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Agro-economic-environmental modelling in the context of the Green Deal and sustainable food systems

The iMAP view

Integrated Modelling Platform iMAP Agro-economic Analysis

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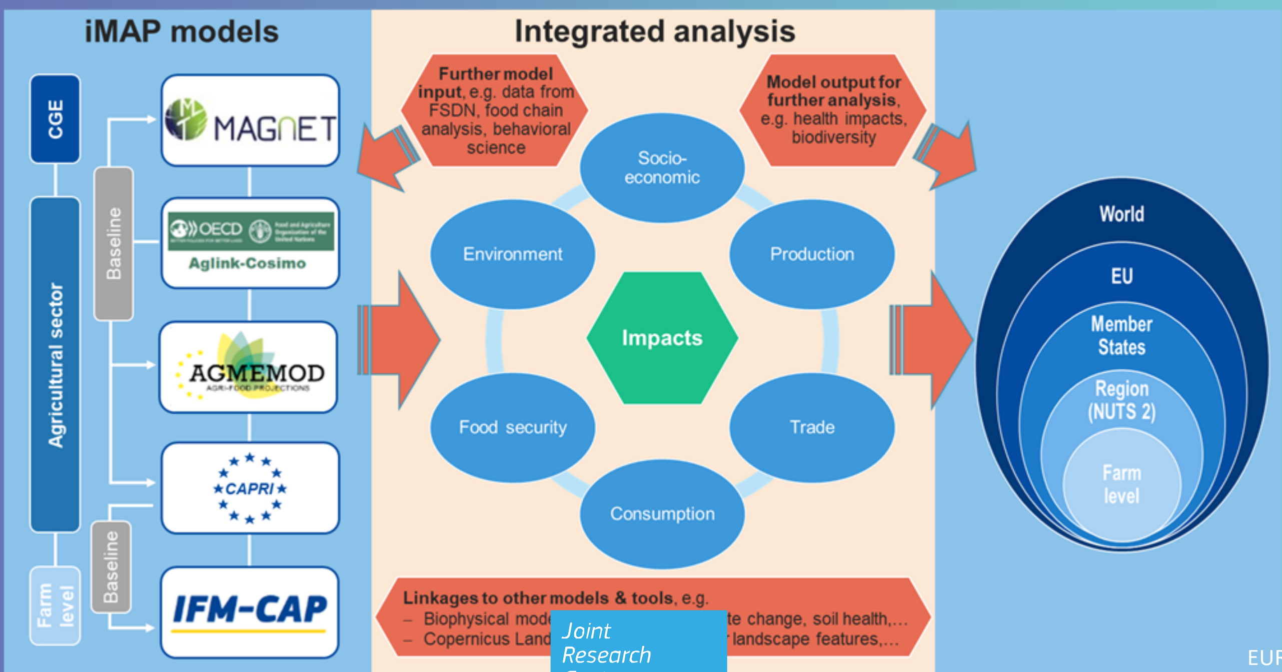

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Contents

Abstract

The Integrated Modelling Platform for Agro-economic Commodity and Policy Analysis (iMAP) provides in-house policy support to the European Commission by assessing a wide range of policies and topics related to sustainable food systems (SFS). Substantially supported by DG AGRI, iMAP is constantly further developed to meet evolving policy needs. Although many developments are ongoing, this report outlines iMAP's enhanced analytical capacity to capture the multidimensional aspects of SFS and assess policy impacts. Considerable progress has been made in capturing production and environmental aspects of policies and strategies, particularly those related to the European Green Deal (EGD). Significant developments have been achieved in integrating biophysical models, other sector-specific models, and satellite imagery data into iMAP's analytical framework. However, comprehensive modelling of environmental aspects of farming practices remains challenging due to the complex interplay of biological and agronomic factors, coupled with data limitations. Limited data on specific aspects of consumer behaviour also remains a constraint for comprehensive assessments. The report shows that iMAP, along with interdisciplinary collaboration and tool integration, provides a suitable framework for assessing EGD-related policies. However, the report also highlights general uncertainties, scientific knowledge gaps, and data constraints that limit a full assessment of all aspects of the transition towards more SFS.

Acknowledgements

The development, maintenance, and application of the Integrated Modelling Platform for Agro-economic Commodity and Policy Analysis (iMAP) has been a long-term project at the JRC since 2005. iMAP was established with the primary objective of providing in-house policy support to the European Commission. The modelling platform has been made possible through collaborative efforts and contributions from past and current colleagues at the JRC, as well as external researchers. Within the European Commission, iMAP has garnered significant support and usage, with DG AGRI being the primary supporter within an administrative agreement that has been continuously renewed since 2006. Since its inception, iMAP has benefited substantially from constructive dialogues and engagement with colleagues from DG AGRI and other Commission directorates. This collaborative spirit continuous to be instrumental in driving improvements to iMAP, ensuring that it remains relevant and aligned with the evolving needs of policy support. In this respect, we are particularly grateful to both current and former AGRI A.2 colleagues. Special thanks are due to Paolo Bolsi from DG AGRI for comments made at earlier stages of the report.

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Contributions

TF lead the conception and writing of the report, with chapters being developed and mainly written by TF, GG (Introduction), AI, TF (The CAP beyond 2022), TF, JH, ALB, IPD (Climate change mitigation and adaptation), TF, CB, AI (Organic farming), AK, TF, KS (Pesticides use), TF, AK, JH, ALB, FW (Biodiversity), CB, TF (Animal Welfare), TF, JH (Dietary changes and health aspects), RMB, TF, BDJ, PG (Circular economy and food waste), PC, TF, KN, CB (Food chain analysis), JBH, TF (Behavioural aspects), TF, OB, EF (International aspects), TF, GG (Conclusions), TF, VN, GG (Future perspectives), with notable model-specific contributions by CE, BF, IPD, SP (Aglink-Cosimo), ALB, CB, TF, JH, AI, AK, FW (CAPRI), EB, DK, PT, DRV (IFM-CAP), BDJ, EF, RMB, BR, AS (MAGNET) and the Food Chain team (FA, PC, KN, JTC).

1 Introduction

1.1 The iMAP framework

The European Commission's Joint Research Centre (JRC) formally created the integrated Modelling Platform for Agro-economic Commodity and Policy Analysis (iMAP) in 2005. iMAP is mainly supported by the Directorate-General for Agriculture and Rural Development (DG AGRI) within an administrative agreement, and its aim is to deliver in-house policy support to the European Commission, assessing a broad range of policies and topics affecting the agricultural and food sector. Since its inauguration, iMAP has been evolving to meet policy needs, in particular baseline projections, policy scenarios for impact assessment, what-if analyses, counterfactual analysis, and evaluations of exogenous shocks (M'barek et al. 2012, M'barek and Delincé 2015, Barreiro-Hurle et al. 2023a).

Over the years, the platform converged towards a set of particularly relevant agro-economic models for the analysis of the EU's agri-food sector, namely MAGNET, Aglink-Cosimo, AGMEMOD, CAPRI and IFM-CAP. These models are only briefly described here.[1] Besides, and in compliance with the EU's Better Regulation Agenda[2], their description and use for policy impact assessments is also publicly described in MIDAS.[3]

- MAGNET (Modular Applied GeNeral Equilibrium Tool) is a recursive-dynamic, economy-wide global CGE model. The model adopts a modular approach, whereby the standard GTAP-based core can be augmented with extensions and modules such as the land supply, land allocation, biofuels, food waste, and SDG modules, depending on the purpose of the study. For iMAP the detailed focus on agricultural policy is particularly useful. MAGNET covers 141 regions and individual countries, including the 27 EU Member States.
- Aglink-Cosimo is a recursive-dynamic, partial equilibrium, multi-commodity market model of world agriculture. Within iMAP and under the lead of DG AGRI, the model is used to provide the EU medium-term outlook for agricultural markets (MTO), which is annually published and also fed into the global OECD-FAO agricultural market outlook. The MTO provides the reference (baseline) for policy assessments to which the other iMAP models are calibrated. Aglink-Cosimo has a partial stochastic module that allows to analyse the variability underlying the outlook projections due to macroeconomic volatility and weather shocks. Moreover, the model allows to assess what-if and policy scenarios. Aglink-Cosimo covers 44 individual countries and 12 regional aggregates, over 90 commodities and 39 world market-clearing prices.
- AGMEMOD (AGricultural MEmber states MODelling) is an econometric, dynamic, partial equilibrium, multi-country, multi-market model. It is composed of econometrically estimated, country-specific, economic models of agricultural commodity markets and can provide significant detail on the main agricultural sectors in each EU Member State and EU candidate countries.
- CAPRI (Common Agricultural Policy Regionalised Impact) is a global, multi-commodity, comparative-static, partial equilibrium model, specifically designed to analyse the CAP, environmental, climate change and trade policies. The model is based on a consistent data set over different regional scales (global, EU, Member State, NUTS2 regions), combining a very detailed and disaggregated representation of EU regional agricultural production with a global market model. CAPRI can be applied for the assessment of a wide range of policy impacts on agricultural and environmental indicators.
- IFM-CAP (Individual Farm Model for Common Agricultural Policy Analysis) is an EU-wide comparative static positive mathematical programming model applied to each individual farm from the Farm Accountancy Data Network (FADN). The model allows for assessing a wide range of farm-specific policies while capturing the heterogeneity of EU commercial farms. It provides disaggregated economic results (farm income, land use, production, etc.) at finer geographical scale.

Models provide a simplified representation of reality, based on a specific perspective. The quality of their results depends on the availability and quality of data. Over the past decade, significant efforts and investments have been made to enhance both aspects within the iMAP framework. These include expanding the models to incorporate additional aspects beyond socioeconomics and integrating them into a comprehensive framework. Additionally, improvements have been made in data collection and management through the related Data-

[1] For more details on the models and links to model documentations see: https://datam.jrc.ec.europa.eu/datam/mashup/IMAP/

[2] Better Regulation: why and how

[3] Modelling Inventory and Knowledge Management System of the European Commission (MIDAS), see also Acs et. al. (2019), Di Benedetto et al. (2023).

Modelling platform of resource economics (DataM)[4]. DataM helps in streamlining data collection and analysis, and supports model integration and the analysis of scenario results as well as the dissemination of study results.

Thematically, iMAP has focused on the analysis of the Common Agricultural Policy (CAP) and its reforms as well as related policies impacting the agri-food sector. As the importance of environmental aspects within the policy discourse has grown over time, iMAP and its associated tools have also evolved to effectively assess and support the agricultural sector's transition towards enhanced environmental sustainability, as well as its role in combating climate change. The constant model developments and integration of new approaches enable the iMAP models to conduct economic assessments of agricultural, environmental, climate change, trade, rural development and other policies. However, the new policy context within the framework of the European Green Deal (EGD) further amplifies the scope for integrated model-based assessments linked to the agricultural and food sector, and therefore, also the requirements related to iMAP.

