management Model) mainly focused on bioenergy, forestry, and agricultural sectors with the main goal to provide policy analysis (Global, EU agriculture); f) CAPRI model supports decision making regarding environmental policies as well as the Common Agricultural Policy (CAP) and is mainly focused on the agricultural sector (EU agriculture); g) GEM-E3 is a model that is mainly focused on covering interactions between the energy system, the environment, and the economy (Global, EU economics); h) POLES-JRC model analyses and provides climate policy context, as well as addresses global energy issues considering demand, supply, and related energy balances (Global energy); and i) AGMEMOD (Agricultural Member State Modelling), a model that mainly focuses on the impact analysis regarding national policies on the agricultural commodity markets (Global, EU agriculture).

In the context of the steps described above, a substantial number of previous works (papers, reports, etc.) were reviewed for the preparation of this report. These were segmented into three sections, namely Trade Dynamic (Section 2), Agricultural Production (Section 3), and Agricultural Production Outcome (Section 4). Each section provides an overview of the related models used in the studies involved. For comparison purposes, a table providing a synthesis of the main features of each model (such as goals, applications, and sustainability dimensions) has been created and illustrated at the beginning of each section. Additionally, each table provides studies with applications referring to Global South countries (a list of the Global South Countries 2022, can be found at: https://worldpopulationreview.com/country-rankings/global-south-countries).
The Trade Dynamic section includes six main model categories, along with their extensions, the Agricultural Production section includes seven main model categories along with their extensions, and, accordingly, the Agricultural Production Outcome section includes six main model categories.

2. TRADE DYNAMICS

2.1 Introduction

In this section, six broad types of computational models are distinguished – all commonly used in analysing trade dynamics:

- Computable General Equilibrium (CGE) models
- Partial Equilibrium models
- The Gravity Approach
- Regression Models
- System Dynamics (SD) Models
- Integrated Assessment Models (IAMs)

CGE models are mostly used in the analysis of the global trade system. They differ from Partial Equilibrium models in respect of the fact that these models limit themselves to a single industry or a narrow number of industries. The Gravity Approach has been frequently used to describe worldwide or regional trade. Compared to other models they have simple mathematical structure and intuitive assumptions. Regression models are widely utilised in impact evaluation, causal analysis, and forecasting as statistical tools. Moreover, System Dynamics modelling frameworks have been widely employed in agricultural land, soil, and water resource management research, as well as in the study of food system resilience to handle complex and nonlinear feedback systems. Finally, Integrated Assessment Models (IAMs) focus on issues relating to the future development of environmental and sustainability topics, by looking at the interactions between human activities and environmental factors. Table 1 presents a synthesis of the main features of the six abovementioned model types.

Table 1. Trade Dynamics – Models' Summary Table

Model	Models	Goal	Applications & Studies Reviewed	Sustainability Dimension	Dataset	Static/ Dynamic	Regional Coverage	Forecasting Time Frame	Degree of Aggregation	Perfect or Imperfect Competition
Computable General Equilibrium (CGE) models	• GTAP • GTAP extensions • MIRAGE • OECD ENV-Linkages • GEM-E3 • GTEM-C	The CGE models represent an economy of many goods which are produced by many sectors and are used to analyse some policy challenges and economic "shocks" including global climate change, trade agreements, and international labour migration, among others.	<u>GTAP</u> Potential impacts of trade policy as an adaptation tool in the face of climate change in Morocco and Turkey, two water-stressed countries (Ouraich et al., 2019). <u>GTAP extensions</u> Effect of export taxes on agricultural products' prices, trade, domestic production, as well as poverty in numerous developing countries (Beckman et al., 2019); The effect that productivity growth due to climate change and trade costs could have on future trading patterns and agricultural prices (Bekkers and Jackson, 2018); Effect of agriculture and trade policy interventions have on food security in China (Mukhopadhyay et al., 2018); Additional studies by: GTAP-AGR (Keeney and Hertel, 2005); GTAP-POV (Hertel et al., 2011); MyGTAP (Walmsley and Minor, 2013; Narayanan et al., 2010); GTAP-E (Burniaux and Truong, 2002);	<u>Economy</u> • Trade • Poverty • Labour • Capital • GDP • Savings • Investments • Tax revenues <u>Environment</u> • Climate change • Energy • GHG emissions <u>Society</u> • Unemployment **Strength**: Economy and Environment	GTAP Database; Social Accounting Matrix (SAM); AgMIP database.	• Dynamic • Static	• Global • National • Regional	~2050, up to 2100	• National • Regional • Farmer level	Both (Standard version of models have the perfect competition hypothesis)

			GTAP-IRTS' (Francois, 1998). <u>MIRAGE</u> Businesses' sourcing decisions for intermediate inputs using the same structure as consumers' final consumption (Belora and Fouré, 2018); Interactions among markets and sectors, as well as between countries (Fontagné et al., 2013). <u>OECD ENV-Linkages</u> Impact of various drivers on GDP growth and through it the eventual impact on the use of energy and greenhouse gas emissions (Chateau et al., 2011); <u>GEM-E3</u> Future shift to a low carbon energy system (Paroussos et al., 2020). <u>GTEM-C</u> GHG emissions scenarios (Porfirio et al., 2018); Calculation of the economic consequences of the biophysical changes in agricultural production (Rosenzweig et al., 2014). <u>*Applications in Global South countries*</u> China (Mukhopadhyay et al., 2018);								

			Morocco (Ouraich et al., 2019).							
Partial Equilibrium models	• IMPACT • GLOBIOM • Latent Class Stochastic Frontier Model • CARD model • TRIMAG • Aglink-Cosimo	Partial equilibrium models confine themselves to one sector or a small group of sectors. In the case of the agricultural market, partial models consider the market as a closed system without linkages with the rest of the economy. Changes in model parameters and exogenous variables may be used to account for the effects of the rest of the economy or the world market on the agricultural system. Partial models can provide much product detail which cannot be obtained from CGE models.	IMPACT Exploring linkages between agriculture production and food security at both the national and regional levels (Waithaka et al., 2013; Hachigonta et al., 2013; Sulser et al., 2011); Population and gross domestic product (GDP) growth as well as climate change on future agricultural productivity, trade, human well-being, and crop area expansion (Nelson et al., 2010); Additional studies by: (Rosegrant et al., 1995; 2012; 2014; Ignaciuk and Mason-D'Croz, 2014; Palazzo et al., 2014; Zhu et al., 2012). GLOBIOM Climate change impacts on US agriculture with and without accounting for climate change impacts in the rest of the world, while also examining scenarios of trade expansion (Baker et al., 2018); Additional studies by: (Takayama and Judge 1971; McCarl and Spreen, 1980). Latent Class Stochastic Frontier Model Understanding intensive and extensive farm	Economy • Technology • Growth • GDP • Yields • Prices. Productivity • Shocks on agricultural markets • Consumption • Tariffs • Market • Exports • Imports • Trade Environment • Climate change • Agri-environmental policy • Carbon emissions • Land-use Society • Food Security **Strength**: Economy and Environment	Depending on the model (e.g. GAMS, Fare-Primont index).	• Dynamic • Static	• Global • National • Regional	~2050, up to 2100	• National • Regional • Farmer level	Both (Standard version of models have the perfect competition hypothesis)

			systems productivity (Dakpo et al., 2020); Additional studies by: (Martinez Cillero et al., 2016; Mekonnen et al., 2015). <u>CARD</u> Impacts of retaliatory tariffs by China on US and global agricultural markets, on US economic activity, and GHG emissions (Carriquiry et al., 2020; Dumortier et al., 2011); Additional studies by: (Hayes et al., 2009; Searchinger et al., 2008). <u>TRIMAG</u> Investigate the way WTO scenarios are applied in simulation models (Listorti et al., 2013). <u>Aglink-Cosimo</u> Agricultural Outlook and policy scenario analysis (OECD, 2007; OECD/FAO, 2015). <u>*Applications in Global South countries*</u> Africa, Asia, and Latin America (Palazzo et al., 2014).							
The Gravity Approach		The Gravity Approach explains international or regional trade. The model uses a function to relate the trade flows between countries to the distance between the origin and destination countries and the various explanatory variables related to the characteristics of both	Examination of the Tunisian olive oil exports during the period 2001-2009 (Angulo et al., 2011); Additional studies by: (Anderson, 1979; Anderson and Wincoop, 2004).	<u>Economy</u> • International or regional trade • Trade agreements • Exchange rates • Income level • Transportation cost <u>Environment</u>	Cross-sectional data	• Dynamic • Static	• Global • National • Regional	The forecasting horizon is relatively short; the exact length depends on the hypothesis of the study.	• National • Regional • Farmer level	Both

		origin and destination countries.	*Applications in Global South countries* Tunisia (Angulo et al., 2011).	• Climate Change Society • Human development • Common official language • Common culture • Colonial past **Strength**: Economy						
Regression Models		The models are used to perform impact evaluation, causal analysis, and forecasting.	Cereal food production under the constraints of agricultural carbon emissions and area sown (Koondhar et al., 2021); The effects of adopting oil palm plantations, on household welfare and economic risk (Mehraban et al., 2021); Additional studies by: (Iorga et al., 2009; Johansen and Juselius, 1990). *Applications in Global South countries* Indonesia (Mehraban et al., 2021).	Economy • International or regional trade • Income Level • Policy Consumption • Expenditure • Welfare benefits Environment • Climate Change • Carbon emissions Society • Human development • Household welfare • Living standard **Strength**: Economy	Time series and Cross-sectional data	• Dynamic • Static	• Global • National • Regional	The forecasting horizon is relatively short; the exact length depends on the hypothesis of the study.	• National • Regional • Farmer level	Both
System Dynamics (SD) Models	• SD Modelling Approach • National Water-Food (NWF) model	The System Dynamics (SD) modelling framework has been widely used in research related to agricultural land, soil, and water resources management, as well as in the examination of the resilience in food systems to address complex and non-linear feedback systems (Sterman, 2000).	System Dynamics Research related to agricultural land, soil, and water resources management, as well as in the examination of the resilience in food systems to address complex and non-linear feedback systems (Sterman, 2000);	Economy • International or regional trade • Income • Policy Environment • Climate change • Agricultural land • Soil, and water resources management	Various bio-economic datasets	Dynamic	• Global • National • Regional	Depends on the setup of the experiment.	• National • Regional • Farmer level	Depends on the setup of the model

			Energy policy development, innovation impact evaluation, environmental policy analysis, public policy evaluation, and strategic planning (Sun et al., 2017); Identification of the key feedback loops influencing the structure and behaviour of trade dynamics in Nigeria's cattle value chain using ST, resulting in a CLD based on qualitative system dynamics (SD) model outlining key indicators and their interrelationships. (Aboah et al., 2021); Additional studies by: (Hamza et al., 2014). NWF Broad links of the water use regarding different sectors, the population dynamics, and their compounding effects on a country's food gap and water self-sufficiency (Alexandratos and Bruinsma, 2012); Additional studies by: (Abdelkader et al., 2018). *Applications in Global South countries* China (Sun et al., 2017); Egypt (Abdelkader et al., 2018); Nigeria (Aboah et al., 2021).	• Energy policy • Innovation, strategic planning, water use Society • Food systems • Population dynamics • Food gap **Strength**: All three						

Integrated Assessment Models (IAMs)		IAMs designed to examine issues related to the future development of environmental and sustainability topics. Such models have examined the interactions between human activities (such as energy use and agriculture) and environmental factors such as land cover and climate systems.	Land-use impacts of biomass production on development indicators such as food security, biodiversity, water resources, and ecosystem services (Hasegawa et al. 2018; IPCC, 2019; Rogelj et al., 2018; Searchinger et al., 2015); Bioenergy in climate change mitigation efforts and the land-use consequences (Bauer et al., 2018; Meller et al., 2015; Rogelj et al., 2018; Rose et al., 2014); Additional studies by: (Creutzig et al., 2015; Hasegawa et al., 2018; Köberle et al. 2022). *Applications in Global South countries* Brazil (Köberle et al., 2022).	Economy • Production Environment • Climate change • Environmental factors • Land-cover • Climate systems • Energy systems • Biomass, Ecosystems • Water use • Biodiversity Society • Food systems • Food security **Strength**: Environment	Various bio-economic datasets	Dynamic	• Global • National • Regional	~2100	• National • Regional • Farmer level	Depends on the setup of the model.

2.2 Computable General Equilibrium (CGE) models

During the last decades, Computational General Equilibrium (CGE) models have been extensively used in the study of trade policies. Several studies have also gone far beyond a static framework, describing adjustment periods, and the corresponding dynamic effects, particularly after Baldwin (1989), who pointed out that numerous forms of dynamic trade effects, can be qualified. Furthermore, there is an increasing spreading of numerous general and partial equilibrium models, which marked the sharing of the heavy data work required for this kind of analysis.

A CGE model is an analytical tool that can provide a better understanding of real-world economic issues. CGE models represent an economy of many goods which are produced by many sectors and are used to analyse some policy challenges and economic "shocks" including global climate change, trade agreements, and international labour migration, among others. The models depict corporations' profit-maximizing conduct and customers' utility-maximizing behaviour. Furthermore, in the macroeconomic behaviour of an economy, such as changes in the gross domestic product, collective saving and investment, government tax revenues and spending, and the balance of trade, producers' and consumers' optimality decisions are taken into account. However, a weakness of the models is that they can't account for or assess the effects of macroeconomic policies at the household or individual level, or the consequences of poverty and income distribution (Mbanda and Ncube, 2021). The CGE models require large databases, and they contain sophisticated model codes.

Jafari et al. (2021) discussed the bias found in analyses caused by bilateral tariff removal from CGE models. It is explained that CGE models do not take into account the tariff exceptions, specifically for products with high levels of protection, that may be set by policymakers and thus the authors investigate bias reduction approaches. To achieve this, the Canada-EU trade agreement is used as a case study, where the authors run a model without bilateral trade liberalization and compare those results with standard CGE model results. The proposed model extends the CGE model with additional equations representing constant elasticity of substitution (CES) for bilateral import demand and representing nested constant elasticity of transformation (CET) for bilateral export supply at the tariff line for specific trade links. The paper concluded that CGE analyses that overlook partial liberalization in some sectors and substitution across tariff lines result in overestimated trade and welfare impacts.

The following examples illustrate the application, strengths, and weaknesses of different kinds of Computational General Equilibrium (CGE) modelling. All of them are commonly used.

2.2.1 Global Trade Analysis Project (GTAP) model

The standard GTAP model is a global, general equilibrium, comparative static model[3] (Hertel and Tsigas 1997; Corong et al. 2017). GTAP is based on an input-output accounting framework that is complete, in the sense that all sources and uses of each economic good are accounted for, as are all inputs into production. The standard GTAP model assumes perfectly competitive markets and constant returns to scale. The optimizing behaviour by firms and consumers assumes that the first minimizes costs and the latter maximizes utility and all agents are price takers. At the same time, the fiction of a representative agent[4] is adopted. Furthermore, all equations in the model display price homogeneity[5] and the model does not incorporate multiple currencies. The GTAP Model provides a wide variety of closure options, such as fixed trade balance closures, unemployment, tax revenue replacement, and a selection of partial equilibrium closures. The standard GTAP model does not consider imperfect competition and increasing returns to scale, multiple households within a region, time dynamics, money, financial instruments, emissions of carbon dioxide, and other pollutants.

Ouraich et al. (2019) investigated the potential impacts of trade policy as an adaptation tool in the face of climate change in Morocco and Turkey, two water-stressed countries. The analysis uses the standard GTAP model to investigate climate change impacts on agricultural crop sectors by 2050 as captured by yield projections. The GTAP database version 7 is used, where agricultural production and harvested area are disaggregated by Agro-Ecological Zones (AEZ). The analysis assumes perfectly competitive markets and constant returns to scale. Results suggest that the more trade is liberalized, the higher global welfare gains are. However, the welfare gains from tariff elimination are not large enough to offset the loss from climate change impacts on agricultural productivity globally.

2.2.2 GTAP model extensions

The standard model has been frequently modified to become more suitable for policy analysis. In particular, the following six modifications of the standard GTAP model are considered for policy analysis: (I) The GTAP-AGR (Keeney and Hertel, 2005) constitutes a modification of the standard model to examine agricultural policy reforms (i.e., changes in farm support and related policies) under the Doha Development Agenda of the WTO. (II) A further extension of GTAP-AGR was

[3] Comparative static model: it does not present changes over time but differences between different possible states of the global economy (i.e., a base case and a policy case) at a fixed point in time, or with respect to two points in time (i.e., base period vs. a future projection period).

[4] Representative agent: the household sector consists of infinitely many identical infinitesimal households, an industry of infinitely many identical infinitesimal firms so that each sector has the budget shares or input-output ratios of its component agents.

[5] Price homogeneity: for any given solution, an alternative solution may be found by scaling all price and money value variables by a common factor, while holding quantity variables fixed.

developed [i.e., GTAP-POV (Hertel et al., 2011)], to evaluate the consequences of agricultural policy reforms on poverty in the world's poorest countries. (III) The MyGTAP extension of the standard model can evaluate the distributional impacts of policy applications by facilitating household disaggregation for individual regions within the global model[6] (Walmsley and Minor, 2013). (IV) Grant et al. (2009) nested within the GTAP model, a detailed, partial equilibrium model of the dairy sector, which allows for sophisticated analysis of tariff-line expansion. Thus, the nested partial equilibrium – general equilibrium analysis (PE-GE analysis) is possible within the overall GTAP framework (Narayanan et al., 2010). (V) The GTAP-E (Burniaux and Truong, 2002) accurately represents energy demands across the economy and binds these to greenhouse gas (GHG) emissions. The GTAP-E focuses on the potential for substituting fossil fuels (the primary source of CO_2 emissions) and between those fuels and other sources of energy and capital/labour. (VI) GTAP-IRTS (Francois, 1998) is an extension that has a variety of market structures, such as monopolistic competition or Cournot oligopoly with scale economies. An additional extension of the standard model is the recursive dynamic version of GTAP (GDyn) which introduces time as a continuous variable in the GTAP model, which, when shocked, moves the economy forward in time (Ianchovichina and McDougall, 2000).

Beckman et al. (2019) examined the effect of export taxes on agricultural products' prices, trade, domestic production, as well as poverty in numerous developing countries by applying a global Computable General Equilibrium (CGE) model, the GTAP-POV model (Hertel et al., 2015). The specific model extends the standard GTAP model by including a poverty module, thus enabling the assessment of global trade on poverty (within different sub-populations of 15 focus countries). In specific, the main adjustments that the GTAP-POV model includes are (Hertel et al., 2015; Beckman et al., 2019) a) the integration of factor supply and demand features from GTAP-AGR (Keeney and Hertel 2005), b) the integration of the AIDADS (An Implicit, Directly Additive Demand System) to capture consumer demand in each country, c) integration of supplementary tax replacement tools that could affect poverty, d) a farm household income module, and e) the poverty module. The study's results showed that removing export taxes in place in 2008 would have a slim impact on poverty, with a slight decrease in poverty in countries that had export taxes in place in the reference year.

Furthermore, there is a set of inter-disciplinary GTAP model extensions: (I) The GTAP-AEZ, where AEZ stands for "Agro-Ecological Zones" (Darwin et al., 1995). The GTAP-AEZ allows for heterogeneous land endowments in each region, and it was at least initially aimed to analyse land-based climate mitigation and, more recently, is used to investigate induced land-use change from biofuels (Hertel et al., 2008; 2010). (II) The GTAP-BIO extension contributed to analysing the global

[6] Global model: it does not cover a single country or a select group of countries, but it does cover the whole world.

land use impacts of biofuels by disaggregating biofuel production (Birur et al., 2008). Further developments and enmeshments of GTAP-BIO included explicitly modelling the by-products from biofuel production. (III) The GTAP-BIO-W extension incorporated water as an additional component of the biofuel products (Taheripour et al., 2013a). Taheripour et al. (2013b) show that irrigation expansion boosts carbon emissions from biofuels by 25%, resulting in more land conversion in more carbon-rich, rain-fed areas. (IV) The GTAP-POWER extension differentiates electric power generation by major types (e.g., coal, nuclear, hydroelectric, etc.), and differentiates base vs. peak load capacities. This model extension obtains a high data quality.

Bekkers and Jackson (2018) applied the WTO Global Trade Model (GTM), a model based on the Global Trade Analysis Project (GTAP) model to examine the effect that productivity growth due to climate change and trade costs could have on future trading patterns and agricultural prices. The features that the GTM adds to the GTAP include endogenous capital accumulation and isoelastic factor supply of land and natural resources. The study examined the results of a baseline projection until 2040, and subsequently investigated the effect of a) productivity growth of crops due to climate change and b) as a consequence of increases in global trade costs. Results indicate that, on average, productivity effects due to climate change lead to increased crop prices than those in the baseline, while increases in trade costs lead, on average, to lower crop prices.

Mukhopadhyay et al. (2018) in an attempt to estimate the effect of agriculture and trade policy interventions on food security in china used the GTAP model in their research. Within the GTAP scheme, regional income is collected by a single representative household in each region or composite region. Additionally, the model's prominent features refer to its distinct recognition of savings by regional economies. The respective savings are entirely spent on investments that are savings driven in the model. Considering the state of equilibrium, global savings are equal to global investment, all households are on their constrained budget and real profit is zero for all firms. Furthermore, by changing the parameters of the model, the impact is derived from a region/country's initial equilibrium towards a new equilibrium position, as a result of the policy scenario under consideration. The scenarios investigated by the study showed that food security is the centre of attention for all the countries in the world, as well as a development strategy of great significance for China, to promote economic development.

2.2.3 Modelling International Relationships in Applied General Equilibrium (MIRAGE) model

MIRAGE is a multi-region, multi-sector computable general equilibrium model used to analyse trade policy (Bchir et al., 2002); it is a recursive dynamic model, where the baseline is calibrated in close relationship with the MaGE model (Fouré et al., 2013) to deal with world structural change from medium (the year 2030) to the very long-run horizon (the year 2100). It describes imperfect competition and horizontal product differentiation in a rather standard way, but with a new procedure, allowing the available information to be used more efficiently (Bchir et al., 2002). The modelling is done in a sequential dynamic set-up, where the number of firms by sector adjusts progressively, and installed capital is assumed to be immobile, even across sectors. Capital reallocation therefore only results from the combined effect of depreciation and investment. It makes it possible to describe the adjustment lags of capital stock and the associated costs. The model uses GTAP 5 database (Dimaranan and McDougall, 2002).

Belora and Fouré (2018) developed a new version of the model MIRAGE, which combines businesses' sourcing decisions for intermediate inputs using the same structure [Armington (1969) CES and variety choice] as consumers' final consumption. Fontagné et al. (2013) conducted a study with a three-phase research to take account of the interactions among markets and sectors, as well as between countries. The first step consisted of deriving and estimating a three-factor (labour, capital, energy) macroeconomic growth model for a large set of individual countries, while the second step consisted of recovering the sectoral detail with the use of the MIRAGE model. In the third step, they confronted the assumptions of their baseline to alternative scenarios.

2.2.4 OECD ENV-Linkages model

The standard OECD ENV-Linkages model is a global, general equilibrium, recursive dynamic model (Burniaux and Chateau, 2008). The two endogenous characteristics that contribute to OECD ENV-Linkages being dynamic are first, the accumulation of productive capital and second, the putty/semi-putty specification of technology and exogenous drivers such as population growth or productivity adjustments. The model can explore and quantify policy responses to a series of government environmental initiatives, through future projections of the link between economic activities and emissions (Burniaux and Chateau, 2008).

Chateau et al. (2011) produced a report with worldwide socioeconomic baseline projections up till the year 2050, which depicted the impact of various drivers on GDP growth and through it the eventual impact on the use of energy and greenhouse gas emissions. The authors to make this baseline used the ENV-Linkages version 3 model in which the global economy is separated into 15 countries or regions and every one of them has 26 economic sectors. ENV-Linkages model has a hypothesis of perfect markets and constant returns to scale technology in a cost-minimizing production. The paper states that emissions of CO_2 related to energy production, are directly associated with the use of various fuels in production. Finally, they claim that other greenhouse gases are linked with outputs.

2.2.5 GEM-E3 Model

General Equilibrium Model for Economy, Energy, and Environment (GEM-E3) is a recursive dynamic CGE model, multi-regional and multi-sectoral that is mainly used for policy analyses and impact evaluations on the three E's. The creators (Capros et al., 2013) aimed to cover the topic of sustainable economic growth and to support the study of associated policy matters. The global version of GEM-E3 represents at the same time 38 regions and 31 sectors, which are connected with endogenous bilateral trade flows. An analysis of emissions and environmental damages demonstrates policy implications. Furthermore, the GEM-E3 model calculates costs and benefits through an equivalent variation measurement of international welfare. Finally, the model includes the same basic form as the standard World Bank models and is constructed on the basis of a Social Accounting Matrix (SAM).

Paroussos et al. (2020) examined the future shift to a low carbon energy system in Italy. The country was chosen because firstly is a manufacturer of the equipment, secondly, its energy systems depend on fossil fuels; and thirdly public debt and deficits are high at present pressuring their financial system. Under the hypothesis of reducing the Greenhouse gas emissions levels of the year 1990 by 76% and considering a framework of global concerted GHG mitigation action, the authors used the GEM-E3 model to calculate the necessary macroeconomic implications of the investments. According to the model results, if the Italian companies and households can acquire low-cost financial resources then the entire economy can benefit from the shift to low carbon energy. In the period 2015-2050, it was estimated by the study that the average GDP growth could be 1.3% provided that certain requirements are met.

2.2.6 Global Trade and Environment Model (GTEM-C)

The Global Trade and Environment Model (GTEM-C) (Cai et al., 2015) is a dynamic general equilibrium and economy-wide model, capable of projecting trajectories for globally-traded commodities (including agricultural products) and builds upon the global trade and economic core of the Global Trade Analysis Project (GTAP) database. Natural resources, land, and labour are endogenous variables in GTEM-C. In GTEM-C, countries of large economic size and distinct institutional structures are modelled separately, while the rest of the world is aggregated into regions according to geographical proximity and climate similarity.

Porfirio et al. (2018) examined the structural changes in the global agricultural trade network from 2008 to 2059, under the two contrasting GHG emissions scenarios [IPCC Representative Concentration Pathways (RCPs)]. To do so, they coupled seven Global Gridded Crop Models from the Agricultural Model Intercomparison and Improvement Project (AgMIP) (Rosenzweig et al., 2014) with five Earth System Models to a global dynamic economic model. To calculate the economic consequences of the biophysical changes in agricultural production they used the CSIRO (Commonwealth Scientific and Industrial Research Organization) version of the Global Trade and Environment Model (GTEM-C). Agricultural productivities were exogenously forced based on projections from the AgMIP database. The study's results show that global agricultural trade may be expressively different from today with or without carbon mitigation, with agricultural trade becoming more centralised under the high CO_2 emissions scenario, and more distributed under the carbon mitigation scenario.