To address the growing complexity of policies, iMAP has been undergoing developments in three key areas for several years:

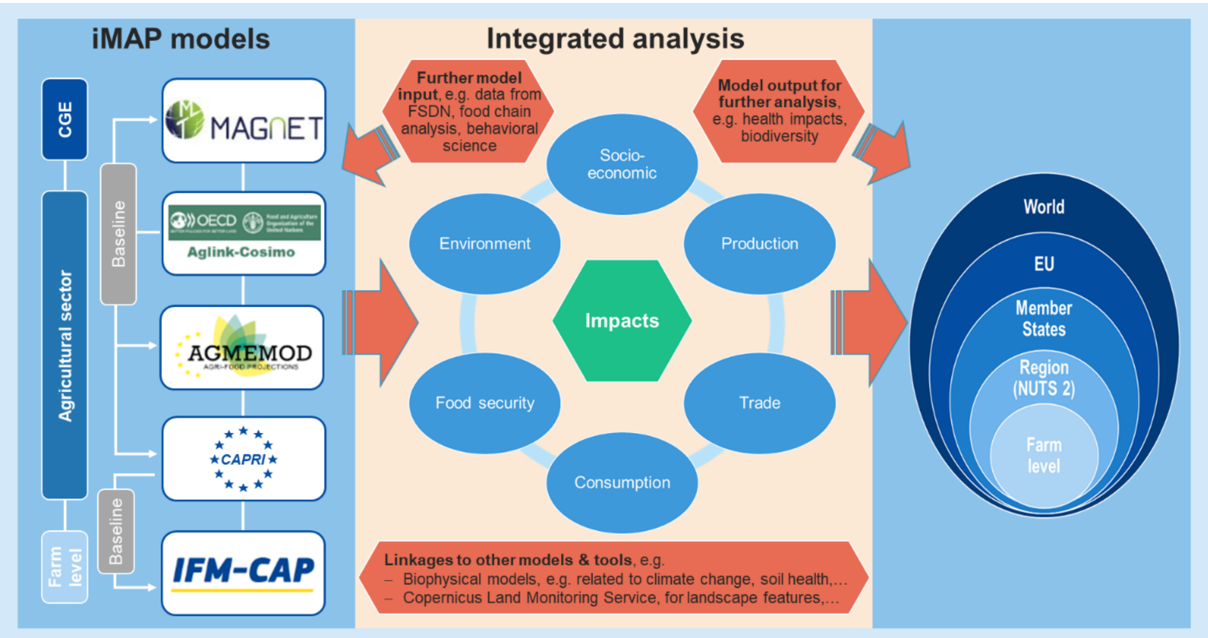
— Expanding the capabilities of individual models within the platform to encompass policy areas beyond the traditional agro-economic ones and incorporate environmental considerations;

— Improving model integration both within the platform at different levels and scales, and in conjunction with biophysical models and satellite imagery. Additionally, efforts are being made to integrate iMAP with other sector-specific models relevant to the agricultural sector, such as energy, land use, and forest models.

— Extending the models and integrating them with other approaches to incorporate aspects and information of the food chain as a whole beyond primary agriculture, for example also addressing changes from the consumer side.

These developments aim to enhance the analytical capacity of iMAP in capturing the multifaceted dimensions of agricultural systems and policy impacts. Although many of the developments are still a work-in-progress, tangible outcomes are already available as a result of research investments made over recent years with the aim of anticipating policy needs.

Figure 1. Integrated policy analysis based on the core iMAP models



Source: Own elaboration

The overall approach for integrated policy analysis based on the core iMAP models is depicted in Figure 1. The starting point for the iMAP models is the harmonisation of the baselines, which are used in each model as a reference for the comparison of policy scenarios. External drivers that are used in the baseline construction play

[4] Data-Modelling platform of resource economics (DataM)

an important role in the final simulation outcomes. As regards the iMAP models, such external drivers, among others, include especially macroeconomic assumptions, such as GDP growth, population, inflation, currency exchange rates, and crude oil prices. Moreover, main policy assumptions, like e.g., agricultural and climate change policies, need to be aligned. If not harmonised across the models, these drivers may cause considerable differences among the simulation results, which is why the major external factors used by the iMAP models are usually aligned before the models are applied for policy assessments. The assumptions for these external drivers are determined in the process of the MTO and accordingly used in the Aglink-Cosimo model. The same assumptions are then used in the MAGNET, AGMEMOD and CAPRI models, and the three models are then calibrated to the baseline results for major agricultural markets of the MTO. Price and yield trends from the CAPRI baseline are used as input for the baseline construction of the farm-level model IFM-CAP. The harmonisation of baseline assumptions facilitates the application of the iMAP models in an integrated manner and the combined use of the models to provide a more complete picture of impacts.

The combined use of the iMAP models for a particular policy question allows to maintain the strength of each individual model applied while bridging scales, where results missing or only available in less detail in one model are provided by another one. This is the case, for example, with respect to spatial resolution, product disaggregation, covered sectors, explicit representation of farming practices, and indicator coverage. As outlined above, depending on the policy question, for an amplified integrated analysis and fostering interdisciplinary cooperation, iMAP models can be fed with input from other (e.g., biophysical) models. The iMAP modelling output can also be used as input for other models and further analysis (e.g., regarding biodiversity indicators). The multidisciplinary cooperation across the JRC is facilitated by the new portfolio structure within the JRC work programme, which brings together different disciplines and teams from across the JRC to address common themes or issues.[5]

1.2 Current policy context for iMAP

In the framework of the EGD, the Commission adopted various strategies and proposals addressing issues relevant for the agri-food sector. These include particularly the Farm-to-Fork (F2F) and Biodiversity strategies, the Climate Law, and a Circular Economy action plan. Moreover, the latest reform of the CAP is seen as a crucial tool for achieving the EGD's objectives. In its core, the EGD presents a comprehensive and ambitious roadmap for transitioning towards sustainable food systems (SFS). Unlike the traditional linear perspective of agriculture and food production (from farm to fork), the concept of food systems encompasses a broader framework that considers various interconnected activities and their impacts (FAO 2018). Food systems encompass a wide range of actors and activities spanning production, consumption and disposal, operating at different scales from local to global. SFS must align with multiple societal, environmental and economic objectives, and given the complexity of food systems, it is crucial to overcome trade-offs and realise synergies (Ruben et al. 2021). By incorporating new and forthcoming EU strategies, policies, and regulations, the EGD seeks to navigate the complexities of food systems to achieve sustainability goals and balance multiple objectives effectively.

Several studies provided first attempts to assess the impact of EGD-related policies and strategies on agricultural production in the EU. These studies examined the effects of policies such as reduced pesticide use, decreased nutrient losses, increased land area for organic farming, and the expansion of high diversity landscape features (Barreiro-Hurle et al. 2021a, Beckman et al. 2021, Bremmer et al. 2021, Henning et al. 2021, Noleppa and Cartsburg 2021). Using agro-economic modelling approaches, these studies simulated various scenarios, primarily focusing on the supply side of the food chain. Although the results vary due to different modelling assumptions, calibrations, and EGD dimensions considered, the studies generally conclude that reducing inputs and land will lead to a significant decrease in EU agricultural production. However, as highlighted for example by DG AGRI (2022a)[6], Barreiro-Hurle et al. (2021b) and Candel et al. (2022), these studies have several limitations. For example, they do not fully account for the breadth of EGD policies, mostly neglect demand-side transformation resulting from changes in consumer behaviour and dietary patterns driven by complementary policies, and do not consider potential positive feedback effects on agricultural production arising from environmentally friendly practices and enhanced food system sustainability. Moreover, farming practices beneficial to both agricultural production and environmental aspects have largely been ignored. These

[5] For more details on the JRC portfolios see: https://joint-research-centre.ec.europa.eu/jrc-science-and-knowledge-activities_en

[6] Green Deal targets for 2030 and agricultural production studies: https://agriculture.ec.europa.eu/news/green-deal-2030-targets-and-agricultural-production-studies-2021-10-18_en

limitations have prompted calls for further research, model development and integration to provide a comprehensive understanding of the impact of EGD-related policies and initiatives on the agri-food sector.

The need for a comprehensive understanding of EGD impacts on the agri-food sector has been reinforced in the context of global economic disruptions caused by the COVID-19 pandemic and Russia's war on Ukraine. These events led to interruptions of trade flows and adverse consequences for the supply of key agricultural commodities and inputs. Their destabilising effects on global food systems particularly raised calls for assessing the EGD initiatives in relation to their possible impacts on food security considerations.

1.3 Scope of the report

The assessment of the EGD, its related policies, strategies and legislations, and the transition to more sustainable food systems pose complex challenges that require comprehensive and integrated approaches. Taking the iMAP perspective, the report provides an overview of needs and capacities for integrated modelling, in particular assessing which modelling needs can be covered by the current iMAP model suite, the gaps in model requirements that can be filled by further developing the current models, and what should be covered by additional models, tools and approaches to accompany and extend the analysis.

Focal points for the mapping of modelling needs and capacities concern specifically the CAP beyond 2022, climate change mitigation and adaptation, organic farming, pesticides use, biodiversity aspects, animal welfare, food waste and circular economy, dietary changes and health aspects, as well as international aspects. Accompanying aspects are also outlined, specifically the broader characteristics of food chain analysis and a better consideration of behavioural aspects of actors of both the supply and demand side. Each of the focal points is assessed in chapter 2 in consecutive subchapters, and chapter 3 provides conclusions.

2 Mapping of modelling needs and capacities

2.1 The CAP beyond 2022

Background and context

The new CAP legislation sets the framework for the 2023-2027 programming period. Aligned with the EGD, the new CAP aims to be a key tool to achieve the objectives outlined in the F2F and biodiversity strategies, and targets for GHG emissions mitigation. Focusing on social, environmental and economic goals, the new CAP is centred around ten key objectives: supporting a fair income for farmers, increasing competitiveness, improving farmers' position in the value chain, contributing to climate change action, fostering efficient management of natural resources, preserving landscapes and biodiversity, supporting generational renewal, fostering vibrant rural areas, protecting food and health quality, and promoting knowledge and innovation.

To meet the EU-level objectives, EU Member States (MS) implemented national CAP Strategic Plans (CSPs). Each CSP incorporates various targeted interventions that are supposed to be tailored to local conditions and specific national needs, and support the goals of the EGD. Within the so-called green architecture, MS have the flexibility to employ different tools, including enhanced conditionality, eco-schemes in the first pillar, as well as agri-environmental-climate measures in the second pillar. While conditionality encompasses mandatory good agricultural practices and legal requirements, eco-schemes and agri-environmental-climate measures are voluntary commitments that provide additional payments to farmers.