2.3 Partial Equilibrium models

Partial equilibrium models confine themselves to one sector or a small group of sectors. In the case of the agricultural market, partial models consider the market as a closed system without linkages with the rest of the economy. Changes in model parameters and exogenous variables may be used to account for the effects of the rest of the economy or the world market on the agricultural system. Partial models can provide much product detail which cannot be obtained from CGE models. Partial models may be single- or multiple-product. Multiple-product models can capture supply and demand interrelationships among agricultural products. Partial models of agricultural international trade focus on agricultural supply, demand, and trade for unprocessed or first-stage processed products. On the other hand, CGE models are economy-wide models which provide a complete representation of national economies together with a specification of trade relations between economies, covering the circular flow of income and expenditure and taking into consideration inter-industry relations.

2.3.1 The International Model for Policy Analysis of Agricultural Commodities and Trade (IMPACT)

The concepts of feeding the world, reducing poverty, and protecting environmental resources were concerning researchers and policy-makers alike in the 1990s; however, their supported future measures were not aligned. This predicament prompted the development of the International Model for Policy Analysis of Agricultural Commodities and Trade (IMPACT model) by the International Food Supply Policy Research Institution (IFSPRI) (Rosegrant et al., 2012). IMPACT is a model that tests the connection of essential food commodities and food demand with security on a national level under the circumstances of future alterations of related factors. It is an integrated modelling system linked mainly to core partial equilibrium, multimarket model and is focused on the agriculture sector considering trade, global production, demand, and prices for agricultural commodities (Robinson et al., 2015); it tests 44 commodities across 115 geopolitical regions and 126 hydrological basins worldwide, the combination of which make up the 281 Food Production Units (FPUs). Hypotheses of changes in global food demand, supply, trade, income, and population are analysed through a system of equations. Rosegrant et al. (1995) examined food security and nutrition status in developing countries taking into account the effects of population, investment, and trade. This model provides policymakers and researchers with the flexibility to examine and compare the effects of changes in socioeconomic trends, biophysical systems, policies, and technologies (Robinson et al., 2015).

General Algebraic Modelling System (GAMS) is the computer software that is used for the creation of the core multimarket model and many of the linked modules. Furthermore, IMPACT modelling especially supports the analysis of alternative scenarios regarding how income, population, climate, as well as technologies could change over the prism of time. The respective traditional scenarios could be grouped into the following categories: 1. socioeconomic, 2. environmental, 3. political, and 4. Technological (Robinson et al., 2015).

The corresponding framework, as well as the one for identifying environmental forces proposed by Wilson (1998), is homogeneous. The IMPACT is a widely used model with notable applications in a) exploring linkages between agriculture production and food security at both the national and regional levels (Waithaka et al., 2013; Hachigonta et al., 2013; Sulser et al., 2011), b) exploring the effects of population and gross domestic product (GDP) growth as well as climate change on future agricultural productivity, trade, human well-being, and crop area expansion (Nelson et al., 2010) c) replicating and testing the effects of large-scale adoption of agricultural technologies consistent with sustainable intensification. After including several technology scenarios, the final model was focused on estimating international and regional effects on agricultural productivity, commodity prices, and food security indicators under climate change conditions, and the respective analysis was conducted by Rosegrant et al. (2014), d) the adoption of technology was conducted in the context of adaptation to climate change in the OECD countries. In such cases, IMPACT was used to compare the effects on yields, prices, as well as food security of development, research, and changes in irrigation technology as strategies that promote adaptation (Ignaciuk and Mason-D'Croz, 2014), e) to evaluate and compare investment policies, such as in Rosegrant et al. (2015), where the cost-benefit analysis was conducted to compare the value of investments in decreasing postharvest loss versus the value of the increased investment in agricultural research and development, and f) additionally IMPACT contributed scenario-based projects in an interdisciplinary approach. That is, by quantifying socioeconomic scenarios for policy development under climate change designed through stakeholder engagement in Africa, Asia, and Latin America (Palazzo et al., 2014).

IMPACT –WATER was developed after the need to make a more precise association between food demand and water availability. The range of this framework is from local to national to international level. The model was constructed by the combination of the original IMPACT model with a water simulation module (IWSM) (Rosengrant et al., 2012). The methodology of IMPACT-WATER includes the calculation of water demand and supply for irrigation and other applications in 281 FPUs and reproduces water transport in 126 hydrological basins. The rules set for water use list use based on importance, with domestic water as the primary use of water, followed by industrial use, livestock use, and finally, irrigation. Moreover, to minimize water shortage, the model utilizes optimization by intersectional allocation aligned with the priorities of water use.

IMPACT- Global Hydrologic Model (IGHM) is another extension of the original model that takes into account climate change effects on food supply and demand (Zhu et al., 2012). IGHM is a semi-distributed parsimonious model that replicates the balance of soil moisture, runoffs, and evapotranspiration. It is applied on the whole land surface of Earth apart from the Antarctic. This model along with other climate models, such as biophysical and process-based, has been developed to deal with the expected climate change impact on agriculture.

2.3.2 Global Biosphere Management Model (GLOBIOM)

The Global Biosphere Management Model (GLOBIOM) is a global, recursively dynamic, partial equilibrium model used to investigate the various trade-offs and synergies around land use and ecosystem services. It uses extensive socioeconomic and geospatial data to capture the numerous interrelationships between diverse systems engaged in the provision of agriculture and forestry products. It includes the 18 most important crops in the world, as well as a variety of livestock production operations, forestry commodities, first- and second-generation bioenergy, and water. Land, management, and weather characteristics are all taken into account in the production process. GLOBIOM classifies the world into 30 economic regions; on the consumption side, consumption is optimised based on income, preferences, and product prices, while on the production side, producers maximize their margins. On this basis, the model solves for a market equilibrium corresponding to the overall welfare maximization based on the spatial equilibrium modelling approach (Takayama and Judge, 1971; McCarl and Spreen, 1980; CSIRO, 2021).

In recent work, Baker et al. (2018) applied GLOBIOM to investigate the climate change impacts on US agriculture with and without accounting for climate change impacts in the rest of the world, while also examining scenarios of trade expansion. The study’s results indicated significant differences in estimated impacts on the US agricultural sector when accounting for global impacts, in relation to when accounting only for US impacts.

2.3.3 Latent Class Stochastic Frontier Model

The Latent Class Stochastic Frontier Model is an error model, which is appropriate for use by researchers who do not have a clear idea of which firms fit with particular production technology or the number of various technologies in the sample (Mekonnen et al., 2015; Martinez Cillero et al., 2016).

Dakpo et al. (2021) innovated by making an extension of the Latent Class Stochastic Frontier Model (LCSFM) that used the transitive productivity Fare-Primont index to understand intensive and extensive farm systems productivity. They used the model to classify the farms according to their intensity, the extent of participation in an agri-environmental policy scheme, and external conditions. After running the LCSFM and the pooled model and comparing the results for livestock farms in France for 14 years, it was observed that productivity changes and their components were similar for both models even though the pooled model ignores heterogeneity. Moreover, in the pooled model the index was either overestimated or underestimated based on the farm type and the productivity change. All in all, regardless of the farm types the intensive class farms are superior in productivity and fixed assets but minor in terms of utilized agricultural area, having higher production cost per livestock unit and more operational subsidies.

2.3.4 Centre for Agricultural and Rural Development (CARD) model

The CARD model, developed by the Center for Agricultural and Rural Development (CARD) at Iowa State University, is a system of econometric, partial equilibrium, non-spatial models for global agriculture, which covers all major temperate crops, sugar, biofuels, dairy, livestock, and meat products for all major producing and consuming regions and countries. The CARD model has been used in various studies to analyse the impact of policies and shocks on agricultural markets (Searchinger et al., 2008; Hayes et al., 2009; Dumortier et al., 2011; Carriquiry et al., 2020). The CARD modelling system is run to generate a baseline, which establishes 10-year projections by country and by crop for production, consumption, prices, and trade. A market-clearing price for a commodity is determined to equate supply and demand. Given that the markets are inter-linked, changes in one commodity market impacts other markets in the modelling system. Once the baseline is established, certain components of the modelling system are modified to simulate a specific scenario and the system is rerun to obtain a new market equilibrium for all commodity markets in the model.

GHG Model - global greenhouse gas (GHG) emissions from land-use change

The GHG Model is an add-on to the CARD model to evaluate carbon emissions related to policy changes. The need to take carbon emissions from agricultural production into account emerged from the discussions about life-cycle emissions from biofuels (Searchinger et al., 2008). To evaluate land use, the model differentiates between cropland, forest, pasture, and barren land. The carbon coefficients are calculated using the methodology and data by Gibbs (2006) for mean and maximum coefficients. The same method is used to obtain minimum carbon coefficients based on the data by Olson et al. (1985).

The paper by Elobeid et al. (2021) combines the CARD, IMPLAN, and GHG models to analyse the impacts of retaliatory tariffs by China on US and global agricultural markets, on US economic activity, and GHG emissions. The CARD model provides the impact on the US and global agricultural commodities in terms of supply, utilization, and prices. The results from the CARD model are used as input to an input-output model of the US economy (i.e., the IMPLAN model, which takes the percentage of changes in the quantities produced of the targeted commodities and turns them into standard economic impact summaries). Both models capture the linkages between sectors (Yao et al., 2018). The output from the CARD model is used in the GHG model to estimate emissions from carbon stock changes due to land-use change (Carriquiry et al., 2020; Dumortier et al., 2021). The results indicate that retaliatory tariffs are both trade destruction (lower overall trade) and trade diversion (trade diverted away from the US and to other exporting countries). Changes in trade due to the tariffs result in a reduction of GHG emissions from the land-use change of up to 83.7 teragram (Tg) of CO_2-equivalent.

2.3.5 Tariff Reduction Impact Model for Agriculture (TRIMAG)

Tariff Reduction Impact Model for Agriculture (TRIMAG) was developed to optimize the domestic agricultural added value after applying the tiered formula considering a maximum number of sensitive tariff lines (Listorti et al., 2011). The model evaluates the impacts of domestic prices from the standard and sensitive tariff cut, based on an 8-digit level database on domestic (Swiss) tariffs, prices and import flows from the EU and the Rest of the World, with the prices and consumption as calculated in the context of WTO negotiations. TRIMAG is capable to estimate for 90 agricultural commodities a list of all the potential impacts on domestic prices from tariff reductions. Furthermore, it can be used as a tool for other partial or general equilibrium models.

Listorti et al. (2013) conducted a study to investigate the way WTO scenarios are applied in simulation models. The authors pointed out that the majority of models represent more aggregated products and chose the Tariff Reduction Impact Model for Agriculture (TRIMAG) because it uses the highest achievable level of disaggregation of 8 digits. TRIMAG lets the user implement tariff cuts and derive the domestic price plunge predicted by alternative trade policy scenarios. After running the TRIMAG for a WTO agreement the researchers took the results and used the partial equilibrium CAPRI model for further analysis. Results indicated that the higher the share of sensitive tariff lines is in consumption, the bigger the tariff increase for the analogous aggregated product is.

2.3.6 Aglink-Cosimo

Aglink-Cosimo is a recursive-dynamic, partial equilibrium model that is used to mainly replicate developments of the balances of the annual market and prices for the main agricultural commodities consumed, produced, and traded at the global level (OECD, 2007). As with most of the General Equilibrium models, the respective model follows several assumptions. It mainly assumes competitive world markets regarding agricultural commodities, as market prices are being set through a global or regional equilibrium in supply and demand. Furthermore, it assumes the homogeneity of domestically produced and traded commodities and it treats the respective commodities as perfect substitutes by buyers and sellers. Particularly, importers do not differentiate commodities by country of origin because Aglink-Cosimo is not a spatial model. However, exports and imports are determined separately. The respective assumption may affect the results of the analysis in which trade is a major driver. Moreover, Aglink-Cosimo is a partial-equilibrium model for the main agricultural commodities. However, nonagricultural markets are not considered in the modelling and thus are treated as exogenous to the model.

Aglink-Cosimo is an economic model that analyses the supply and demand of world agriculture and it is used to create the OECD-FAO Agricultural Outlook and policy scenario analysis (OECD/FAO, 2015). Hence, the Aglink-Cosimo modelling approach is utilized for the conduction of the consistent integration of the main policy and economic assumptions and the derivation of a set of baseline projections regarding the global market. In addition, to the consumed, produced, and traded quantities, the respective baseline also incorporates projections for nominal prices, in local currency units, regarding the commodities under consideration. Aglink-Cosimo provides a comprehensive policy-specific and dynamic economic depiction of the standard temperate-zone commodities, as well as for cotton, vegetable oils, and rice. Moreover, the OECD-FAO Agricultural Outlook is used mainly for the analysis presented to the Committee of FAO considering Commodity Problems and its several Intergovernmental Commodity Groups.

2.4 The Gravity Approach

The Gravity model has often been used to explain international or regional trade, mainly because of the simplicity of its mathematical form and the intuitive nature of its assumptions (Sen and Smith, 1995). A vast body of theoretical and empirical literature examines international trade issues using the gravity approach (Anderson, 1979; Anderson and Wincoop, 2004). The model uses a function to relate the trade flows between countries to the distance between the origin and destination countries and the various explanatory variables related to the characteristics of both origin and destination countries. Among the variables with a positive effect on trade, flows are the size of importing economy, per capita income differential of the trading countries, their degree of openness, the existence of a favourable exchange rate, the presence of general trade agreements, and if the trading partners share a common official language and/or currency and/or a colonial past. On the other hand, transport cost harms trade volumes, which usually depends on the distance between the trading countries.

The conventional econometric formulation of the gravity model uses cross-sectional data for several years to estimate a regression model with the volume of trade between counties as a dependent variable and the corresponding explanatory variables as independent variables. However, this approach has two weaknesses: i) the effect of possible omitted variables correlated with the included ones, and ii) the need to introduce dynamics into the model specification.

These two problems can be solved using spatial and panel data econometrics. The use of traditional least-squares regression to estimate gravity models ignores possible spatial dependence in the sample data of flows (LeSage and Pace, 2008). As a result, the estimated parameters could be biased and inconsistent (LeSage and Pace, 2004). LeSage and Pace (2008) proposed the so-called Spatial Durbin Model (SDM) to correct the bias due to possible omitted variables and the Spatial Autoregressive model (SAR) for introducing dynamics into the gravity model. In the case of panel data, instead of estimating the model for all data, we can estimate it by considering what is known as unobserved heterogeneity to prevent bias for the omission of relevant variables. Furthermore, in the context of the panel data set, the gravity model can be dynamic, considering the strong inertia in trade relations between countries. This can be achieved by applying the Generalized Method of Moments (Arellano and Bond, 1991) or the System Generalized Method of Moments (Blundell and Bond, 1998).

The study by Angulo et al. (2011) examined the Tunisian olive oil exports during the period 2001-2009, estimating a gravity model using spatial and panel data econometrics to consider the omitted variables problem and introduce dynamics into the analysis. The results show inertia in export volumes, with a strong time dependence effect. In other words, trade relations anchored in the past are likely to continue in the future. Also, the results support the existence of an apparent similarity in olive oil flows between neighbouring importing countries. The results show that the following variables affect olive oil trade flows positively: importing country's income level, importers' human development index, sharing a common language, and precipitation. On the other hand, the distance between countries harms trade flows.

2.5 Regression Models

Regression models, as statistical methods, are mainly used to perform impact evaluation and causal analysis, as well as forecasting. The primary goal of causal regression analysis is to estimate the causal effects of a policy (or a characteristic) on an outcome of interest to enhance the credibility of the estimated results. On the other hand, forecasting regressions mainly focus on analysing time-series data to forecast the future and inform financial decision-making under uncertainty.

Iorga et al. (2009) examined the existence of a common stochastic trend (long-run equilibrium relationship) between the domestic absorption, the RON/EUR exchange rate, and Romania's imports of agricultural products. The methodology used has been introduced by Johansen and Juselius (1990) to test the Co-Integration Vectors for Multivariate Models, in which all variables are addressed simultaneously to explain the behaviour variable based on its past and other variables (Johansen, 1991). The co-integration analysis revealed that there is only one co-integrating relationship between the investigated variables. In the long term, the domestic absorption and the imports of agricultural products are moving in the same direction. In addition, the direct relationship between Romania's imports of agricultural products and the RON/EUR exchange rate was recorded due to the existence of a wide range of dysfunctions in the key components of the agricultural food sector: production of raw materials, food industry, distribution and the high level of self-consumption of rural inhabitants.

Mehraban et al. (2021) analysed the effects of adopting oil palm plantations, on household welfare and economic risk. The expectations regarding farmers' profitability during the initial period of cultivation may not be precise or may fluctuate as the prices of the international commodity markets change. However, the cultivation of oil palm may cause spill-over effects to additional economic activities related to households. Welfare is measured in terms of annual household consumption expenditure. Particularly, expenditures related to consumption are mainly considered an indicator of high significance to the living standard rather than income amongst rural households in developing countries income (Deaton, 1997). To estimate the effect of oil palm cultivation (adoption) on the consumption expenditure of households, Regression Modelling is being used by Mehraban et al. (2021). The respective results confirm that a large part of the welfare benefits of oil palm cultivation is channelled through farm size expansion and additional off-farm activities. After controlling jointly for the different mechanisms, the direct effect of oil palm cultivation becomes statistically insignificant. Regression models with pseudo-fixed effects showed that oil palm cultivation raises household living standards by 13% on average, after controlling for possible confounding factors (Wooldridge, 2010). Oil palm requires less labour per hectare than alternative crops, allowing oil palm farmers to expand their farm activities or pursue more off-farm economic activities. Both these mechanisms contribute to the gains in income and consumption expenditure.

Koondhar et al. (2021) conducted a study that investigates the increase in cereal food production under the constraints of agricultural carbon emissions and area sown. The effect of limitations of agricultural carbon emissions on the production of cereal food suggests that changing to organic fertilizer can augment farm productivity in a sustainable environment. For this study, time-series data from 1985 to 2018 was used to examine the long-run and short-run nexus between selected variables by estimating ARDL[7], VECM[8], and DYNARDL[9] models. The results demonstrate that the co-integration correlation is running from agricultural carbon emission, area sown and food production index to the green growth of cereal food production.

2.6 System Dynamics (SD) Models

2.6.1 SD Modelling Approach

The Systems Thinking (ST) and System Dynamics (SD) modelling frameworks have been widely used applied in research related to agricultural land, soil, and

[7] Autoregressive Distributed Lag (ARDL) model is an ordinary least square (OLS) based model.

[8] Vector Error Correction Model (VECM) is the basic VAR, with an error correction term incorporated into the model.

[9] DYNARDL is a Stata module to dynamically simulate autoregressive distributed lag (ARDL) models

water resources management, as well as in the examination of the resilience in food systems to address complex and non-linear feedback systems (Sterman, 2000). While ST is used to create a qualitative map of the system and its dynamics, also referred to as Causal Loop Diagrams (CLD), SD is used to develop fully quantified models that allow for simulation over time. In terms of addressing policy issues, these models are mainly used for energy policy development, innovation impact evaluation, environmental policy analysis, public policy evaluation, and strategic planning (Sun et al., 2017). Thus, the inherent strength of the System Dynamics (SD) modelling methodology framework is its inherent ability to describe capture non-linearity of the induced by changes in the system states over time responding to ST, or more specifically CLDs, are usually used to visualize external drivers in general of change in the context of wider systemic dynamics and are usually used to develop efficient Decision Support Tools (DST) to inform policy development and decision-making.

Aboah et al. (2021) worked on the identification of the key feedback loops influencing the structure and behaviour of trade dynamics in Nigeria’s cattle value chain using ST, resulting in a CLD based on qualitative system dynamics (SD) model outlining key indicators and their interrelationships. The SD Modelling Approach has been used to map the feedback structure and conduct ex-ante impact assessments in the livestock (territorial and aquatic) sector in past decades (Dizyee et al., 2017). SD models, rather than optimizing for a specific outcome, are usually used to simulate “What if” scenarios to provide insights into what could happen under different scenarios that provide useful analytical tools to policymakers to test the likely impact of different policy options on livestock systems and value chains (Hamza et al., 2014). Furthermore, the model considers an annual supply and demand of cattle and beef. The findings suggest that the key feedback loops that govern Nigeria’s cattle value chain are upstream-focused. These feedback loops are economic (e.g. producers’ price, assemblers’ purchase price, and the proportion of producers’ supply to assemblers) and bio-economic (maturation period of heifers, and producers’ sale of cattle) in nature (Aboah et al., 2021). Findings also suggest two countervailing strategies that producers can adopt to curtail potential exploitation by cattle wholesalers (assemblers): (i) regulating the supply of cattle to other distribution channels other than wholesalers through online marketing platforms; and (ii) regulating the timing and proportion of sales, which requires investments (including financing options) that will boost producers’ capacities related to cattle inventory management and marketing.

2.6.2 National Water-Food (NWF) Model

The National Water-Food (NWF) modelling framework examines the broad links between the water use in different sectors, the population dynamics, and their compounding effects on a country’s food gap and water self-sufficiency (Alexandratos and Bruinsma, 2012; Abdelkader et al., 2018). The technical development of the respective modelling approach incorporates two components.

The first component consists of a system dynamics model of the water-food supply and demand at a national level and the second component refers to a gravity modelling approach to the international virtual water trade at the national level. The two different component analyses are being evaluated in parallel to facilitate their comparison.

Virtual water traded internationally in the form of food, and other products, makes water a global resource; national water analysis and management should not only address the (real) water resources within the country but import and export water in virtual form as well. In this context, Abdelkader et al. (2018) applied the NWF model to evaluate a set of future scenarios of Egypt's water and socioeconomic conditions up to the year 2050; all scenarios revealed that Egypt is facing the challenge of widening food and water gaps.

The NWF modelling framework can be easily adapted to other countries and also expand the nexus to other sectors, such as energy. This framework can be slightly modified to be applied to regional study areas rather than a single nation, so it can assist decision-making at different levels (Abdelkader et al., 2018).

2.7 Integrated Assessment Models (IAMs)

Integrated assessment models (IAMs) are tools designed to examine issues related to the future development of environmental and sustainability topics, by investigating the interactions between human activities (such as energy use and agriculture) and environmental factors such as land-cover and climate systems. Hence, these models can help examine climate mitigation strategies such as those set out in the Paris Agreement (United Nations, 2015).

IAMs are integrated because they span multiple academic disciplines, such as economics and climate science, and for more comprehensive models also energy systems, land-use change, and agriculture, among others. They are used to answer policy questions. Integrated assessment models estimate what possible scenarios look like and they do not provide predictions for the future. The high complexity and high amount of aggregation (or other simplifications) required to ensure computational tractability are disadvantages (Verkerk et al., 2021).

There are various types of integrated assessment models. A) Process-based models: one classification differentiates between models that quantify future developmental pathways or scenarios and provide detailed, sectoral information on the complex processes modelled. B) A second classification includes models that aggregate the costs of climate change and climate change mitigation to find estimates of the total costs of climate change. C) A third classification makes a distinction between models that extrapolate verified patterns (via econometrics equations), or models that determine (globally) optimal economic solutions from the perspective of a social planner, assuming (partial) equilibrium of the economy.

Applications of these models often show a critical role in bioenergy (Creutzig et al., 2015). This is an important finding as the land-use impacts of biomass production may negatively affect other development indicators such as food security, biodiversity, water resources, and ecosystem services (Searchinger et al., 2015; Hasegawa et al., 2018; Rogelj et al., 2018; IPCC, 2019). On the global scale, quite some attention has been paid to the role of bioenergy in climate change mitigation efforts and the land-use consequences (Rose et al. 2014; Meller et al. 2015; Bauer et al. 2018; Rogelj et al. 2018). Köberle et al. (2022) using IAMs focus on global model projections concerning the role of bioenergy in Brazil's future energy and land systems, and implications for the country's GHG emissions and land use.

3. AGRICULTURAL PRODUCTION

3.1 Introduction

This section is dedicated to seven types of models used in agricultural production studies. These types are:

- Computable General Equilibrium (CGE) models
- Partial Equilibrium models
- Optimal Crop Allocation models
- Calibrated programming models
- Regression Models
- System Dynamics models
- Spatial models

CGE models, Partial Equilibrium models, Regression Models, and System Dynamic models are also described and analysed in previous section 2 regarding the analysis of Trade Dynamics. Optimal Crop Allocation models are utilized to solve diverse types of optimization matters. Calibrated programming models are empirical analysis tools that allow the use of all available information. Spatial models such as InVEST can utilize map and value key ecosystem services to answer inquiries on a local, regional or global level. Table 2 presents a synthesis of the main features of the seven abovementioned model types.

Table 2. Agricultural production – Models' Summary Table

Model	Models	Goal	Applications & Studies Reviewed	Sustainability Dimension	Dataset	Static/ Dynamic	Regional Coverage	Forecasting Time Frame	Degree of Aggregation	Perfect or Imperfect Competition
Computable General Equilibrium (CGE) models	• National Computable General Equilibrium model • Dynamic CGE (DCGE) model • MAGNET model • MyGTAP model	Able to capture characteristics and general functionalities of an economy; quantitative policy analysis tools of high significance.	<u>National Computable General Equilibrium model</u> Biofuel development has on land use. Land-use change (LUC) has raised concerns regarding sustainability (Weng et al., 2019). <u>DCGE</u> Inferences of uncertainty in the process of improvements considering the efficiency of irrigation water use (Sánchez Chóliz and Sarasa, 2019); Ethiopia's agricultural sector's production climate change impacts in the next 40 years (Solomon et al., 2021). <u>MAGNET</u> Limit inconsistencies in the analysis of the future impact of climate change on agricultural production (Van Meijl et al., 2018). <u>MyGTAP</u> How trade liberalization and trade protectionism affect the biggest sector of the Pakistani economy (Ahmad et al., 2021).	<u>Economy</u> • Bio-economy • Farm optimization • Socio-economic factors • Taxes • Prices • Outputs • Demand • Trade liberalization • Trade protectionism <u>Environment</u> • Climate change • Energy • Climate-yield linkages • Climatic conditions • Agricultural systems • Landscape • GHG emissions Water resources <u>Society</u> • Socio-economic factors • Securing food supply • Labour **Strength**: Economy and Environment	GTAP Database; Social Accounting Matrix (SAM).	• Dynamic • Static	• Global • National • Regional	~2050	• National • Regional • Farmer level	Both (Standard version of models have the perfect competition hypothesis)