The CSPs combine a wide range of targeted interventions, categorised into:

- Direct payments, categorised into decoupled and coupled income support (CIS), with decoupled support further distinguished as: (i) Basic income support for sustainability (BISS), (ii) Complementary redistributive income support for sustainability (CRISS), (iii) Complementary income support for young farmers (CIS-YF), and (iv) Schemes for the climate, the environment and animal welfare (Eco-schemes).
- Sectoral interventions: paid to certain sectors (e.g., fruits and vegetables, apiculture products, wine, hops, olive oil and table olives).
- Rural development interventions, differentiated into eight main types of interventions: (i) Environmental, climate-related and other management commitments (ENVCLIM), (ii) Natural or other area-specific constraints (ANC), (iii) Area-specific disadvantages resulting from certain mandatory requirements (ASD), (iv) Investments, including investments in irrigation (INVEST), (v) Setting-up of young farmers and new farmers and rural business start-up (INSTAL), (vi) Risk management tools (RISK), (vii) Cooperation (COOP), and (viii) Knowledge exchange and dissemination of information (KNOW).

The individual CSPs are accessible on the DG AGRI website, together with a summary overview on the approved 28 CSPs (DG AGRI 2023).[7]

Modelling needs and challenges

The modelling of CSPs is essential to gain insights of their impacts on agri-food markets and the environment. The primary requirement for modelling CSPs is to gather and process the information on the measures implemented and the corresponding financial information and obligations that must be met to receive the payments. Once this information is processed, modelling the CSPs requires several key considerations, most prominently how measures may impact agricultural production activities and income (i.e., establishing a link from specific payments and requirements to production activities) and how they affect the environmental performance of the agricultural sector and contribute to climate change mitigation (i.e., by linking production activities and environmental and climate change-related indicators).

When modelling the CSPs, a first aspect to consider is that farmers receiving CAP payments are required to adhere to mandatory rules (standards) regarding Good Agricultural and Environmental Conditions (GAECs). In their CSPs, each MS applies nine GAEC standards across the EU, with some MS implementing an additional one. From a modelling perspective, the main considerations are how these GAECs may affect production levels, and their environmental and climate change-related impacts. With respect to the CAP payments, each MS has

[7] See https://agriculture.ec.europa.eu/cap-my-country/cap-strategic-plans_en. It needs to be noted that Member States amend and correct data related to their CSPs. Regular CSP updates are available at the Agri-food Data Portal: https://agridata.ec.europa.eu/extensions/DataPortal/pmef_indicators.html.

developed its own CSP, resulting in diverse MS-specific policy implementations. Variations in direct payment allocations and their linkages to production can affect agricultural activities and output differently across MS. While a production impact (in the sense of a coupling effect to specific crops and animals) is straightforward to establish for coupled support or sectoral interventions, methodological challenges arise especially in the modelling of eco-schemes and aspects of rural development payments. Such challenges concern the quantification of possible effects on production activities (levels), because even if an intervention has a primarily environmental target, it may impact (i) productivity (e.g., farm extensification schemes, organic production, fertilizer and nutrient reduction-schemes), (ii) land and animal allocation (e.g., due to restrictions on production systems or areas with high landscape diversity features), and (iii) production costs (e.g., payments related to a reduction of pesticides use can increase costs due to alternative pest control measures).

Modelling the CSPs is further challenged by the more country-specific policy implementations compared to the previous CAP. While this allowed MS to better address their specific needs, CSPs are quite diverse across MS, containing unique details, varying numbers and structures of interventions and, consequently, the planned unit amounts (i.e., the financial information) belonging to the interventions. This diversity of interventions and diversity across CSPs increases the information needs and complexity of the overall modelling approach, making the modelling more challenging.

Modelling capacities

By incorporating the specific elements and interventions of the CSPs into the iMAP models, insights of their impacts on agri-food markets and the environment can be gained, specifically regarding their potential effects on agricultural markets, farm incomes, land use patterns, environmental indicators (including GHG emissions), and overall sustainability. The iMAP modelling suite is well equipped to analyse the market impacts of the CAP and also the broader effects on environmental indicators, as the models were specifically developed for this kind of analysis. To effectively model the CSPs, the iMAP models need to update the broad CAP financial envelopes for MS and integrate the various CSP elements. While it is not necessary to depict every element of the CSPs in all iMAP models, a certain level of representation is needed in all models to reflect the latest policy and economic setup. However, the modelling of eco-schemes and rural development interventions requires more detailed information and interpretation (as outlined above) to ensure accurate representation. The heterogeneity across the CSPs can require case-by-case approaches, especially in the more detailed models IFM-CAP and CAPRI, whereas the other, more aggregated models may employ a summary or standardised approach instead of detailed scheme modelling. Regardless, comprehensive information and data on the interventions are crucial for modelling purposes.

Information and data requirements on the CSPs are very high due to the complexity and differences across MS. There are 28 single CSPs[8], each with its own set of interventions, planned unit amounts, obligations, etc. Although there is a common reporting structure for the CSPs, the information and data were submitted by MS in text format, i.e., the information is not readily available in harmonised data files. However, harmonised data files are essential not only for accessing the information needed, but also for achieving comparable modelling across MS. To address this, the JRC invested substantial time and effort in gathering the necessary information and creating a "Master file of the CAP Strategic Plans of the EU Member States" (Isbasoiu and Fellmann 2023). This comprehensive file includes information required for reflecting the CSPs in the models and for additional non-model related analyses. It encompasses information and data for the interventions and planned unit amounts (i.e., the financial information) related to direct payments (including basic income support, complementary redistributive income support, complementary income support for young farmers, eco-schemes, and coupled income support), rural development and sectoral interventions, as well as result indicators, GAECs, and minimum requirements. Constructing the CSP master file involved an in-depth examination of each of the 28 CSPs (which range from 460 to 3900 pages, and sum up to a total of almost 35000 pages). The file was started on the draft CSPs and completed in May 2023, incorporating the adopted CSP versions. The master file enables a harmonised reflection of the CSPs in the iMAP models, but with a total of around 2400 different interventions across MS and approximately 10300 Planned Unit Amounts across the EU (including around 8700 related to rural development payments), the volume and diversity of interventions require a step-by-step integration process into the models.

For the iMAP models, a two-step approach was decided for measures potentially affecting production levels. The first step involves updating the financial envelopes in the policy files of each model by linking them to the CSP master file. This process is finalised by the end of 2023, incorporating also considerations on GAECs and other

8 One CSP per MS, and two for Belgium (BE-Flanders, BE-Wallonia)

minimum requirements that impact production levels. The second step, the implementation of eco-schemes and rural development payments, is more challenging due to both the amount and diverse range of interventions and the methodological complexities. For this, the most important interventions in terms of uptake and production effects need to be singled out and considered in the models, a task that is expected to be completed at the beginning of 2024. Environmental impacts based on broader model results like changes in land use or production levels (such as GHG and LULUCF emissions) will then be available with the first modelling runs.

Environmental aspects dependent on specific technological (i.e., technical and management-based) farming practices are more time consuming and complex to be incorporated. Specifically eco-schemes and rural development interventions are often directly linked to farming practices. In the case of the iMAP models, this is relevant for CAPRI and IFM-CAP, as these models consider certain farming practices in detail. Again, information needs for these practices are immense and not readily available in data files. Therefore, in addition to the CSPs master file, the JRC conducted a detailed mapping of the planned unit amounts of the interventions provided in the CSPs to specific farming practices. Among others, the mapping entailed the challenge that the CSPs are submitted in the original language of the MS and English versions are only available as internal machine-based translations, sometimes prone to errors. To ensure accuracy, the mapping had to be verified and completed by JRC colleagues fluent in the original language in which each CSP was submitted, and in some cases by selected colleagues of the scientific community related to iMAP. The mapping includes substantial details on the farming practices, such as the planned unit amount attached to the practice, if a farming practice is mandatory or optional, and differentiations like basic and supplementary payments for additional commitments. The mapping file was finalised in June 2023, but verification processes are still ongoing. CAPRI and IFM-CAP will incorporate the mapped farming practices, prioritising those already reflected in the models and gradually including additional practices based on their importance with respect to production and environmental impact. For the incorporation of new farming practices in the models, it is essential to obtain additional data on their costs and environmental impacts. Within the framework of the administrative agreement with DG AGRI, the JRC conducted literature reviews to collect information on the environmental aspects of a large set of farming practices. While this information served as references when setting up the CSPs, for the integration of these practices into the CAPRI and IFM-CAP models it is necessary to gather further data on their costs and agronomic implications in a suitable manner. In addition, the JRC commissioned a study that collects cost information on certain farming practices, mainly by reaching out to extension services. The study is conducted to serve both CAPRI and IFM-CAP, and farming practices are systematically incorporated into the models as adequate information is accumulated. The following topic-specific subsections in this report provide more details on the capacities of the iMAP models to reflect CSP interventions targeting aspects of climate, environmental (including biodiversity, and reductions in fertilizer and pesticides use), animal welfare, and the food chain.

It needs to be highlighted that to achieve accurate modelling of the CSPs and their impacts, reliable data on intervention implementation in each MS is necessary, which particularly includes the uptake of the CSP measures by farmers. Accordingly, collaboration between policymakers, researchers, and data providers is essential to ensure data availability and quality for modelling exercises. Additionally, continuous monitoring and evaluation of the implemented CSP measures, combined with stakeholders' feedback can contribute to the refinement and improvement of the models over time. Considering that detailed data on farming practices applied by farmers is often missing, a successful conversion of the Farm Accountancy Data Network (FADN) into a Farm Sustainability Data Network (FSDN)[9] will be crucial to better understand and analyse environmental, economic and social aspects of farming practices.

[9] FADN monitors income and business activities of farms in the EU. It is an important source for understanding the impact of measures taken, under the CAP and other policies. Expanding the scope of the current FADN network to FSDN aims at collecting farm level data that is essential to understand also environmental and social aspects of farming practices. See https://agriculture.ec.europa.eu/data-and-analysis/farm-structures-and-economics/fadn_en

2.2 Climate change mitigation and adaptation

2.2.1 Climate change mitigation

Background and context

Emissions from the agriculture, forestry and other land use (AFOLU) sector, comprising the two UNFCCC reporting sectors "Agriculture" and "Land Use, Land Use Change and Forestry (LULUCF)", account for about 22% of global GHG emissions (IPCC 2022)[10]. Taking a broader view, food-system emissions are reported to represent about a third of total GHG emissions, accordingly two thirds corresponding to agriculture and land use/land-use change activities (Crippa et al. 2021). Therefore, rapid GHG mitigation in the AFOLU sector is considered essential for staying within the limits for reaching the 1.5°C target (IPCC 2022).

The 2021 EU European Climate Law set the target of at least 55% net emission reduction by 2030 compared to 1990, which in 2023 led to a revision of the EU's LULUCF Regulation. The regulation established the target of removing 310 million tonnes of CO_2eq by 2030 at EU level, also setting individual net removal targets for MS from 2026 onwards. Agricultural non-CO_2 emissions are covered by the EU Effort Sharing Regulation (ESR). While no specific mitigation targets are set for agriculture, considerable contributions are expected from the sector to achieve the overall EU mitigation target. For example, MS had to set their CSPs in line with the targets of the ESR and LULUCF regulation, with the CSPs specifically providing support for measures that contribute to GHG mitigation and enhance carbon sequestration in the sector (DG AGRI 2023, DG CLIMA 2023).

Modelling needs and challenges

GHG emission mitigation in agriculture can be achieved by three main approaches (Himics et al. 2020): reduction of production levels (e.g., less cows), implementation of technological options (e.g., precision farming), and changes in the composition or intensity of farming activities based on current management practices. As regards GHG mitigation and carbon sequestration in the LULUCF sector, approaches relate to managing land resources and vegetation cover (Nabuurs et al. 2022). In particular, technological (i.e., technical and management-based) mitigation and adaptation options can help diminish adverse effects on food production that may arise from mitigation efforts in the agricultural sector, which is why their development, transfer and adoption plays an important role to achieve AFOLU emission reductions and removals (Smith et al. 2014; Frank et al. 2019, IPCC 2022). For a comprehensive consideration of mitigation potentials and possibilities, agro-economic models need to accurately account for GHG emissions and relate them to production activities. Several modelling assessments underline that the general integration of agriculture into national and global climate change mitigation policy frameworks and strategies requires (i) a targeted but flexible implementation of mitigation obligations at regional, national and global level, (ii) consideration of a wide range of technological mitigation options, (iii) multilateral commitments for agriculture to limit emission leakage, and (iv) options that address the reduction in GHG emissions from the consumption side (Fellmann et al. 2018, Hasegawa et al. 2018, Frank et al. 2019, Nabuurs et al. 2022).

There are general challenges related to the accounting of emission mitigation and especially carbon sequestration. A general accounting for GHG mitigation in terms of changes in production levels is relatively straightforward. Mitigated emissions mean that even if a farmer increases emissions in the future, the benefits of past mitigation still prevail. Compared to this, carbon sequestration has the major limitation of potential reversibility and non-permanence of carbon stocks. For example, CO_2 storage through vegetation and soil management can be reversed and the sequestration benefits may be lost again. A further challenge is to account for specific contributions to GHG mitigation and carbon sequestration by technological mitigation options, which requires a detailed reflection of such technologies in the models (Smith et al. 2014, Nabuurs et al. 2022). Another general methodological challenge relates to the GHG emission metric used for methane emissions accounting. The commonly reported 'CO_2-equivalents' under IPCC rules are calculated using the global warming potential (GWP) 100, which does not account for how the relative impacts of different gases change over time. Methane emissions have a short atmospheric lifetime and their impacts rapidly decline after a few decades, while CO_2 emissions have a long lifetime and exert a relatively stable impact on global temperature over the long term.

[10] According to the Common Reporting Format of the UNFCCC, the source category 'agriculture' covers mainly the emissions of nitrous oxide and methane. Emissions (and removals) of carbon dioxide (CO_2) are reported separately under the category "Land Use, Land Use Change and Forestry (LULUCF). Moreover, CO_2 emissions related to energy consumption at farm level (e.g., in buildings and machinery use) or to the processing of inputs (e.g., mineral fertilizers) are attributed to other sectors.

Therefore, the relative valuation of methane to CO_2 is highly sensitive to the metric used, particularly its time horizon. The debate on the usefulness of alternative metrics is ongoing in the scientific community and the common IPCC reporting for methane remains the standard. However, it is well established that the impacts of methane emissions are different whether viewed over the shorter or longer term (Pérez Domínguez et al. 2021).

Modelling capacities

The iMAP models MAGNET, CAPRI and Aglink-Cosimo are equipped to directly account for GHG emissions related to agricultural production in the EU and at global level. In IFM-CAP, the estimation of the GHG emissions from each farm in FADN is currently under development. Especially MAGNET and CAPRI have been widely applied with JRC contribution for the assessment of GHG mitigation policies and potentials, often together in global multi-model assessments (e.g., Hasegawa et al. 2018, Van Meijl et al. 2018, Frank et al. 2019, Fujimori et al. 2022). For assessments focusing on GHG mitigation in the EU's agricultural sector, especially CAPRI has been employed in various JRC studies (e.g., Leip et al. 2010, Pérez Domínguez et al. 2012, 2016, Van Doorslaer et al. 2015, Fellmann et al. 2018, 2021, Himics et al. 2020). The wide adoption and application of iMAP models underscore their significance in the field of agro-economic modelling and climate change research.

As mitigation technologies can play a substantial role for mitigation efforts in the agricultural sector, DG AGRI and JRC initiated the project "Economic assessment of GHG mitigation policy options for EU agriculture" (EcAMPA) based on the CAPRI model. The primary objective of this project is to assess the potential of specific technological GHG mitigation options. Since its inception in 2014, the EcAMPA project has undergone continuous development and refinement (Van Doorslaer 2015, Pérez Domínguez et al. 2016, 2020, and forthcoming 2023). A key contribution of the EcAMPA framework is the comprehensive integration of endogenous technological GHG mitigation options in the CAPRI model. The methodology has undergone multiple refinements regarding the representation of mitigation technologies. Initially, the focus was on non-GHG emissions from agriculture. Subsequently, the model and approach were expanded to incorporate agricultural CO_2 emissions (and sinks) related to the LULUCF sector. This inclusion allows for the evaluation of LULUCF-related CO_2 emissions and removals, considering both GHG accounting and technological mitigation options. Analysis under the EcAMPA projects demonstrates that technological options need to be considered in combination (instead of simply summing up individual mitigation potentials), and regional heterogeneity of biophysical and economic circumstances need to be taken into account (Fellmann et al. 2021). By accounting for the intricate relationship between agricultural activities, GHG emissions, and technological options, the EcAMPA project provides valuable insights for policy-making and the development of sustainable agricultural practices. Moreover, CAPRI results for the technological mitigation potential can be used as input for the more aggregated iMAP models MAGNET and Aglink-Cosimo.

The implementation of further technological mitigation technologies is ongoing in the CAPRI model. However, a major effort is currently dedicated to connect already represented mitigation technologies with agricultural and environmental aspects beyond mitigation, which is essential to account for possible synergies and trade-offs in their application by farmers. As outlined in the section on the CAP, the efforts are taken for both CAPRI and IFM-CAP. Although not strictly a management practice, fallowing of histosols, which basically reflects stopping agricultural production activities on peatlands, is implemented in CAPRI as one of the most promising mitigation options in terms of GHG mitigation in agriculture. In EcAMPA 4, this option has been further refined, based on new peatland maps and also by including costs for peatland restauration, although for the latter, data on rewetting costs is scarce and has to be implemented in a pragmatic manner for the time being.

Another ongoing research activity across different JRC teams focuses on refining and improving existing methodologies for assessing emissions and removals from agriculture, including biofuel feedstocks, and a better accounting for emissions and removals from forestry and land use change in the EU. The activity specifically aims at the integration of multi-sectoral JRC modelling tools within a harmonised analysis framework to assess the AFOLU sector's emissions and removals consistently. The AFOLU framework builds on the respective strengths of different JRC models in the areas of agriculture, land use, forestry and energy. Active links are established between the CAPRI model, the Land Use-based Integrated Sustainability Assessment modelling platform for BioEconomy and Ecosystem Services (LUISA—BEES), the Carbon Budget Model (CBM) and the Policy Oriented Tool for Energy and Climate Change Impact Assessment (POTEnCIA).[11] Within this framework, main assumptions and boundary conditions of the selected specialised models are aligned, and the models are linked together to integrate the modelling inputs and outputs, and capture cross-sector dynamics. By doing so, the developed

[11] Detailed information on these models is provided in MIDAS: https://web.jrc.ec.europa.eu/policy-model-inventory/

framework allows for estimating the impacts of specific policies targeting emissions reductions in the entire AFOLU sector or parts of it, ensuring consistency across sub-sector boundaries. Additionally, the integrated modelling framework provides insights into the consequences of bioenergy consumption in the energy sector as a substitute for fossil fuels, thereby capturing the implications for the AFOLU sector. However, the AFOLU project also underscores some limitations and challenges in the integrated modelling of the sector. Integrating models across different spatial and disciplinary domains brings complexity and practical issues. Aligning models related to land use proves particularly challenging due to differences in their architectures, including benchmark and model-specific calibration databases, mapping of different categories, and differences in time or spatial granularity. Despite the complexities, the integrated modelling in the AFOLU project offers valuable insights for planning pathways towards climate neutrality. It helps to facilitate the implementation of integrated policy scenarios and enables a more comprehensive understanding of the interactions and dynamics within the sector (Sahoo et al. 2021, Barbosa et al. 2023).

2.2.2 Climate change impacts and adaptation

Background and context

Climate change has become a growing concern within the agricultural sector due to its potential medium- to long-term impacts on the global agri-food system. These concerns arise from the adverse biophysical effects resulting from changes in mean temperature, precipitation, and the impacts of climate extremes, which directly affect crop yields in terms of quantity and quality (EEA 2019, IPCC 2014, 2022). Notably, there is reliable evidence that climate change has detrimental effects on food and water security, impeding progress towards achieving the Sustainable Development Goals. Despite an overall increase in agricultural productivity, global growth has been slowed by the impacts of climate change over the past five decades. Negative impacts have been primarily observed in mid- and low-latitude regions, while some high-latitude regions have experienced positive effects. The pressure on food production and access is expected to rise as climate change progresses, particularly in vulnerable regions, leading to compromised food security and nutrition. Furthermore, the increasing frequency, intensity, and severity of droughts, floods, heatwaves, and rising sea levels will heighten the risks to agricultural production and food security (IPCC 2022).

One key aspect in the context of climate change and agricultural production is the availability of an adequate quantity and quality of water. Projections indicate that average precipitation rates will decrease in the Mediterranean region, while they will increase in Northern Europe (IPCC 2021). Moreover, a larger proportion of precipitation is expected to occur as heavy rainfall across most parts of Europe. In addition, an escalation in the frequency and intensity of extreme weather events is expected, particularly with respect to droughts and heatwaves (Toreti et al. 2019, Vogel et al. 2020, IPCC 2021). As the availability of water is becoming scarcer both in terms of time and location this will lead, together with higher temperatures, to increased irrigation requirements and water deficits (Gelati et al. 2020).