			<u>Applications in Global South countries</u> China (Weng et al., 2019); Ethiopia (Solomon et al., 2021); Pakistan (Ahmad et al., 2021).							
Partial Equilibrium models	• IMPACT • CAPRI • UKAMM • AGMEMOD	Partial equilibrium models confine themselves to one sector or a small group of sectors. In the case of the agricultural market, partial models consider the market as a closed system without linkages with the rest of the economy. Changes in model parameters and exogenous variables may be used to account for the effects of the rest of the economy or the world market on the agricultural system. Partial models can provide much product detail which cannot be obtained from CGE models.	<u>IMPACT</u> Effects on income and other factors of faster productivity development for 20 food crops in 106 developing countries in 2030 (Wiebe et al., 2021). <u>CAPRI</u> Effects of CAP policy instruments at the EU or Member State level, as well as at the sub-national level (Britz and Witzke, 2014); Price feedback regarding simulated changes in policies along the primary supply chain, from commodity markets to EU farms and vice-versa. Moreover, the CAPRI model is mainly used for ex-ante impact assessment of environmental, agricultural, and trade policy options (Witzke et al., 2009); Additional studies by: (Barreiro-Hurle et al., 2021). <u>UKAMM</u> Consumption patterns, production processes, and international trade flows, mainly used to describe economic relationships regarding the sectors of dairy,	<u>Economy</u> • Income • Production • Development, Investment • CAP policy • Consumption • International trade flows • Policy or additional changes in the agri-food sector <u>Environment</u> • Climate change • Agri-environmental policy <u>Society</u> • Hunger **Strength**: Economy and Environment	Various data sources, such as EUROSTAT, FAOSTAT, OECD.	• Dynamic • Static	• Global • National • Regional	~2050, up to 2100	• National • Regional • Farmer level	Both (Standard version of models have the perfect competition hypothesis)

			crops, oilseed processing, livestock, and sugar (Department for Environment, Food & Rural Affairs the UK, 2021). <u>AGMEMOD</u> Effects of CAP 2003 reform on the agri-food sector (Niemi et al., 2006). *<u>Applications in Global South countries</u>* 106 developing countries (Wiebe et al., 2021).							
Optimal Crop Allocation models	• Flower Pollinated Algorithm • Linear Programming Models • Stochastic and Math Algorithm	To solve diverse types of optimization matters.	<u>Flower Pollinated Algorithm</u> Optimal crop allocation (Ejieji and Akinsunmade, 2020). <u>Linear Programming Models</u> Grain production farms (Osaki and Batalha, 2014); Improve and maximize agricultural production taking into account the agro-metrological phenomena which may disrupt it (Ivanyo et al., 2020). *<u>Applications in Global South countries</u>* Brazil (Osaki and Batalha, 2014); Nigeria (Ejieji and Akinsunmade, 2020).	<u>Economy</u> • Production planning • Profit • Risk management • Yield • Market prices <u>Environment</u> • Land • Planting • Agro-metrological phenomena **Strength**: Economy and Environment	Various bio-economic datasets	• Dynamic • Static • Stochastic	• Global • National • Regional	Depends on the setup of the experiment.	• National • Regional • Farmer level	Depends on the setup of the model.
Calibrated programming models		Calibration methods for models of agricultural production and water use.	Water market allocation (Howitt, 2012).	<u>Economy</u> • Agricultural production • Management • Policy <u>Environment</u>	Various bio-economic datasets	• Dynamic • Static	• Global • National • Regional	Depends on the setup of the experiment.	• National • Regional • Farmer level	Depends on the setup of the model.

				• Water use • Agronomic, hydrologic, and other biophysical models **Strength**: Economy and Environment						
Regression models		The models are used to perform impact evaluation, causal analysis, and forecasting.	<u>ARIMA forecasting model for time series data</u> Rice (paddy) production (Kannan and Karuppasamy, 2020). *<u>Applications in Global South countries</u>* Egypt (Kannan and Karuppasamy, 2020).	<u>Economy</u> • Prices • Demand • Policy • Expenditure <u>Environment</u> • Climate change • Carbon emissions <u>Society</u> • Human development • Household welfare **Strength**: Economy	Time series and cross-section data	• Dynamic • Static	• Global • National • Regional	The forecasting horizon is relatively short; the exact length depends on the hypothesis of the study.	• National • Regional • Farmer level	Both
System Dynamics (SD) Models	• The Green Economy Model (GEM)	The System Dynamics (SD) modelling framework has been widely used in research related to agricultural land, soil, and water resources management, as well as in the examination of the resilience in food systems to address complex and non-linear feedback systems (Sterman, 2000).	<u>GEM</u> Outcomes of agriculture production at the national level were the development of Ethiopia's NDC (GoE, 2021). *<u>Applications in Global South countries</u>* Ethiopia (GoE, 2021)	<u>Economy</u> • International or regional trade • Income • Policy • Productivity <u>Environment</u> • Climate change • Land • Productivity • Climate projections <u>Social</u> • Population **Strength**: All three	Various bio-economic datasets	• Dynamic	• Global • National • Regional	Depends on the setup of the experiment.	• National • Regional • Farmer level	Depends on the setup of the model.

Spatial models	• InVEST (Integrated Valuation of Ecosystem Services and Tradeoffs)	InVEST is a suite of spatially explicit models that can be used to map and value key ecosystem services allowing potential users to address questions at local, regional, or global scales (The Natural Capital Project, 2020). InVEST models allow defining how changes in the structure and the functioning of ecosystems can affect the flows and values of ecosystem services across a landscape.	InVEST The relationship between crop yields and hydrological regulating services and habitat maintenance in the Ethiopian highlands (Yohannes et al. 2021); Investigation of the different sustainable watershed management options is crucial to mitigate soil erosion in Sri Lanka, which lowered local crop yields (Piyathilake et al., 2021). *Applications in Global South countries* Ethiopia (Yohannes et al. 2021); Sri Lanka (Piyathilake et al., 2021).	Economy • Trade flows • Agricultural production Environment • Ecosystem services • Landscape • Carbon sequestration • Water yield • Pollinator abundance • Sediment and nutrient retention • Crop yield • Nutrient value for a fixed set of crops • Habitat quality **Strength**: Economy and Environment	Various bio-economic datasets	• Dynamic • Static	• Global • National • Regional	Depends on the setup of the experiment.	• National • Regional • Farmer level	Depends on the setup of the model.

Before presenting in detail the seven model types based on the categorization made in the context of the present work, the results of two review studies (Holzkamper et al., 2007; Jones et al., 2017) having worked on the classification of the relevant model types, are provided.

Holzkamper et al. (2007) reviewed the literature on models used in agricultural practice adjustments responding to climate change effects. Adaptation is broadly categorized into short-term responses that are primarily locally determined by farmers and long-term responses that include strategic planning on a larger scale. The study presented five types of agriculture production models:

- Empirical crop models: These models use empirical time series or panel data of climate and yield data to estimate climate-yield linkages. A disadvantage of these models is that they can only implicitly account for adaptation.
- Regional suitability models: These models allow the estimation of current and future biophysical land based on current and predictive climatic conditions at a regional scale.
- Biophysical models: These models allow the simulation of biophysical processes. An advantage of these models is that it allows explicit account for adaptation.
- Meta-models: These models allow the collation of information from a variety of sources which is then used as input for multi-criteria decision making. The advantage of such models can be found in time-saving.
- Decision models: Also known as bio-economic models, these models combine a biophysical model or an empirical production model with an economic farm optimization model. The focus of such models is on farmer decision-making based on socio-economic factors. The advantage of such models is that allow simulation of agriculture practice adjustments.

In a more recent study, Jones et al. (2017) reviewed the current state of agricultural systems science, focusing on the capabilities and limitations of agricultural systems models. The paper discussed the state of models relative to five different Use Cases spanning field, farm, landscape, regional, and global spatial scales and engaging questions in past, current, and future periods. The study identified common limitations across all Use Cases, namely a) scarcity of data for developing, evaluating, and applying agricultural system models, and b) inadequate knowledge systems that effectively communicate model results to society. The study argued that these limitations are greater obstacles to progress than gaps in conceptual theory or available methods for using system models. The study summarized the advantages and limitations of the most important economic models, categorizing them as follows:

- Farm management linear programming models: These are linear economic optimization models of farm systems and provide a basis for farm management advice (Heady and Dillon, 1964). The production possibilities available to a farmer are characterized by a complex set of linear inequality constraints and the simplex optimization algorithm is used to select the optimum production possibilities. One disadvantage of this approach is that the solutions are restricted to extreme points in the decision variable space, and it is unable to explore intermediate solutions. Another problem is that they need complex constraint structures and thus restrict alternative solutions.

- Econometric production models: Econometric methods have been developed for single crop and livestock production models as well as single-equation and simultaneous system models that represent input demand and output supply behaviour (Lau and Yotopolous, 1971; Chambers 1988). Econometric estimation of agricultural systems was expanded to represent multi-crop production, agricultural supply responses, and the imputed value of some key agricultural inputs that are often incompletely priced (Just et al., 1983). The advantage of the econometric approach is the importance of the interaction of multi-crops in a farm unit. However, the approach did not include formal linkage to biophysical models of agricultural processes. Furthermore, this approach is unable to extrapolate responses that are outside the estimation sample or those that employ systems that are not present in the data sample (Antle and Capalbo, 2001).

- Risk behaviour models: Risk is important in farm decisions and for this reason, early articles on risk analysis have developed linear optimization models of farm systems (Lin et al. 1974; Hazell and Scandizzo, 1975). More recently quadratic optimization approaches have been used to develop a mean-variance measure of risk and impute a risk-aversion value based on observed farmer actions (see Hazell and Norton, 1986; Just and Pope, 1978). Furthermore, Antle (1983) introduced a general moment-based approach to studying production risk behaviour, including downside risk. Recent research has extended this approach to investigate the impacts of climate change (Tack et al., 2012).

- Spatial equilibrium models: Space in agricultural production is important and first introduced in terms of trade between regions with different comparative advantages. Spatial equilibrium conditions and transport costs between different production regions could be presented as a quadratic optimization problem (Takayama and Judge, 1964). Spatial econometrics advanced to include rates of development and specialization of production (Anselin, 1988). Recently, spatial econometrics methods were used to address spatially varying farm production (Anselin et al., 2004; Staal et al., 2002). Techniques are emerging that use both remotely sensed data and spatial econometrics to conclude resource use or the effect of spatial variation on the agricultural supply response.

- Structural simulation models: Structural simulation models can be useful for representing a combination of behavioural relationships based on theory and empirical measurements. They are, however, subject to interpretation in the absence of robustly estimated relationships, since the feedback systems of the structural simulation models are not very stable and reproducible. Various microeconomic models have been developed to simulate the economic behaviour of agricultural systems and connect behaviour to environmental processes and economic sustainability indicators. van Wijk et al. (2014) present the large number and diversity of such models that include: household models (i.e., models that combine production systems with household behaviour such as food consumption and labour supply); agent-based models that incorporate spatial and temporal interactions among households; and models that link economic models with the bio-physical crop, livestock, and environmental models. The population-based modelling approach of Antle et al. (2014) was designed to represent agricultural system heterogeneity. It links economic simulation models to biophysical models to evaluate the impacts of technology, policy, and environmental changes on sustainability.

- Calibrating optimization models: Optimization models that use shadow values of resources and calibration constraints derive nonlinear calibrating functions, which are termed positive mathematical programming (PMP) (Howitt, 1995). PMP models are now being formally linked with biophysical models [see Mérel and Howitt (2014)].

- Computable general equilibrium models: CGE models are macroeconomic models, useful in developing country farm economies where much of the labour is supplied by family members with little or no pay. Another advantage of village-level equilibrium models is that they account for the utility gained from subsistence food grown in a village. These CGE models also use a social accounting matrix that accounts for flows within and outside the economy. Moreover, they fit standard functional forms such as a constant elasticity of substitution production, supply, or transformation functions (Taylor and Adelman, 2006). CGE models have the disadvantage of being data and computationally intensive due to their more general specification and the quite restrictive assumptions required for their solution. Compared with more detailed partial equilibrium models, general equilibrium models are harder to incorporate detailed process models.

- Integrated bio-economic models: Flichman (2012) reviewed recent studies on models that combine bio-physical and economic models to represent agricultural systems. Flichman and Allen (2012) and van Wijk et al. (2009), presented economic agricultural system models, categorizing bio-economic models into the farm, landscape, regional, and national models, while systems in crops, livestock, and socioeconomics components that interact in complex ways. The three prominent areas of application of integrated bio-economic models are Climate Change Impact Assessment Models, Hydro-Agricultural Economic System Models, and Integrated Economic Livestock Models.

3.2 Computable General Equilibrium (CGE) models

Computable General Equilibrium (CGE) models are empirical models that can capture the characteristics and general functionalities of an economy and they are quantitative policy analysis tools of high significance (Arrow and Debreu, 1954). Currently, these models are mainly used to examine the effects of GHG emissions, climate change as well as the management of water resources. Moreover, in comparison to partial equilibrium models, CGE models can take into consideration the international impact on all sectors and agents posterior to a shock in a particular sector, including price and rebound effects of technological improvements, which are not incorporated in partial equilibrium models.

3.2.1 National Computable General Equilibrium model

The National Computable General Equilibrium model is an amplified national CGE model that combines economic factors with biophysical models which take into account land heterogeneity and market mechanisms. It is a static model and it eliminates the impact of economical dynamic factors which may be unconnected with the bioethanol extension, the only variable factor that alters at the base year level of the model.

Weng et al. (2019) studied the effect biofuel development has on land use. Land-use change (LUC) has raised concerns regarding sustainability. The model used to test this scenario was the national CGE which was constructed with the hypothesis of a closed economy to a) eliminate international trade from affecting the LUC and b) achieve self-sufficiency in complying with the bioethanol mandate. The results of this study show that marginal land is the most suitable to grow non-grain energy crops while ensuring sustainability and securing food supply and forest protection.

3.2.2 Dynamic Computable General Equilibrium (DCGE) model

The DCGE model explores the association between domestic and international markets by assuming imperfect price-sensitive substitution between domestic production and imports (Breisinger et al., 2010).

Sánchez Chóliz and Sarasa (2019) used a recursive DCGE model including characteristics that allow the consideration of separate alternatives regarding its simultaneous evolution, involving all the general equilibrium model variables (i.e. taxes, prices, outputs, demands, etc.), while -however- assuming perfect foresight of water supply into the distant future for each alternative. Particularly, the work evaluated the inferences of uncertainty in the process of improvements considering the efficiency of irrigation water use. The respective inferences of uncertainty were evaluated by the concurrency of the introduction and take-up of newly developed technologies and by the uncertainty associated with the occurrence of each alternative. The work indicated that a policy of irrigation modernization through enhancement in water use always reduces the ramifications linked to water constraints, considering that the price increases due to water scarcity. However, increased technology profits could be reduced or even missed under the condition that the implementation of the newly developed advanced technology is delayed.

Solomon et al. (2021) estimated Ethiopia's agricultural sector's production climate change impact in the next 40 years. The authors used a DCGE to test scenarios regarding the national growth rate of crop net revenue which is expected to decrease. The climate change impact was enforced in the first year of the test which was 2009/10 using a Social Accounting Matrix (SAM) and the dynamic model was solved for every single year till 2050, taking into account the annual population and labour expansion. The DCGE model was able to predict how climate change will affect agricultural production across different zones, with the help of the SAM which has broken down the production and income in five Agro-ecological Zones of Ethiopia. After the model was tested, the researchers concluded that the impact will not leave unaffected households and labour. An overall reduction of the real GDP, due to a decrease in income, with a decline in consumption especially from poorer rural households, is expected by the year 2050 and hence it is suggested the Ethiopian government must take action.

3.2.3 The MAGNET model: Module description

The Modular Applied GeNeral Equilibrium Tool (MAGNET) is a standard, dynamic, global general equilibrium model, whose modular structure can be modified according to specific questions research is inquiring about (Woltjer et al., 2014). MAGNET was developed based on the standard GTAP and GEMPACK, which means it offers a general equilibrium modelling framework on a global scale. Moreover, MAGNET is also based on the LEITAP model used in policy analyses but is more flexible in aggregation and changes in structure. Researchers chose MAGNET to replicate the impacts of agricultural, trade, land, and bioenergy policies on the worldwide economy highlighting the impacts of land use, agricultural prices, nutrition, and household food security.

van Meijl et al. (2018) conducted a study in which they compared multiple models to limit inconsistencies in the analysis of the future impact of climate change on agricultural production. The paper took into account five global climate and agro-economic models and ran various scenarios (IMAGE, CAPRI, GLOBIOM, MAgPIE, and MAGNET). The goal was to evaluate a variety of potential effects of climate change on the agricultural sector by 2050 and hence all five models were harmonized regarding basic model drivers. It was found that on the subject of the producer prices MAGNET and MAgPIE produced more pronounced climate change impacts. All in all, the results from comparing scenarios pointed out that a mitigation strategy that considers residual climate change effects has a negative impact on global agricultural production in comparison to a no mitigation strategy with stronger climate impacts, which is moderately explained by the narrow effects of the climate change scenarios by 2050.

3.2.4 Extension of GTAP model: MyGTAP model

MyGTAP model is an extension of the standard GTAP model; the benefit of this approach can be found in its use in linking different sectors of the economy. MyGTAP model offers flexibility in data requirements since it integrates multiple households from one country and excludes areas that are not essential for the investigation, while also assisting in identifying income inequality [i.e., the difference in income between distinct households in the same area (Litchfield, 1999)].

Ahmad et al. (2021), based on the MyGTAP model, examined how trade liberalization and trade protectionism affect the biggest sector of the Pakistani economy, agriculture (25% of the country's GDP). The study set up a simulation experiment in which a reduction of an ad-valorem tariff of 10% was imposed for trade liberalization and an increase of 10% for trade protection. The Gini Coefficient was used to test for inequality and the Hoover Index (HI) to test the need for wealth redistribution. The study concluded that trade liberalization is a favourable strategy in terms of an increase in public welfare; however, the impact on income inequality remained unclear since it declined under both trade liberalization and trade protectionism.

3.3 Partial Equilibrium models

3.3.1 IMPACT and GLOBE models

IMPACT is a model that can combine a partial equilibrium along with climate, water, and crop models (see Section 2.2.1 for a more detailed description).

Driven by USAID's pursuit to develop public plant breeding in developing countries, Wiebe et al. (2021) conducted a study to estimate the effects on income and other factors of faster productivity development for 20 food crops in 106 developing countries in 2030. The researchers used two economic models, IMPACT and GLOBE, to test the effect on the value of the production and each country's income, taking into account the hypothesis that amplified investment will increase annual rates of the yield growth by 25% beyond baseline growth rates for the next 15 years. Firstly, through IMPACT a group of alterations in the prices demanded and supplied quantities of crops were produced under the scenario of productivity augmentation. Secondly, the results were then entered into the GLOBE model[10], created by McDonald et al. (2007), to capture wider economical effects. The GTAP 9 database version of GLOBE was used for this study because it can account for multiple sectors of an economy and simulates the complete circular flow of income from wage, land, capital to taxes, investment, and consumption. Thirdly, to facilitate the original request, the effects on gross household income from GLOBE were then put into the IMPACT model to estimate the impact on food demand and alterations of all affiliated parameters. All in all, even though the analysis of faster production of selected crops (rice, wheat, maize, banana, and yams) produced positive outcomes related to income and decline in hunger, the final comment on the paper is that there is a differentiation of results from one region to another pointing out the significance of unique policy-making for each one.

3.3.2 CAPRI model

The CAPRI (Common Agricultural Policy Regionalized Impact analysis) modelling framework is considered to be a global static partial equilibrium model regarding the agricultural and primary processing sectors, used to assess the effects of CAP (Common Agricultural Policy) instruments at the EU or Member State level, as well as at sub-national level (Britz and Witzke, 2014). The CAPRI modelling system utilizes its specific databases, methodologies, and software implementation. The respective databases exploit wherever possible well-documented, official, and harmonized data sources (i.e. EUROSTAT, FAOSTAT, and OECD). Certain modules ensure that the data used in CAPRI are mutually compatible and complete in time and space. The respective modules include about 50 agricultural primary and processed products for the EU from farm-type to global scale including input and output coefficients. The model is split into two major modules (Adenaeuer, et al. 2004). One module is supply-oriented and consists of independent non-linear programming models showing the activities of farmers at regional or farm type levels captured by the Economic Accounts for Agriculture (EAA). The other module is market-oriented and there the main behavioural functions for feed, supply, processing, and human consumption utilize flexible functional forms where calibration algorithms preserve full compliance with the microeconomic theory. CAPRI’s framework structure allows the extraction of the price feedback regarding simulated changes in policies along the primary supply chain, from commodity markets to EU farms and vice-versa. Moreover, the CAPRI model is mainly used for ex-ante impact assessment of environmental, agricultural, and trade policy options (Witzke et al., 2009).

Barreiro-Hurle et al. (2021) attempted to evaluate how far the CAPRI (Common Agricultural Policy Regionalized Impact analysis) model, which is used to evaluate the CAP, is appropriate to incorporate the most up-to-date climate and environmental ambition in the analysis of the agricultural sector. Thus, they

[10] A SAM (Social Accounting Matrix) based Global CGE Model using GTAP Data (McDonald et al., 2007)

concluded that the CAPRI model would require remarkable improvements to account for the characterization of some of the targets (e.g. pesticide and organic farming) more efficiently. Additionally, they inferred that there are several targets and instruments that are not represented by the model such as food waste reductions, dietary shifts, etc. Moreover, the empirical results showed that by utilizing certain assumptions, the model can be used to project how the respective targets could potentially affect the agricultural sector. Mainly due to standard characteristics of the CAPRI model such as risk management, considering that the model is deterministic, it can be pointed out that, considering the capacity of the CAPRI model several measures that are addressed directly to the agricultural sector will never be incorporated in the analysis. Furthermore, such measures could be addressed more efficiently by using other models that are connected to a weaker or stronger degree with CAPRI (i.e. farm level responses to incentives with IFM-CAP, land use changes linking with GLOBIOM, structural change from Agent-Based Models).

3.3.3 UK Agricultural Market Model (UKAMM)

The UK Agricultural Market Model (UKAMM) is a system of consumption patterns, production processes, and international trade flows, mainly used to describe economic relationships regarding the sectors of dairy, crops, oilseed processing, livestock, and sugar (Department for Environment, Food & Rural Affairs the UK, 2021). That is due to the high importance for the UK government to be able to project the state of UK agriculture considering a span period of approximately ten years, intending to analyse the effects of potential policy proposals or simulate hypothetical scenarios. Hence, the UKAMM is a dynamic partial equilibrium model that aims to project how UK agriculture might fluctuate over time. However, due to limitations related to the nature of partial equilibrium models, the UKAMM investigates how the markets work only in one economic sector without taking into account existing relationships between agriculture and other sectors. Moreover, the UKAMM is closely related to other agriculture market models such as the Aglink-Cosimo model, which is related to global agriculture, as well as the Food and Agricultural Policy Research Institute (FAPRI) model, which is another dynamic partial equilibrium model that examines the UK agriculture.

3.3.4 Agricultural Member State Modelling (AGMEMOD)

AGMEMOD stands for Agricultural Member State Modelling and was established in 2001 (Riordan, et al., 2002). AGMEMOD is represented as a dynamic, econometric, multi-product partial equilibrium model in which a bottom-up approach is utilized. It is mainly based on a collection of commodity-specific model templates, country-specific models that were developed to reflect the specifications of agriculture at the Member State level. At the same time, AGMEMOD allows for the combination of the abovementioned specifications in an EU model (van Leeuwen et al., 2012). The respective approach captures the inherent heterogeneity of the agricultural systems existing across the EU, as well as ensures consistency across the country models through the adherence to agreed commodity model templates. The preservation of this consistency across the country models is substantial for the successful aggregation of country models to the EU level. AGMEMOD also promotes the significant comparison of the policy impact changes across the different Member States. The main aim of the AGMEMOD is to maintain and develop a partial equilibrium modelling system with the capability to handle economic model-based analysis regarding the impact of policy or additional changes on the agri-food sector of each EU Member State and the EU as a group.

Niemi et al. (2005) utilized the AGMEMOD modelling approach to examine the empirical effects of the 2003 reform of the CAP on Finland's agri-food sector. Thus, they produced results to compare the long-term results of the CAP reform from 2003 to 2010 along with the long-term results of a scenario that are related to the normal continuation of the agricultural policy agenda of the 2000s. They concluded by indicating the necessity for extending their AGMEMOD modelling framework considering more EU countries into a multi-country model.

3.4 Optimal Crop Allocation models

3.4.1 Flower Pollinated Algorithm

The Flower Pollinated Algorithm (FPA) (Yang, 2012) is utilized to solve diverse types of optimization matters, with its algorithm being based on the pollination principle.

Ejieji and Akinsunmade (2020) extended the FPA by developing the Pollination Intelligence Algorithm, to construct an agricultural model for optimal crop allocation, based on total land available, planting costs, crops' expected yield, and market prices. The work focused on a case study of a farmer in Nigeria, indicating that in order achieve the optimal profit, crop allocation should be based on planting cost, crops' yield, and market prices, instead of being randomly allocated, based on farmers' intuition.

3.4.2 Linear Programming Models

Agricultural production planning models at the farm level should take into consideration what products will be produced, which areas will be assigned to each of them, which production operational procedures will be used, and what level of production costs will be followed (Osaki and Batalha, 2014). To improve production systems, linear programming models have been frequently employed to develop this plan. These models often integrate the production of various goods with various soil management and agricultural approaches, allowing for effective resource allocation and cost minimization (Heady, 1954; McCorkle, 1955).

Osaki and Batalha (2014) proposed a decision support model focused on production planning in multiproduct farms under risk conditions, while applying this model in grain production farms in Brazil (Sorriso region), in the context of examining diverse resource allocations. The model assists in the selection of the best production proportion of each agricultural product, in terms of greater profit and lower risk. The innovation of this work compared to previous relevant work [see Osaki and Batalha (2014) for a list of previous farm planning studies that have incorporated the risk factor in the linear programming model], is that it puts forward an agricultural planning model that takes into account two harvest seasons in the same harvest year, while also using specific means to estimate agricultural planning risks. The linear programming MOTAD (Minimization of Total Absolute Deviations) method was used to estimate the relation between the farm's combined activity and income variability. The results of the study indicated that the farms under investigation maximized their production factors, achieving respectable financial returns with lower risks.

3.4.3 Stochastic and Math Algorithm

Stochastic models were used to prevent severe phenomena that could affect production. Ivanyo et al. (2020) constructed an algorithm to improve and maximize agricultural production taking into account the agro-metrological phenomena which may disrupt it. The authors suggested an algorithm that consists of the following steps: a) data of severe events which take a toll on agricultural production in specific areas, b) a moment is found where there is a low probability for such occurrence, c) the association of natural resources and the impact of the phenomena need to be verified, d) the mathematical model uses parameters whose variability needs estimation and their probability distribution is depicted, e) afterward, the maximizing model is set up by picking the case of the smallest likelihood in the previous distribution and f) considering the scattering of probability, the optional solution is found. Researchers applied this method to a case study crop producer in the Irkutsk region in Siberia and concluded that better risk management choices can be achieved.

3.5 Calibrated programming models

Howitt et al. (2012) described calibration methods for models of agricultural production and water use. The central model is the California Statewide Agricultural Production Model (SWAP), a PMP model of California irrigated agriculture. Calibrated programming models such as SWAP provide a tool for regional water management and policy as well as a framework for integrating many aspects of regional water and agricultural management. Models such as SWAP can be easily linked to agronomic, hydrologic, and other biophysical models which provide the researcher with a flexible modelling framework. The analysis of the paper links regional production functions with a water supply network. The results show that a more flexible water market allocation can reduce revenue losses from drought by up to 30%. These results highlight the potential of self-calibrated models in policy analysis.

3.6 Regression models

3.6.1 ARIMA forecasting model for time series data

When referring to time series analysis, the ARIMA model is one of the most useful techniques for future event forecasting. The model, being made known by Box and Jenkins (1976), estimates a value in a response time series as a linear combination of its past values. The technique is denoted as ARIMA (p, d, q), with "p" referring to the order of the autoregressive model, d to the degree of difference, and q to the order of the moving-average model.

Kannan and Karuppasamy (2020) applied the ARIMA forecasting model for time series data, to forecast rice (paddy) production in south India and compare the results between different states (Andhra Pradesh, Karnataka, Kerala, and Tamil Nadu). The results of the specific study forecasted an increase in rice prices and the demand for the crop.