Modelling needs and challenges

For the assessment of climate change impacts on the agricultural sector, modelling analyses concentrate mainly on impacts on the crop sector. Implementing climate change-induced crop yield impacts into agro-economic models is necessary, because these biophysical yield effects can change considerably when considering price and trade feedback from global markets, as related market adjustments can result in significantly different net yield reactions reflecting farmers' production decisions (Nelson 2014, Hristov et al. 2020). In general, considering climate change-related biophysical yield shocks in the iMAP models is not particularly challenging once respective mapping procedures between the biophysical and economic models are in place. However, a more general challenge is that there are still many uncertainties in fully understanding and modelling climate change impacts in agriculture. One significant source of uncertainty can be the choice of which crop model to use, as crop models can have divergent responses (Müller et al. 2017). Moreover, inconsistencies in yield estimates derived from regional biophysical models can also arise because these models usually do not consider global agro-economic changes that may influence agricultural yields in the region of interest. An additional modelling need is to consider the impact of CO_2 fertilization on crop productivity (Toreti et al. 2020). Enhanced atmospheric CO_2 concentration stimulates photosynthesis and growth while reducing leaf transpiration. This so-called fertilization effect varies by plant species and growing conditions, and is more pronounced in C3 crops (e.g., wheat, barley, rye, rice, and soybeans) than in C4 crops (e.g., maize and sugarcane).[12] However, the overall effects of enhanced CO_2 fertilization on crops are still unclear and it can also lead to negative effects on the nutritional value of crops (Myers et al. 2014, Dong et al. 2018). Although the consideration of enhanced CO_2 fertilization increases the complexity of the modelling exercise and challenges in the interpretation of the results, the iMAP models can generally apply scenarios with and without enhanced CO_2 fertilization. Integrating water availability in the agro-economic models becomes more important in the context of climate change. It can be explicitly included in the production functions of the models or indirectly as yield shock in climate change scenarios when the underlying biophysical crop model already considers water availability and distinguishes yield impacts from rain-fed and irrigated areas. As the occurrence of extreme climate and weather events is expected to increase, including in key producing regions of the world (IPCC 2012, 2021, Toreti et al. 2019), related yield and production losses may need to be better quantified in current agro-economic modelling frameworks along with related adaptation measures (Chatzopoulos et al. 2020).

Despite the common practice of using climate change-induced yield shocks as input in various iMAP models, there are persistent methodological limitations and uncertainties that pose challenges in the development and testing of sustainable adaptation strategies within the agricultural sector. These challenges primarily arise from the use of different climate and crop models, variations in emission and warming scenarios, diverse assumptions regarding irrigated and rain-fed yields, and the consideration of enhanced atmospheric CO_2 concentrations under specific growing conditions. Adjustment of cost factors related to water prices and irrigation costs in the agro-economic models depends strongly on data availability, and like with other farming practices, the biggest challenge is also in this context to reflect irrigation as specific technical and management practice in detail. An additional challenge is an accurate modelling of the impacts of extreme weather and climate events. While advancements in the detection and attribution of extreme events have facilitated the assessment of their effects on productivity, fully incorporating and analysing them in agro-economic models, which typically focus on the medium- and long-term (rather than on single years or extreme events), remains challenging.

Modelling capacities

All iMAP models can generally be applied for the assessment of climate change impacts on crop production in combination with climate and crop growth models, with CAPRI and MAGNET being the ones frequently used in this context based on IPCC climate change scenarios. CAPRI was recurrently employed within several JRC projects related to PESETA (Projection of Economic impacts of climate change in Sectors of the European Union based on bottom-up Analysis) (Feyen et al. 2020), specifically focusing on the impacts at the EU regional level (e.g., Shrestha et al. 2013, Blanco et al. 2017, Pérez Domínguez and Fellmann 2018, Hristov et al. 2020, 2023). The JRC is also regularly involved with both CAPRI and MAGNET in global multi-model agro-economic assessments of climate change impacts, for example comparing impacts of climate change and mitigation (van Meijl 2018, Hasegawa et al. 2018). The JRC is an integral part of the Agricultural Model Intercomparison and Improvement Project (AgMIP)[13] global economics team, actively supporting the project with initiatives like AgCLIM50 (Challenges of Global Agriculture in a Climate Change Context by 2050; van Meijl et al. 2017).

Assessments done with agro-economic models (including iMAP ones) commonly use a combination of climate, crop growth and economic models, systematically integrating the results of the models to assess how agriculture responds to climate change. The approach commonly uses three steps: in the first step, general circulation models (GCMs) use representative GHG concentration pathways (RCPs), producing data on changes in climate variables such as temperature and precipitation. Thus, these climate scenarios produce the primary climate data for all biophysical models. In the second step, the climate results are incorporated into Global Gridded Crop Models (GGCMs) as inputs to simulate climate-driven biophysical yield effects. In the third step, these biophysical yield impacts are introduced in agro-economic models as exogenous yield shocks, which then can provide related impacts on agricultural production, trade, prices, consumption, income, and welfare (see Nelson et al. 2014 for a general explanation). In the recent past, iMAP model-related assessments mainly used climate scenarios and the crop model projections from the Fifth Assessment Report (AR5) of the IPCC (2014), but for future assessments the latest results of the IPCC's Sixth Assessment Report (AR6, IPCC 2022) should be used.

To address and assess uncertainties related to the crop model used, an innovative modelling approach was applied within the PESETA 4 project (Hristov et al. 2020). The approach was based on a new version of the WOrld

[12] C3 and C4 crops refer to two different photosynthetic pathways that plants use to fix carbon dioxide during the process of photosynthesis.

[13] AgMIP: https://agmip.org/

FOod Studies (WOFOST)[14] crop model (driven by 10 bias-adjusted regional climate models) and the Inter-Sectoral Impact Model Intercomparison Project (ISI-MIP, consisting of results from 35 global scenarios). The WOFOST model was adjusted at the JRC, and using these two approaches allowed to calculate a range of impacts in Europe with a relatively high accuracy, while uncertainty resulting from diverse models was more comprehensively calculated by the ISI-MIP model ensemble. Both WOFOST and ISI-MIP approaches consider irrigation and water availability as constraints. While these are fixed to historical averages in ISI-MIP scenarios, WOFOST can run scenarios with current agro-management as well as with simplified adaptation strategies (Hristov et al. 2020). However, when then using the biophysical crop yield effects as input for an agro-economic model (in that case CAPRI), in order to account for the feedback of agricultural markets, it leads to inconsistencies when using the adjusted WOFOST yield projections, because these projections are limited to Europe. As the market effects and related price effects are global, also yield projections from other parts of the world need to be considered, which is why global yield simulations like the ones from ISI-MIP or CMIP usually need to be used (Pérez Domínguez and Fellmann 2018, Hristov et al. 2020, Pérez Domínguez et al. 2023). Accordingly, the advantage of having a more detailed model for yield effects in Europe, and hence reducing uncertainties coming from the biophysical crop model used, may be lost if the underlying crop model does not consider all world regions equally.

With respect to water availability, the MAGNET model has a water module that attributes quantity of physical water use by the agricultural sector. The model is also prepared for implementing change (reducing or increasing) in the share of crop output that is irrigated and its impact on land productivity. The IFM-CAP model is currently further developed to include water as a production factor, including irrigation costs, and explicitly distinguishing between rainfed and irrigated production. The incorporation is scheduled to be finalised by mid-2024. The CAPRI model has an embedded water module which considers WOFOST data on crop specific irrigated (potential) and rain-fed (limited) yields, evapotranspiration, and irrigation efficiency. The CAPRI water module integrates detailed water considerations in the supply module at NUTS 2 level, and more recently it was also extended to the market module, i.e., towards non-EU countries or regional aggregates. For the EU, land is separated as irrigated (where water input can be supplemented with irrigation) and non-irrigable land (which only receives water input from precipitation). However, a limitation of the current approach is that expansion of irrigation is only considered on irrigable land (i.e., which is already equipped for irrigation), not on rain-fed land. Therefore, regions without irrigable land in the baseline will not have irrigation in a scenario. Scenarios can incorporate water costs or prices to reflect, for example, changes in water pricing policies or increased competition for water with other sectors. Irrigation water use is restricted to potential available water for irrigation at NUTS 2 level. While specific irrigation methods are not explicitly modelled, irrigation efficiency calculations consider coefficients for different methods. For livestock, water use includes both daily drinking and service water requirements. Moreover, through the water balance, the CAPRI water module also considers water demand competition between agriculture, households, industry and energy sectors. Thus, changes in water availability in the non-agricultural sector (introduced exogenously) will impact agriculture as the end user and trigger endogenous responses related to irrigated and rain-fed production activities. In addition, for agriculture different water sources for irrigation are considered (surface, groundwater, treated wastewater and desalinated). The CAPRI water projections draw inputs from other models, such as trends in irrigated and rain-fed yields from the biophysical model WOFOST and water balance trends from the LISFLOOD[15] hydrological and water use model (Blanco et al. 2015, 2018).

As regards assessing the impact of extreme climate and weather events, Aglink-Cosimo with its stochastic module is very suitable to be used for related assessments, whereas this is methodologically challenging with the other agro-economic models. Aglink-Cosimo was applied on various occasions to run simulations of single-year/single-country as well as concurrent and recurrent climate shocks (including extremes), showing that climate anomalies can significantly distort expected market developments while trade and stockholding can operate as important alleviative mechanisms (Chatzopoulos et al. 2020, 2021, Araujo Enciso and Fellmann 2020, DG AGRI 2022).

Like in the context of technological GHG mitigation options, specific technologies and management-based options also become increasingly important for the agricultural sector's adaptation to climate change.

[14] WOFOST is one of the key components in the JRC MARS crop yield forecasting system (MCYFS). This system is operationally used to provide end-of-season crop yield forecasts for Europe and neighbouring regions, and contributes to the global agricultural market information system (AMIS).

[15] The JRC LISFLOOD model was also used within several PESTA projects, although not in connection with iMAP models, as it is able to provide information on water resources as well as for climate change impacts on droughts and river flooding (Feyen et al. 2020). For further information see: https://midas.jrc.cec.eu.int/discovery/midas/explore/models/model-lisflood

Technological options, such as advanced seed varieties, precision farming and innovative irrigation systems, can play an important role in reducing severe impacts of climate change and extremes on food production (EEA 2019). Similar to GHG mitigation measures, also adaptation options interact and influence each other, and their overall effectiveness can only be fully understood when analysed in a combined manner considering regional or local circumstance. Furthermore, when assessing the application of adaptation technologies, their synergies, trade-offs, and co-benefits with mitigation efforts, as well as agronomical aspects should also be taken into account. In this regard, the CAPRI and IFM-CAP models are best suited for incorporating detailed information on adaptation technologies. However, it is currently not planned to specifically address technological options for climate change adaptation beyond irrigation in these models. Nonetheless, certain adaptation measures, such as the use of new seed varieties, do not need to be implemented specifically as new technological option, but can be accounted for as factors that help maintain or enhance yield potentials under climate change scenarios.

2.3 Organic farming

Background and context

Organic farming is getting increased attention within the EU's policy agenda. Under the F2F and biodiversity strategies, the EC has set the goal of at least 25% of the EU's agricultural land being under organic farming management by 2030. Organic farming is considered to be a concrete example for enhancing the sustainability of food systems. By promoting crop rotations, foregoing the use of synthetic pesticides and fertilizers, and concentrating on soil fertility and closed nutrient cycles, a wide range of literature highlights the positive environmental benefits of organic farming (e.g., Mäder et al. 2002, Mondelaers et al. 2009, Stolze et al. 2000, Meier et al. 2015, Reganold and Wachter 2016). Organic farming, however, has lower yields compared to conventional farming (Seufert et al. 2012), which implies that more land is required to produce the same quantity of output, which may jeopardize the environmental benefits (Tuomisto et al. 2012, Meier et al. 2015, Seufert and Ramankutty 2017). Moreover, relying mostly on manure leads to concerns of a possible nutrient undersupply in the production system (de Ponti et al 2012, Muller et al. 2017, Meemken and Qaim 2018).

Modelling needs, challenges and capacities

For the analysis of the 25% UAA under organic farming target, assessments have to take into account production effects, considering the yield gaps between organic and conventional farming. Moreover, positive impacts on the environment associated with organic farming practices need to be captured. In addition, following the EU's organic action plan, changes in consumer preferences and consumption patterns need to be incorporated if it turns out that consumers increasingly value organic products.

Regarding the impacts on overall production levels of agricultural commodities in the EU, it is necessary to establish the yield gaps between organic and conventional farming. Based on FADN data, the JRC recently estimated that the average yield gap between organic and conventional farms is 20%. This is consistent with results from major meta-analyses that report average yield gaps ranging from 19% to 25%, with considerable variability (De Ponti et al. 2012, Seufert et al. 2012, Ponisio et al. 2015). In line with the literature, the JRC estimates show substantial differences in the yield gaps across different crop types. Organic fruits and oilseed crops tend to have smaller differences compared to conventional counterparts, whereas larger gaps are observed in cereals and vegetables. These variations may be attributed to the better organic performance of perennial crops over annual crops, and legumes over non-legumes, with the FADN-based estimations showing an average yield gap of 15% for legumes and almost 29% for wheat. In addition, the literature points out that yield comparisons between organic and conventional farming are highly context-dependent, influenced by factors such as system characteristics, site conditions, and management practices. In summary, the yield gap between organic and conventional farming varies depending on crop types and management practices. Although organic farming generally exhibits lower yields on average, the differences are not uniform across all crops, with factors such as crop characteristics and pesticide use playing significant roles in shaping these yield disparities. Modelling approaches need to take these differences into account.

The new JRC estimations for yield gaps between organic and conventional farming provide a useful starting point for the iMAP models to conduct a more differentiated assessment of impacts on overall agricultural production levels in the EU. However, there are several ways to further refine the modelling approaches. In the absence of a distinct market for organic products in the models, three critical but common assumptions need to be made: Firstly, establishing price premiums that cover additional production costs of organic farming (such as certification costs) need to be established so that producers do make some additional profits from engaging in organic production. Second, all organic production volumes are sold on the conventional markets with price premiums, meaning the average prices of the corresponding domestic EU markets increase. Third, an increased preference for EU products needs to be assured by adjusting trade assumptions, for example the traditional Armington assumption regarding imports and exports.

An essential aspect of organic farming is its documented environmental benefits that come along with its farming practices. To capture these benefits, detailed modelling of respective farming practices is necessary. The CAPRI model already includes several farming practices that are important for organic farming, although the model does not yet distinguish between organic and conventional agriculture. An approximation could be achieved by considering an increase in the uptake of such practices relative to an assumed increase of organic farming. The IFM-CAP model is the only iMAP model that already has a specific representation of organic farming (as a specific farm type). As described in the CAP section, IFM-CAP is currently further developed to consider certain farming practices and connecting them to environmental impacts. By connecting farming practices to farm types, IFM-CAP will also be able to provide insights into environmental indicators related to increased organic farming in scenario analyses. The systematic integration of farming practices is an ongoing process, progressing as sufficient information is gathered.

Except for IFM-CAP, the iMAP models (and, to the best of our knowledge, other commonly used agro-economic PE or CGE models) do not explicitly distinguish between conventional and organic farming. However, given the current emphasis on organic farming in the economic and policy setup, also a close reflection of the organic sector in iMAP models seems to be required. To address this issue, DG AGRI and the JRC initiated a project that seeks a complete split between organic and conventional agriculture in the CAPRI model. Within this project, the JRC is working together with main CAPRI modellers across various institutions, and several tasks are underway to realise the implementation of organic farming into CAPRI. As already mentioned, so far, organic farming was neither treated as a separate activity from conventional farming nor an endogenous production practice with information on costs and yields. Thus, the first steps in this project involved the general technical preparation of CAPRI for the split, and the collection of data on organic farming in the EU. These technical preparations and data collection have already been done. With the collected data, an update of the entire CAPRI database needed to be established, specifically separating the activities into conventional and organic farming. The CAPRI database preparation and construction relies on a complex technical procedure that is executed in several steps and forms a bridge between raw data and their consolidation to impose completeness and consistency (Britz and Witzke 2014). Various adjustments in coding are required in nearly all CAPRI steps that lead to the established database.

The tasks necessary for a complete split of conventional and organic farming activities in CAPRI are manifold and complex. Currently, time series data on production activity levels and yield differentials for organic and conventional production activities have been implemented in the CAPRI database at the EU MS level. The regionalisation of the time series is prepared, including a full split of activity and related parameters for organic and conventional production at NUTS2 level. Further tasks are either under development or can only be started once preceding tasks are completed. For example, a model for introducing organic farming into the CAPRI fertilizer module is under development, as the split of production activities into organic and conventional also requires adaptation of the fertilizer distribution. Organic farmers cannot apply mineral fertilizers and must meet plant nutrient requirements using alternative sources, like manure, crop residues, biological fixation, and atmospheric deposition. This differentiation needs to be reflected in the fertilizer distribution and the respective equations of the CAPRI supply model. A split of variable costs and pesticides use between organic and conventional production also needs to be implemented, considering a separation at NUTS2 level as input costs differ. Additionally, modules relevant for building a calibrated base year, namely the feed distribution and PMP calibration, require updates. Feed ratios differ for organic and conventional animal activities, as for example, certain feeding components are not allowed in organic production. Therefore, a new concept is under development and data or estimates need to be collected for parameterisation. The feed distribution for organic and conventional livestock production activities needs to be implemented into CAPRI, and feed and fodder for livestock production must be distributed to livestock production activities at regional level, reflecting the requirement that feed for livestock under organic production must originate from organic production and, in addition, mainly from own (in case of CAPRI this means regional) production. The calibration of the CAPRI supply model needs to consider new parameters and equations from the fertilizer module, feed module and input module. An additional task is to split and update CAP payments: it involves implementing necessary adaptations of the CAP premium module to explicitly link premiums for organic farming to the organic production activities.

The CAPRI developments so far only focus on the supply side of organic farming, which is most important in order to reflect production and associated environmental aspects. However, eventually also the market side should be specifically considered. Therefore, a feasibility assessment is foreseen to evaluate the options and achievability of implementing organic production and commodities into the CAPRI market module. This assessment should cover aspects such as data availability and possibilities for the adjustment of price elasticities, demand, international trade, and baseline calibration.

In summary, especially developments in CAPRI and IFM-CAP aim to provide a comprehensive reflection of production and environmental aspects of organic farming. Once established, the modelling output generated by the two models can serve as input for other iMAP models or additional tools for further assessments, including biodiversity aspects. However, a challenge remains in appropriately reflecting consumer reactions to increased supply of organic products. The organic action plan outlines specific action points in this regard. Nevertheless, the extent and timing of consumer shift towards organic products are still largely uncertain. Close monitoring and data collection from consumer surveys or behavioural experiments are essential for gaining a sound understanding for the reflection of the demand side related to organic commodities.

2.4 Pesticides use

Background and context

Pesticides have proven to be effective in preventing yield deficits and ensuring yield stability, thus contributing to food security. While pesticides serve a positive function as damage control agents, their (mis)use can also result in unintended consequences, especially regarding environmental and human health impacts. Pesticide residues have been detected in soils, surface water, groundwater, non-target plants, food and feed, animals, and humans (Aktar et al. 2009, Köhler and Triebskorn 2013, Popp et al. 2013, Carvalho 2017, Sharma et al. 2019, Silva et al. 2019, La Porta et al. 2021, Edlinger et al. 2022). However, it is important to note that instances of pesticide residues exceeding legal limits in food products are rare in the EU (Carrasco Cabrera and Medina Pastor 2022). In response to societal concerns surrounding pesticides use, one of the main goals of the F2F strategy is a 50% reduction in the use and risk of chemical pesticides and a 50% reduction in the use of more hazardous pesticides by 2030. The same target is also set at a global level by the Kunming-Montreal Global Biodiversity Framework (GBF) adopted by the UN Convention on Biological Diversity (2022). The EC proposal for the Regulation on the Sustainable Use of Plant Protection Products (SUR) establishes these targets at EU-level and the relative contribution of each MS to the global targets, but individual MS have to design own reduction plans to achieve the target. This may ensure that the EU-wide target is met while considering the specific capabilities and historical developments of each MS.

As regulating pesticides application is considered a key pathway to promoting biodiversity and achieving a more sustainable food system in Europe, food system modelling approaches need to assess the related impacts, adequately reflecting pesticides use and the linkages to food production but also functional biodiversity. Moreover, pesticides reduction can be achieved by the adopting of targeted technical and management-based farming practices, aligned with the principles of Integrated Pest Management (IPM). The integration of novel technologies, including precision agriculture and New Genomic Techniques (NGT), alongside advancements in IPM practices, organic farming, agro-ecology, and nature-based farming practices, is anticipated to facilitate the shift towards decreased reliance on pesticides. These innovative strategies offer potential solutions for achieving sustainable pest management and reducing the overall dependency on chemical inputs in agricultural systems.

Modelling needs, challenges and capacities

Most agro-economic approaches for modelling a reduction in pesticides use in the context of the EGD so far focused on the possible impacts on yields reduction, under the assumption that expenses for plant protection products are a sound proxy of pesticide use. However, these approaches may not accurately reflect the real production impacts, particularly when generalised across different crops and areas, and without considering alternative technical and management options. Crucially, such approaches usually do not account for the potential positive effects associated with pesticides reduction on biodiversity, which could partially offset yield losses resulting from reduced pesticides application. Although economic models readily incorporate changes in expenses (i.e., an assumed reduction in cost due to reduced pesticides use), there is a lack of an accurate yield response function to effectively assess the impact of reduced pesticide use on crop yields. Consequently, general assumptions on yield losses are made (e.g., 10% across all crops and areas in Barreiro-Hurle et al. 2021a). However, such general assumptions lack robust evidence and do not account for potential variations across different crops and bioclimatic regions. Furthermore, the general assumptions do not incorporate alternative strategies that can mitigate pests and without necessarily resulting in yield losses (Barreiro-Hurle et al. 2021a, Schneider et al. 2023). The JRC undertakes substantial efforts to improve its modelling capacities within the iMAP framework in order to address the need for a better and more comprehensive modelling of pesticides use and hence improve the assessment of pesticides reduction.

Challenges for a comprehensive agro-economic modelling and assessment of pesticides use (reductions) arise due to various aspects, among others the wide range of biological, agronomic, economic, and social factors that determine the use of pesticides by farmers, as well as due to uncertainties regarding which approaches MS will pursuit in setting and achieving reduction requirements. Pesticides use intensity depends on many aspects, including: (i) biological factors, e.g. pest abundance, local climate, soil type, and regional crop diversity, (ii) agronomic factors, such as choices regarding tillage, sowing date, plant variety, fertilisation, and crop rotation, (iii) economic factors, e.g. expected yield, on-farm economic condition, and financial situation, and (iv) social, as well as political, factors (Schneider et al. 2023). The multitude of relevant factors results in a considerable spatial heterogeneity in pesticides use, possible mitigation strategies and accordingly in a variation of potential impacts of a reduction in pesticides use, which needs to be reflected in sound assessments.