3.7 System Dynamics (SD) models

3.7.1 The Green Economy Model (GEM)

GEM is an integrated assessment model developed by the United Nations (UNEP, 2011) and since then applied in more than 40 countries. The model is used to analyse the impacts of sustainable development-oriented policies across sectors and actors over time, and if integrated with spatial modelling, space. The agriculture module in GEM captures agriculture production dynamics at varying levels of detail, however, at the core of the module are land use for crop production and land productivity as well as the total livestock herd. The level of aggregation at which crops and livestock are captured in the model depends on the focus of the assessment and can range from having one stock of land with a productivity parameter to subnational disaggregation of different climatic zones and types of crops.

GEM forecasts agriculture land use and livestock herd based on total population, productivity, and climate-related variables. Forecasts are usually aligned with relevant development plans and/or validated by relevant project stakeholders. The visually explicit way in which connections are modelled in SD allows the user to follow the causal chains from changes in population to changes in agriculture production and value-added. The flexibility of SD as an underlying methodology lends itself well to exploring a range of "What if" scenarios, which are especially useful for testing agriculture interventions related to climate change adaptation and mitigation, including the evaluation of their impacts and costs. GEM includes a range of parameters that capture the impact of climate on agriculture production (e.g. water availability for irrigation, water scarcity impacts, flooding of cropland, etc.) and provides the option to use downscaled climate projections for the simulations. Recent examples where SD models were used for analysing, amongst others, the outcomes of agriculture production at the national level were the development of Ethiopia's NDC (GoE, 2021). Regardless of the application, GEM has proven a versatile tool for conducting agriculture production-related analyses at the national level while involving key stakeholders throughout the process.

3.8 Spatial models

3.8.1 InVEST (Integrated Valuation of Ecosystem Services and Tradeoffs)

InVEST is a suite of spatially explicit models that can be used to map and value key ecosystem services allowing potential users to address questions at local, regional, or global scales (The Natural Capital Project, 2020). InVEST models allow defining how changes in the structure and the functioning of ecosystems can affect the flows and values of ecosystem services across a landscape. InVEST returns results in either biophysical terms (e.g., tons of carbon sequestered) or economic terms (e.g., the net present value of that sequestered carbon).

InVEST allows modelling a variety of ecosystem services that are relevant for agricultural production, including carbon sequestration, water yield, pollinator abundance, sediment and nutrient retention, crop yield, nutrient value for a fixed set of crops, and habitat quality. Different studies have used InVEST to model crop yields. For example, Yohannes et al. (2021) assessed the relationship between crop yields and hydrological regulating services and habitat maintenance in the Ethiopian highlands, while Piyathilake et al. (2021) used InVEST to investigate different sustainable watershed management options is crucial to mitigate soil erosion in Sri Lanka, which lowered local crop yields.

4. AGRICULTURAL PRODUCTION OUTCOME

4.1 Introduction

The Agricultural Production Outcome section is dedicated to six types of models. These types are the following:

- Computable General Equilibrium (CGE) models
- Sustainability Assessment Models
- Regression Models
- Agricultural Production Growth Models
- System Dynamics Models
- Economic and Financial analysis

The CGE, Regression, and System Dynamics models are found in all sections of this report since they are widely used in studies. In the agricultural production outcome studies, additional types of models are analysed. Sustainability assessment models evaluate dimensions and subjects with respect to farm management strategies. Furthermore, Agricultural Production Growth Models Examine the relationship between agricultural production and important inputs of production such as physical capital stock, labour, and land. Finally, economic, and financial models can be developed to analyse investments in the agriculture sector. Table 3 presents a synthesis of the main features of the six abovementioned model types.

Table 3. Agricultural production output – Models' Summary Table

Model	Models	Goal	Applications & Studies Reviewed	Sustainability Dimension	Dataset	Static/ Dynamic	Regional Coverage	Forecasting Time Frame	Degree of Aggregation	Perfect or Imperfect Competition
Computable General Equilibrium (CGE) models	• CGE models • Dynamic CGE-Water model	The models analyse some policy challenges and economic "shocks" (including global climate change, trade agreements, and international labour migration, among others).	CGE Gender productivity gap in the agriculture sector (Ikhide et al., 2021); Segmentation of the labour market according to gender (Arndt and Tarp, 2000; Fontana, 2015); Distributional impacts of government interventions on the rural economy through agriculture (Mbanda and Ncuba, 2021); Additional studies by: (Viana et al., 2018; Decaluwe et al., 2012). Dynamic CGE-Water Model Water stress scenarios, with respect to the role of sustainable water supplies with regard to agricultural and additional sectors (Zeshan and Shakeel, 2021). *Applications in Global South countries* Mozambique (Arndt and Tarp, 2000); Kenya (Decaluwe et al., 2012); Brazil(Viana et al., 2018); Nigeria (Ikhide et al., 2021);	Economy • Trade • Tariffs • Agricultural production • Imports • Prices • Government interventions • Yield • Investment • Return • Domestic production Environment • Climate change • Energy • Water sector • Water stress scenarios Society • Gender productivity gap • Labour market • Food security **Strength**: Economy and Environment	GTAP Database; Social Accounting Matrix	• Dynamic • Static	• Global • National • Regional	~2050, up to 2100	• National • Regional • Farmer level	Both (Standard version of models have the perfect competition hypothesis)

			Pakistan (Zeshan and Shakeel, 2021); South Africa (Mbanda and Ncuba, 2021).							
Sustainability Assessment Models	• Sustainability Assessment of Food and Agricultural Systems (SAFA) • Sustainability Standard of the German Agricultural Society (DLG) • Sustainable Farming (KSNL) • Multi-Objective Decision Support Model for Agri-Ecosystem Management Model (MODAM) • Model for Nitrogen and Carbon Dynamics in Agro-Ecosystems (MONICA) • Agricultural Production Systems sIMulator (APSIM) • Agricultural sustainability assessment framework • SALCAsustain methodology • Sustainable food profiling models	MacPherson et al. (2020) reviewed sustainability assessment (SA) tools and models to examine if they are suitable for incorporating ecosystem services and contributing to achieving the United Nations Sustainable Development Goals (SDGs) at the farm level.	<u>SAFA</u> Indicator-based sustainability tool to support farmers in distinguishing precise on-farm deficiencies in sustainability performance (Grenz et al., 2016). <u>DLG</u> Documentation and communication to support an agricultural sustainable economy (Doluschitz et al., 2009). <u>KSNL</u> Identification of deficiencies of different SA criteria and advice farmers (Breitschuh et al., 2008). <u>MODAM</u> Crop and livestock production at the farm level (Zander et al., 1999; Zander et al., 2003). <u>MONICA</u> Crop growth and analysis of its relationship with soil characteristics in changing climate conditions and cropping practices (Nendel et al., 2011). <u>APSIM</u> New indicators for sustainability assessment in	<u>Economy</u> • Agricultural policies • Sustainable economy • Growth • Production • Profitability • Liquidity • Stability <u>Environment</u> • Ecosystem services • Climate change • Bio-physical conditions • Nutrient-related environmental impact • Resource use • Ecotoxicity • Biodiversity • Soil quality <u>Society</u> • Landscape quality • Well-being • Food • Food security • Nutrition • Food labels • Nutritional impact **Strength**: All three	Various, such as the EUROSTAT database.					

			agriculture (Streimikis and Balezentis, 2020). <u>SALCAsustain</u> Framework on farmers (Roesch et al., 2021). <u>Sustainable food profiling models</u> How food labels inform consumers on nutritional value and environmental impact (Bunge et al., 2021).							
Regression Models		The models are used to perform impact evaluation, causal analysis, and forecasting.	Impact of maize price shock on the growth of children from food producers and food non-producers (Bonis-Profumo et al., 2021); Women empowerment in agriculture (Mkupete et al., 2021). *<u>Applications in Global South countries</u>* Tanzania (Mkupete et al., 2021); Timor-Leste (Bonis-Profumo et al., 2021).	<u>Economy</u> • Prices • Demand • Growth • Production <u>Environment</u> • Climate change <u>Society</u> • Food • Households **Strength**: Economy	Time series and cross-section data	• Dynamic • Static	• Global • National • Regional	The forecasting horizon is relatively short; the exact length depends on the hypothesis of the study.	• National • Regional • Farmer level	Both
Agricultural Production Growth Models		Examine the relationship between agricultural production and important inputs of production such as physical capital stock, labour, and land	Investigation of the relationship between agricultural production and employment in the agricultural sector (Ngalawa and Derera, 2020). <u>Applications in Global South countries</u> South Africa (Ngalawa and Derera, 2020).	<u>Economy</u> • Agricultural production • Capital stock <u>Environment</u> • Land <u>Society</u> • Labour • Gender **Strength**: Economy	Time series and cross-section data	• Dynamic • Static	• Global • National Regional	The forecasting horizon is relatively small; depends on the setup of the experiment.	• National • Regional • Farmer level	Both
System Dynamics (SD) Models	• System Dynamics models for food-energy-	The System Dynamics (SD) modelling framework has been widely used in research related to	<u>FEW</u> Analysing agriculture production under various management	<u>Economy</u> • Agricultural production • Productivity	Various bio-economic datasets	• Dynamic	• Global • National • Regional	Depends on the setup of the experiment.	• National • Regional • Farmer level	Depends on the setup of the model.

	water (FEW) nexus • Integrated Sustainable Development Goal (iSDG) model	agricultural land, soil, and water resources management, as well as in the examination of the resilience in food systems to address complex and non-linear feedback systems (Sterman, 2000).	scenarios (DIW Econ, 2021). <u>iSDG</u> Focusing on SDG-2 policy analysis for Malawi, and identifying policies' favourable and not favourable effects across sectors and SDGs (Arquitt, 2020). *<u>Applications in Global South countries</u>* Malawi (Arquitt, 2020).	• Agricultural GDP <u>Environment</u> • Climate change • Water security • Sustainable agriculture • Water vulnerability • Policy • GHG emissions <u>Social</u> • Employment • Undernourishment • Population • Poverty • Labour **Strength**: All three						
Economic and Financial Analysis		Models can be created to analyse the economic and financial outcomes of investments in the agriculture sector (e.g. for climate-smart agriculture practices).	Project Finance Assessment focuses on investment performance (Pinto, 2017).	<u>Economy</u> • Cash flows • Cost-Benefit Analysis • Investment performance • Financing • Expected return on equity investment • Net present value (NPV) • Internal rate of return (IRR) • Expected income <u>Environment</u> • Climate-smart agriculture practices **Strength**: Economy	Various bio-economic datasets	• Dynamic	• National Regional	Forecasting ability is relatively short; depends on the setup of the experiment.	• National • Regional	Depends on the setup of the experiment

4.2 Computable General Equilibrium (CGE) models

Based on our discussion in Sections 2.1 and 3.1, CGE models consider an economy of many goods which are produced by many sectors. CGE models describe all parts of an economy simultaneously and how these parts interact with each other. The models consider the maximizing behaviour of producers and the utility-maximizing behaviour of consumers as well as the macroeconomic behaviour of an economy, such as changes in the gross domestic product, aggregate saving and investment, government tax revenues and spending, and the balance of trade. Note that the CGE models require large databases.

4.2.1 CGE models

Viana et al. (2018) developed a CGE model to evaluate the economic impact of water reduction in Brazilian agriculture which included endogenous demand for water and used econometric estimates of the parameters of that demand. The study provided insights from three exogenously restrictions of water availability scenarios (10%, 20%, and 30% reduction). The CGE model can calculate the economic impacts by replicating the tariffs in both the agricultural and water sector. The CGE model calibrated the parameters using the Social Accounting Matrix 2009 and integrated the estimated demand system. One of the paper's findings is that the total demand for raw water decreased more than for agriculture production in the scenario of a 30% water availability restriction.

Ikhide et al. (2021) used a CGE model to assess the impacts of the gender productivity gap in the Nigerian agriculture sector. CGE models presume that consumers maximize utility given a budget constraint while producers minimize production costs. A single-country static model [extended PEP 1-1 model (Decaluwe et al., 2012)] is employed. The study segments the labour market according to gender (Arndt and Tarp, 2000; Fontana, 2015). It also disaggregates these gendered labour shares into unpaid household labour or paid hired labour. The study finds that the gender productivity gap decreases agricultural production potentials. Thus, agricultural exports are lower and imports higher, and prices of agricultural commodities are higher. The combination of lower production, higher prices, and dependence on imports create food security risks. In terms of policy interventions, the study finds that access to farm inputs for female-managed crops in terms of capital stock leads to an increase in agriculture production in both male and female-managed crops, with a disproportionately higher increase in the output of female-managed sectors.

Mbanda and Ncuba (2021) analysed the economy-wide and distributional impacts of government interventions on the rural economy through agriculture, focusing on the possible differential impacts in terms of location and gender. This study first uses CGE modelling to estimate the macro impacts of reallocating land from commercial agriculture to smallholder agriculture in South Africa. The results from the macro analysis were used to assess consequent effects on welfare. The first simulation modelled the redistribution of land from commercial agriculture to smallholder agriculture. The second increased capital for the agricultural sector, given that farming takes place largely in rural areas. Results from both simulations indicated that support for the agricultural industry could yield positive results for the South African economy. Based on the study's results, a proposed policy for the government would be the reallocation of land from commercial to smallholder agriculture to have a significant impact on reducing gender inequality and poverty.

4.2.2 Dynamic CGE-Water Model

The dynamic CGE-Water modelling framework is a multi-sector, multi-region, recursively dynamic modelling approach, extending the standard GTAP model (Hertel, 1997). Fundamentally, the dynamic CGE-Water model combines the static GTAP-Water model with the dynamic GTAP-Energy model (Calzadilla et al. 2011; Golub, 2013). Thus, the main characteristic that determines the differences between the dynamic GTAP model from other dynamic CGE models is its disequilibrium approach to depicting capital mobility.