A particular challenge also arises from the flexibility that MS have in reaching reduction requirements. The F2F targets for pesticides reduction are established at EU-level, and the Sustainable Use Regulation requires that MS will set their own national reduction targets within defined parameters to ensure that the EU wide targets are achieved, but the MS have the flexibility to establish their own national targets. The heterogeneity in current pesticides use and economic conditions across MS will likely result in a diversity of national strategies to meet pesticides reduction requirements. While this allows MS to tailor approaches according to the specific circumstances of their national agricultural sector, it makes an accurate ex-ante impact assessment of the F2F pesticides reduction targets challenging without data on pesticide use across crops and regions. It seems likely that different crops will be affected to varying degrees across MS. It should be also mentioned that this implies that the overall impacts on agricultural production will be quite diverse across MS, spread across different commodities, and could in turn result in lower overall impacts than those assumed in initial studies attempting to assess the pesticides reduction targets at EU level.

Specific technologies and farming practices can help in reducing pesticides use. Accordingly, a selection of important farming practices would need to be considered within the iMAP framework to reflect their impact on pesticides reduction, as well as changes in operational costs associated with implementing these practices. In particular integrated pest management (IPM) is considered an important approach for reducing pesticides usage is. IPM encompasses a comprehensive set of practices that consider all available methods of plant protection. It involves the integration of appropriate measures that deter the development of harmful organisms while maintaining the use of plant protection products and other interventions at levels that are both economically and ecologically justified, and reduce or minimise risks to human health and the environment. IPM relies on eight principles, related to prevention and suppression, monitoring, decision-making based on monitoring and thresholds, non-chemical methods, pesticide selection, reducing pesticide use, and preventing pesticide resistance.[16] The project "Farmer's toolbox for integrated pest management practices from across the EU", commissioned by DG AGRI, provides background knowledge on the most promising ways for scaling up the reduction of the dependency on pesticides use across the EU. The corresponding report also provides a comprehensive description of the main drivers and barriers for the full uptake of IPM practices (Arcadia et al. 2022). As part of the project, a database with IPM practices, techniques and technologies, and with crop- and sector-specific IPM guidelines currently developed in the different MS was created. The JRC developed a visualisation tool on the iMAP-related DataM platform, where stakeholders can search for IPM documents developed in the different MS for specific crops or crop groups.[17]

The IPM toolbox provides valuable information and insights on IPM, which can also be used for the inclusion of respective management practices in the iMAP framework. However, in the toolbox a total of 273 IPM guidelines and 1342 IPM practices are listed, which indicates the complexity, vast possibilities and alternative options IPM provides. For an implementation of some of the technological options associated with IPM within agro-economic models, the most important options would need to be selected, preferable also considering their synergies with other agro-economic benefits in terms of production impacts as well as further environmental benefits. This link could indeed be established in CAPRI, as the model already reflects a wide range of technical and management-based farming practices, and since recently also features a pesticides module, albeit a connection from farming

[16] For more information see Arcadia et al. (2022) and DG SANTE's IPM website: https://food.ec.europa.eu/plants/pesticides/sustainable-use-pesticides/integrated-pest-management-ipm_en

[17] Farmer's toolbox for integrated pest management practices from across the EU: https://datam.jrc.ec.europa.eu/datam/mashup/IPM/

practices to pesticides use is not (yet) established. Leveraging synergies between pesticide reduction and other goals, such as nutrient management and soil conservation, can lead to more effective adoption of management practices, although there are also potential trade-offs in terms of reaching different policy goals. For example, soil conservation practices generally have positive effects on pest pressure and pesticide requirements, but challenges may arise, such as the difficulty of replacing chemical weeding with mechanical systems in minimum/no-tillage soil management. Synergies also exist between the pesticide reduction targets and nutrient loss reduction goals, which can ultimately lead to reduced fertilizer use. Digital and precision farming, involving the use of new tools, real-time data, and smart farming techniques, offer opportunities to achieve pesticides reduction targets while also aligning with other ambitions of the EGD in addressing climate, environment, and health targets.

In general, a detailed and adequate reflection of pesticides use allows to more realistically simulate future policy scenarios, and hence better prepare for any potential consequences lower pesticides use may entail. Not all iMAP models are equally suitable to model pesticides use in detail. While models like Aglink-Cosimo, MAGNET and AGMEMOD may have to rely on simplified assumptions regarding yield impacts when modelling reductions in pesticides use, CAPRI was considered as suitable for a more comprehensive reflection of pesticides use, mainly due to its detailed reflection of production activities at regional level. Accordingly, since 2019 the CAPRI model undergoes model developments for a detailed inclusion of pesticides use. The developments so far have been implemented in two phases, with the first phase being mainly exploratory and to establish a feasible approach for pesticides modelling, and the second phase aiming at further refining the approach and also establishing links between pesticides use (reduction) and biodiversity.

In the first phase of the CAPRI pesticides project, pesticides application was incorporated into the model taking into account five macro pesticides groups: insecticides, herbicides, fungicides, growth regulators, as well as a category 'other' (capturing all remaining products). To address questions on production and possible impacts on food security when less pesticides are used, a link between the use of pesticides and yields was implemented through a damage avoidance function. This function feeds the model with the necessary information on changes in crop yields following changes in pesticides used. Although the damage avoidance function is based on expert knowledge, and relates to observed data on the yield gap between organic and conventional farming, it certainly remains a simplification, partially because pesticides are represented only through the five macro groups specified. Furthermore, certain assumptions had to be made when deriving the yield impacts related to pesticides use from the data capturing the observed yield gap between organic and conventional farming. However, one of the main advantages of modelling pesticides at the aggregated group level is the availability of data with respect to usage by MS, reported in FAOSTAT and Eurostat.

The modelling capabilities of CAPRI with respect to pesticides were further extended within a subsequent project launched at the end of 2021. In the second phase of the project, a database consolidation of the regional pesticide use quantities of the five pesticide groups from different reporting sources (such as Eurostat and FAOSTAT) was performed to have one consistent database of pesticide applications differentiated by crop and NUTS2 region. To implement specific modelling capabilities for active substances (AS), an econometric approach was chosen, to derive prices of AS from pesticide products sold across the EU. However, given the lack of officially published statistics on pesticides prices, this approach could only be established based on price information published by private sellers and other unofficial and non-representative information. Despite this limitation, a plausible differentiation is expected to strongly improve the empirical content of pesticide modelling in CAPRI. Related model developments are expected to be consolidated by the end of 2023. Results from applying the CAPRI model to specific pesticides use-related scenarios can serve as input information to adjust other iMAP models for their scenario analysis.

A specific objective of the second phase of the CAPRI pesticides project was also to establish a relationship between pesticides use and biodiversity considerations. An essential aspect of reducing pesticides usage involves the positive impacts it can have on biodiversity. To adequately incorporate the linkage between pesticides and biodiversity in agro economic models, at least two aspects need to be accounted for. Firstly, indicators that capture the impact of pesticide reduction on biodiversity ingest data specific to AS, i.e., the chemicals in a pesticides product that act to control the pest and whose toxicity levels to various groups of living organisms are reported. Secondly, the potential positive feedback loop of improved biodiversity on yields, with biodiversity promoting, for example, natural pest control and pollination, and hence supporting yields, should also be considered. The JRC assessed various approaches for a detailed modelling of pesticides use at AS level and its connection to indicators, evaluating their utility, robustness, and the feasibility for implementation in iMAP models.

The Harmonised Risk Indicators (HRIs) for pesticides seemed to be relevant indicators for modelling, as they are used for monitoring the EGD target on pesticide reduction. HRI 1 is calculated based on sales per AS, incorporating a weighting factor that depends on the risk classification of each AS. HRI 2 is based on the number of emergency authorisations granted. Especially HRI 1 gives an indication of trends in risk reduction, but a decrease in HRI 1 could primarily be the result from reduced sales of substances in the category 'not approved' (ECA 2020). Accordingly, progress towards the pesticide reduction targets of the F2F strategy could be achieved without impact on approved AS, which in turn also may mean less impact of the targets for agricultural production, but still with environmental and social benefits. The rationale behind the weighting of AS into different risk categories lies in the recognition that more hazardous substances generate more severe externalities and, therefore, warrant prioritisation in reduction strategies. Accounting for the toxicity of substances is essential because relying solely on quantities can unintentionally incentivise a shift towards more toxic AS that can be applied in smaller amounts, thereby increasing the toxic burden on non-target organisms, i.e., increasing risks to the environment and human health (Schulz et al. 2021, Cech et al. 2022, Bub et al. 2023). This also exemplifies, why a detailed modelling at AS level is necessary. The HRI provides a general indicator for the overall trend in risk, but it does not give a clear indication on which AS to concentrate, for example when the focus is on biodiversity.

As mentioned above, for a comprehensive assessment that covers impacts on production and biodiversity, it is necessary to connect each AS to both its production and biodiversity effects. Both impacts are AS-specific, which means that when reducing the use of one AS, it is crucial to also account for the impacts of its potential substitutes that farmers may choose to apply instead. This is particularly important to avoid the aforementioned unintended consequence of substituting one AS with others that have higher toxicity to non-target organisms, potentially exacerbating the negative effects on biodiversity. Modelling specific AS, therefore, requires in-depth knowledge of the agronomic and biodiversity effects not only of the AS under consideration but also its potential substitutes (which, depending on the pest, can be manifold). While the JRC managed to extract data on biodiversity-related toxicity impacts of AS, limited data on AS use, the need for extensive knowledge of agronomic aspects, and computational constraints related to the model infrastructure limit the ability to assess all AS at the same time. Given the limitations associated with a comprehensive assessment of pesticides use, the JRC decided that for the future policy process it may be most useful to develop an approach that enables the CAPRI model to provide information on production and biodiversity impacts on a case-by-case basis. This approach would for example involve assessing the impact of banning or reducing specific AS as individual case studies.

Following the before mentioned considerations on pesticides use and biodiversity, the JRC improved an existing, and implemented an additional, biodiversity indicator linked to pesticides use in the CAPRI model. To identify a suitable indicator that can be implemented in CAPRI, the JRC reviewed literature and subsequently decided to assess the impact of pesticides on biodiversity by applying the pesticide load index (PLI) and toxicity levels associated with one or multiple AS, operational for case studies. The PLI, as well as its integration into an existing biodiversity indicator, is explained in the following biodiversity section. Additionally, the JRC explored possibilities to consider potential positive feedback loops between improved biodiversity and yields. These feedback loops have the potential to mitigate production impacts that may be related to pesticides reduction. The case study conducted focuses on the quantification of agricultural production benefits of natural pest control potential provided by landscape features in the context of a scenario with reduced pesticides use. The case study is also briefly explained in the biodiversity section.