The research of Zeshan and Shakeel (2021) developed a dynamic CGE-Water model to explore the different water stress scenarios in Pakistan, with respect to the role of sustainable water supplies regarding agricultural and additional sectors. In the corresponding scenarios, the findings demonstrated that the expected rate of investment, return, as well as domestic production, had a significant decline specifically after 2020. The respective results implied that joint endeavours are required with a view to a viable water management policy in Pakistan. Additionally, the results implied the provision of water conservation methods as well as adaptation measures to be indigenized in the industrial and agriculture sectors. Moreover, there should be defined legislation and ownership for licensing of groundwater, as well as an increase in the groundwater recharge for rural and urban areas under legitimate frameworks.

4.3 Sustainability Assessment Models

MacPherson et al. (2020) reviewed sustainability assessment (SA) tools and models to examine if they are suitable for incorporating ecosystem services and contributing to achieving the United Nations Sustainable Development Goals (SDGs) (e.g., SDG6: Clean Water, SDG13: Climate Action, SDG14: Life Below Water, SDG15: Life on Land) at the farm level. The authors listed agricultural Common International Classification of Ecosystem Services (CICES) classes and SDGs in an effort of linking them to available tools and models. On the one hand, three tools were analysed:

- Sustainability Assessment of Food and Agricultural Systems (SAFA) focuses on observation and self-assessment of enterprises in the food and agricultural sector with a goal of worldwide recognized standard for agriculture sustainability assessment (FAO, 2013);

- Response Inducing Sustainability Evaluation (RISE) that focuses on production at the farm level; a holistic, indicator-based sustainability tool to support farmers in distinguishing precise on-farm deficiencies in sustainability performance (e.g. environmental issues such as biodiversity, water usage, and soil quality; social and economic issues such as working conditions and economic viability) (Grenz et al., 2016);

- The Sustainability Standard of the German Agricultural Society (DLG) focuses on analysis and certification for German farms and agricultural products, food, energy crop, and livestock with a goal of documentation and communication to support an agricultural sustainable economy (Doluschitz et al., 2009);

- Criteria for Sustainable Farming (KSNL[11]) focuses on analysis and certification for the sustainable farm-level crop, livestock, and bioenergy production to identify deficiencies of different SA criteria and advise farmers (Breitschuh et al., 2008).

On the other hand, the models were:

- Multi-Objective Decision Support Model for Agri-Ecosystem Management Model (MODAM), a static, process-based model with multi-objective linear programming. Its' goal is to assess the economic and environmental sustainability of crop and livestock production at the farm level (Zander et al., 1999; Zander, 2003);

- Model for Nitrogen and Carbon Dynamics in Agro-Ecosystems (MONICA), a dynamic, process-based model with a goal of simulation of crop growth and analysis of its relationship with soil characteristics in changing climate conditions and cropping practices (Nendel et al., 2011);

- Agricultural Production Systems sIMulator (APSIM), is a dynamic, process-based model with the goal of Simulation of plant growth in a variety of bio-physical and economic conditions (McCown et al., 1996).

The paper concluded that the SAFA tool was the best compared to the others in covering the Ecosystem Services and SDGs with RISE being second and KSNL third. All in all, the review suggests that models were not as suitable as the SA tools and that more research is needed to sufficiently incorporate ecosystem services.

4.3.1 Agricultural sustainability assessment framework

Streimikis and Balezentis (2020) developed new indicators for sustainability assessment in agriculture which allows for achieving harmonization of sustainable development, climate, and agricultural policies in the EU. The main SDGs linked to agriculture are SDG2 (aiming to end hunger, achieve food security, improve

[11] Kriteriensystem nachhaltige Landwirtschaft (KSNL) in German

nutrition and promote sustainable agriculture) and SDG13 (calling for urgent action to combat climate), so the developed agricultural sustainability indicators framework for the EU addresses these main SDGs and provides linkages between them and other policy areas. The selected relevant indicators are combined in the framework which allows for achieving harmonization of climate change and agriculture policies by selecting relevant policy actions for targeted indicators. This study has limitations as the developed agricultural sustainability assessment framework was not empirically applied and case studies were not developed. However, all selected indicators in the developed agricultural sustainability indicators framework can be easily collected from the EUROSTAT database for all EU Member States (MS). The various multi-criteria decision aiding techniques can be applied to create a composite index from these indicators for monitoring and comparative assessment of progress achieved by EU MS toward agricultural sustainability.

4.3.2 SALCAsustain methodology

SALCAsustain is an indicator-based sustainability method that evaluates dimensions and subjects. It is a more complex model compared to others that can give researchers answers to their queries and analyses of various farm management strategies (Roesch et al., 2021).

In a recent paper, Roesch et al. (2021) evaluated the use of the novel SALCAsustain method to include all three dimensions of sustainability (environmental, economic, and social). The method was piloted with Swiss farms. The authors analysed the whole procedure of the use of SALCAsustain methodical framework on farmers, with questionnaires, in-depth face-to-face interviews, and data analysis. The analysis indicated that there was a low correlation between environmental impact and socioeconomic indicators. The results corroborated the hypothesis and the existing literature. According to farmer responses, there are intentions to optimize their work to achieve sustainability. All in all, the paper provides sufficient feedback based on a set of indicators (social: well-being, landscape quality; economic: profitability, liquidity, stability; environmental: resource use, climate change, nutrient-related environmental impacts, ecotoxicity, biodiversity, soil quality) that the SALCAsustain method is a reasonable, acceptable, and robust method for assessing farm sustainability.

4.3.3 Sustainable food profiling models

Sustainable Food Profiling Models (SFPMs) are the models used which give information about food products since they are the base of the labelling of goods. The products are categorized based on their environmental and nutritional impact and hence enhance the consumer’s knowledge (Bunge et al., 2021).

Bunge et al. (2021) conducted a literature review on (SFPMs) to investigate how food labels inform consumers about the nutritional value and environmental impact. The findings were multiple; on the one hand, 10 models classified labels following two environmental indicators, greenhouse gas emissions, and water use. On the other hand, six SFPMs used 29 aggregated indicators for nutritional quality and the environment and few SFPMs included nutritional value of sustainability. The authors presented the main benefits and drawbacks of the existing SFPMs. The benefits are the extensive range of system boundaries, reference units, approaches for essential cut-off values, design proposals for food labelling schemes, and comprehensive geographical scope of the lifecycle inventory database used in the development. The drawbacks are inconsistency in the methods for food classification and disability to mimic due to ambiguous methods, unavailable code for environmental and nutritional impact calculation, and vague cut-off values. The authors stress the need for national and international reference values for a standardized food labelling to be developed.

4.4 Regression Models

Regression models refer to the wider concept of using statistical methods to perform impact evaluation and causal analysis, as well as forecasting (see Section 2.4 for a more detailed description).

Mkupete et al. (2021) investigated the impact of maize price shock on the growth of children from food producers and food non-producers, based on the hypothesis that high maize prices do not affect negatively children from food non-producer households more than children from food producer households. The Ordinary Least Squares (OLS) model was applied to perform the analysis, using data between 2008 and 2013 from Tanzanian households. The results of the study indicated that an increase in maize price leads to the reduction of the growth of food non-producers' children and an increase in the growth of food producers' children. The specific study makes addition to previous relevant research [see Yamauchi and Larson (2019)] by taking into consideration specific socioeconomic characteristics (i.e., gender and age).

Bonis-Profumo et al. (2021) examined women empowerment in agriculture in Timor-Leste, in combination with household production and children (12-59 months old) and maternal dietary diversity. To do so, the Abbreviated Women's Empowerment in Agriculture Index (A-WEAI) (Meinzen-Dick et al. 2017) was utilized, through the application of OLS multivariable regression models. The A-WEAI consists of Five Domains of Empowerment (production, resources, income, leadership, time), based on which its scores are calculated. A limitation of the A-WEAI is that it provides a narrow measure of empowerment, as structural barriers that shape women's inequality are insufficiently considered. The results of the study showed that dietary diversity scores were higher for empowered women and their children, compared to disempowered women.

4.5 Agricultural Production Growth Models

Agricultural production models examine the relationship between agricultural production and important inputs of production such as physical capital stock, labour, and land.

Ngalawa and Derera (2020) investigated the relationship between agricultural production and employment in the agricultural sector in South Africa disaggregated by gender in the short and long run. The study estimated an autoregressive distributed lag framework (Pesaran and Shin, 1999; Pesaran et al. 2001) of an agricultural production growth model using quarterly data from 2008:Q1 to 2019:Q1. Model estimations showed that an increase in aggregate labour has a positive contribution to agricultural production in the short run and a negative effect in the long run. The study recommends adopting a ruralisation policy to absorb the excess labour in rural and peri-urban communities.

4.6 System Dynamics (SD) Models

4.6.1 System Dynamics models for food-energy-water (FEW) nexus

In addition to assessments at the national level, often done using GEM (UNEP, 2011), SD models lend themselves well to sectoral assessments. For example, under UNEP's The Economics of Ecosystems and Biodiversity (TEEB) program, SD was used to analyse the impacts and outcomes of different land management strategies resulting from establishing the Southern Agriculture Growth Corridor of Tanzania (SAGCOT) within the Rufiji River Basin in Tanzania (TEEB, 2017). The Rufiji watershed is critical for Tanzania's development, specifically when it comes to food and water security. The assessment found that the implementation of agriculture intensification strategies has the potential for mitigating unfavourable migration patterns by increasing the basin's carrying capacity for agriculture production. In addition to dampening seasonal migration patterns, the implementation of water efficiency and intensification actions also increases the total sectoral value-added while ensuring minimum threshold water flow in the Rufiji River to maintain downstream ecosystem integrity.

The SD KAZ model is another instance for which a sectoral SD model was developed for analysing agriculture production under various management scenarios (DIW Econ, 2021). The model was developed under the umbrella of developing Kazakhstan's carbon neutrality doctrine spearheaded by GIZ with the support of UN PAGE (UN PAGE, 2021). The development of the SD model for Kazakhstan required the disaggregation of agricultural land into four climatic zones, whereby each zone was calibrated according to sub-national production statistics. In total, the model is covering four climatic zones with respective precipitation and temperature forecasts, and within each zone, seven different crops. The analysis emphasized climate change impacts on agriculture production, such as the loss of topsoil (and related impacts on productivity), flooding of agricultural land, changes in precipitation patterns, and resulting impacts of water availability on crop yields, pre-harvest losses, and more. The assessment aimed to analyse the impacts of implementing sustainable agriculture practices on total sectoral outputs and related key indicators, such as value-added, tax revenues, employment, and GHG emissions.

4.6.2 Integrated Sustainable Development Goal (iSDG) model

Arquitt (2020) presented the Integrated Sustainable Development Goal (iSDG) model, an integrated System Dynamics (a theory and methodology focusing on the interpretation of complex systems) model intended to assist policymakers and policy planners to determine efficient pathways toward the SDGs. The iSDG model is largely applied at the national or regional level and is not seen as a substitute for detailed sector-focused models. The model comprises 30 sub-sectors being placed in the three dimensions of environment, economics, and society while including causal linkages and feedback loops running across dimensions, sectors, and within sectors. It should be noted that the iSDG model takes into account all 17 Sustainable Development Goals (SDG) through the utilization of about 80 SDG indicators [detailed description can be found at https://www.millenniuminstitute.org and Pedercini et al. (2018, 2019)]; the model is customized for each country or region, in collaboration with national modelling teams.

Following this, Arquitt (2020) presented an application of the iSDG model, focusing on SDG-2 policy analysis for Malawi, and identifying policies' favourable and not favourable effects across sectors and SDGs. In specific, the example used had to do with the investment in water-efficient irrigation to promote SDG-2 in Malawi. The performance indicators selected within the simulation were cereal production, crop production per unit of labour, the prevalence of undernourishment, population below the poverty line, agricultural GDP, and water vulnerability index. The results of the simulations can assist in the identification of policy combinations leading to better results, in comparison to the results that would be accomplished if each policy was individually implemented.

4.7 Economic and Financial Analysis

Models can be created to analyse the economic and financial outcomes of investments in the agriculture sector (e.g. for climate-smart agriculture practices). These models are often developed in Excel and represent the cash flow of the project, with the consideration of externalities and their economic valuation. Such models are used to perform a Cost-Benefit Analysis (CBA) and Project Finance Analysis (PFA).

CBA is a tool that allows supporting investment decisions (IFAD, 2015). Since costs and benefits of investments do not usually occur at the same time, the comparison is not straightforward, especially considering that costs often occur before benefits. Therefore, the CBA is a decision-making tool that can be used to compare two or more projects using the same framework of analysis.

CBAs usually consider only direct costs and benefits, but they can be also "integrated" or "extended" so that they can also include the economic valuation of both indirect and induced outcomes (usually labelled as externalities), such as avoided costs arising from the implementation of a project (such as increased carbon sequestration) as well as added benefits like increased land productivity.

PFA focuses instead on the investment performance (Pinto, 2017), considering both capital and operation and management costs (in the form of cash flow outlays), as well as revenues (in the form of cash flow inflows). It also considers the costs of financing and the expected return on equity investment. In other words, it calculates relevant indicators such as the Net Present Value (NPV), the Internal Rate of Return (IRR) of the project, and the Benefit to Cost Ratio (BCR) (Fürtner et al., 2022).

The NPV shows the economic viability of an investment by calculating the discounted expected income over a certain period. The IRR indicates the share of interests arising from the investments. The BCR shows the ratio between discounted benefits and costs. A BCR larger than 1, indicates that the benefits exceed the costs.

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