It is important to note that modelling pesticides is certainly a multi-disciplinary exercise, as pesticides affect human health, environmental fate, biodiversity, and agricultural production. While it is challenging to capture all these elements within a single model, it is important to acknowledge their significance and strive for the most comprehensive analysis possible. In this respect, the new JRC portfolio structure enables more effective collaboration between different teams dealing with agricultural production, pesticides, health, and biodiversity. Moreover, close collaboration with colleagues of DG AGRI, SANTE and ENV can also support model integration and development.

Finally, to conduct comprehensive analyses, reliable data on pesticide use is essential. This includes detailed information on the types of pesticides used, application rates, timing, and frequency of application. However, current data collection efforts, such as those conducted by Eurostat, suffer from fragmentation and limited coverage. As a consequence, the CAPRI approach needs to compute data for certain MS-crop-pesticides combinations, e.g., based on EU averages for application rates. There is a pressing need to improve data collection methods to provide a comprehensive and detailed understanding of actual pesticide use. Efforts are underway to address this issue through the revision of the European agricultural statistics system and the proposed new framework regulation for agricultural input and output (SAIO). Moreover, valuable additional information, including on relevant farming practices and IPM, could be provided in the context of the conversion of FADN into a Farm Sustainability Data Network (FSDN).

2.5 Biodiversity and soil health

This section provides information on the context, needs and challenges of considering biodiversity aspects in iMAP-based modelling as well as concrete examples of the capacities to take into account biodiversity in the assessment. In addition, context and capacities specific to soil health modelling are described at the end of this section.

Biodiversity

Background and context

The relationship between agricultural production and biodiversity is complex and multifaceted, with important implications for conservation and sustainable development efforts. Agricultural production systems can put significant pressure on biodiversity, primarily through land use change and management as well as unsustainable intensification (in particular through intensive fertilizer and pesticides use), which lead to simplified agricultural landscape structures and a loss in biodiversity (Ramankutty et al. 2018, IPBES 2019, Sánchez-Bayo and Wyckhuys, 2019, Wagner 2020). Biodiversity plays itself an important role in supporting agricultural productivity through various mechanisms. Natural pollinators, such as bees and butterflies, help pollinate crops, improving yield and quality. Predatory insects and birds help control agricultural pests, reducing the need for synthetic pesticides. Soil biodiversity, including earthworms and microorganisms, supports nutrient cycling, soil fertility and crop yields. Biodiversity in agricultural landscapes also contributes to ecosystem resilience, reducing environmental disturbances, and improving the long-term sustainability of agricultural systems (Liquete et al. 2022).

Sustainable management and use of biodiversity, including valuing, maintaining and enhancing ecosystem functions and services, are among the long-term goals of the Kunming-Montreal Global Biodiversity Framework adopted by the UN Convention on Biological Diversity (2022). Likewise, the EGD sets targets for nature restoration and biodiversity conservation. Moreover, in the new CAP, the biodiversity vocation is detailed in three specific objectives (article. 6 of the CSPs regulation): to contribute to halting and reversing biodiversity loss, enhance ecosystem services, and preserve habitats and landscapes. However, there is still a knowledge gap on how the policies and targets will impact on biodiversity and how biodiversity improvements may positively impact on crop yields and agricultural production (i.e., via a positive feedback-loop on crop yields).

Modelling needs and challenges

Scenarios and modelling approaches are valuable tools for analysing the interplay between potential trajectories of drivers, policy interventions, and their impacts on biodiversity and ecosystem services (IPBES 2019, Nicholson et al. 2019, Rosa et al. 2020). Modelling biodiversity aspects requires consideration of both ecological and economic factors, yet synergies between agricultural production and biodiversity are usually not explicitly reflected in agro-economic models (including the iMAP models). Accordingly, there is a need to develop integrated methodologies to provide insights of the EGD objectives and CSPs regarding biodiversity conservation. Two aspects have to be considered in this context. One is the provision of biodiversity indicators, which provide information on impacts of changes in policy and farming practices on biodiversity. The second aspect concerns the consideration of positive feedback loops between biodiversity and crop yields that may come with enhanced biodiversity.

The major challenge for modelling biodiversity aspects is that biodiversity is a complex and interconnected system, with many species, habitats, and ecological processes interacting at various spatial and temporal scales. Aspects of biodiversity are highly context-specific, and spatial scale and heterogeneity are key considerations in biodiversity modelling. Policies can have different impacts depending on the spatial context, and biodiversity patterns often show spatial variations. Accordingly, approaches for modelling biodiversity aspects need to account for spatial heterogeneity, incorporating fine-scale data and considering the spatial dynamics of species dispersal, habitat fragmentation, and landscape connectivity. Scaling-up approaches can then bridge the gap between local processes and regional or global policy assessments, which is especially relevant for the use in the iMAP models. A prerequisite for modelling biodiversity and policy impacts is to have accurate and comprehensive data on the current state of biodiversity and the potential impacts of various policies as well as management techniques on biodiversity. This requires the integration of data from multiple sources and resolution, including field surveys and remote sensing. A challenge in this context is the loss of high-resolution information when integrating into coarser (e.g., NUTS2) agro-economic models. This is currently applied and tested with two iMAP models for several specific aspects (see examples below). Further challenges arise from data gaps, inconsistencies, and accessibility issues. Advances in remote sensing and data integration techniques, machine learning and big data analytics, provide opportunities to enhance availability and quality of biodiversity data for modelling purposes. A need as well as a challenge is that modelling biodiversity requires multidisciplinary collaborations among ecologists, economists, and social scientists. Such collaborations between different disciplines and teams in the JRC are facilitated by the new JRC portfolio structure.

Modelling capacities

Bearing in mind the challenges outlined above associated with the context-specific nature of biodiversity aspects, as well as data availability and scalability, establishing biodiversity indicators can be relatively straightforward under two conditions: (i) if standardised and generic data is available, and (ii) if the indicators can be directly linked to broader aspects, such as (pressures from) land use and land use change, which are commonly included in the standard reporting of agro-economic modelling outcomes. However, establishing a direct link between biodiversity indicators and specific land management and farming practices presents greater challenges, as this requires explicit modelling of these practices and detailed knowledge of their impact on biodiversity. Among the iMAP models, only CAPRI incorporates specific technical and management-based farming practices, while IFM-CAP is currently developed in this direction. Regarding the broader impacts of agricultural production and land use on biodiversity, both the CAPRI and MAGNET models include biodiversity indicators. With respect to accounting for positive feedback loops on yields, the CAPRI model is undergoing further development to assess associated impacts. The specific biodiversity indicators available in iMAP models as well as a current case study for assessing positive yield impacts resulting from enhanced biodiversity are briefly outlined below. Especially the case study showcases the ability to integrate remote sensing data and its appropriate scaling for consideration in the iMAP models.

Case study for the consideration of positive feedback loops between biodiversity and crop yields

The JRC currently conducts a case study on the integration of positive feedback loops between biodiversity and crop yields into assessments conducted with iMAP models. Biodiversity aspects are manifold and positive feedback loops on crop yields can come from various mechanisms. However, as the positive impacts are context-specific and vary depending on the specific biodiversity service provided and local circumstances, generic quantifications of the positive yield impacts are typically not available. Consequently, the generic data needs to be created. The case study conducted by the JRC concentrates on the quantification of agricultural production benefits of natural pest control (NPC) potential provided by landscape features (LF), referred to as LF-NPC potential. NPC is provided by natural enemies (such as predatory insects, parasitoids, and birds) and can reduce reliance on synthetic pesticides while fostering yield stability (Sutter et al. 2016). In agricultural systems, NPC can be promoted through landscape features, i.e., small areas of natural or semi-natural vegetation within an agricultural landscape that increase landscape complexity (Rega et al. 2018, Czúcz et al. 2022). For the assessment, yield observations derived from FADN are combined with a map of the EU's LF-NPC potential at 100-meter resolution, derived by combining high-resolution geospatial layers, provided by the Copernicus Land Monitoring Service[18], with extensive field surveys of insects, flying predators and parasitoids (Rega et al. 2018). First, the regional yield gaps between organic and conventional farms that are attributable to differences in synthetic pesticide use are estimated for several crops. Second, it is assessed whether regions with higher LF-NPC potential exhibit a lower yield gap due to the greater likelihood of natural enemies providing the ecosystem service of NPC. Finally, to evaluate the economic implications of LF-NPC potential, the CAPRI model is parametrised to simulate the EU agricultural sector in 2030 taking into account a reduction in pesticides use and the previously estimated yield gaps, which are a function of the landscape complexity in the NUTS 2 regions. The computed income under the simulation provides an estimation on the financial benefits of LF-NPC potential for farmers (regions). The estimations and modelling runs are finalised and a related paper is currently under scientific review to validate the scientific soundness of the approach (Klinnert et al. forthcoming).

[18] Copernicus is the EU's Earth observation programme, which provides information through six thematic services: land, marine, atmosphere, climate change, emergency management and security, see https://land.copernicus.eu/

The impact of specific farming practices on biodiversity

As outlined in the section on the CAP, the CAPRI model considers specific technical and management-based farming practices in relation to their production and environmental impacts. The implementation of certain farming practices in IFM-CAP is ongoing, whereas the other iMAP models do not reflect specific farming practices in detail. It is planned to implement further farming practices that could positively impact biodiversity into CAPRI during 2023 (and eventually also into IFM-CAP). Based on literature reviews conducted by the JRC for AGRI, environmental impacts of certain farming practices were collected. However, the information from literature reviews regarding their impact on biodiversity is very limited. For example, data was gathered on the impact of hedgerows, field margins and flower strips on pollinators, but there is neither an indicator in CAPRI on pollinators nor exists reference data. Similarly, the literature reviews provide data on species richness related to field margins, hedgerows and fallow, but CAPRI does not have an indicator for species richness nor exists an official indicator on this that could be used as benchmark. Likewise, impacts of some grazing and grassland management practices (but also other farm practices, like winter cover, etc.) on different biodiversity metrics are known, but the respective official reference data and biodiversity indicators in CAPRI are missing. The development of new biodiversity indicators, which might be linked to these metrics found in the literature reviews, is currently not in preparation for CAPRI basically due to the lack of official reference data. If respective data becomes available, it can be incorporated in the below mentioned BFFP index.

Biodiversity indicators

For iMAP models, considering biodiversity aspects is mainly based on the modelling output, i.e., the scenario results are used to calculate biodiversity indicators. In the following, biodiversity-related indicators available in the iMAP modelling suite are briefly outlined. As biodiversity is very context-specific, CAPRI is the model that can provide the most detailed information to be related to biodiversity impacts. Accordingly, past and ongoing model developments on this topic concentrate mainly on CAPRI.

Farmland Bird Index (FBI). Indices of bird populations have been recognised as indicators of the health of wildlife in the countryside, due to the birds' position near the top of the food chain, their visibility and relative ease to be monitored. Land-use change, unsustainable agricultural intensification (including intensive fertilizer and pesticides use, and decline in landscape heterogeneity), biodiversity resource exploitation, and climate change are among the main pressures driving avian biodiversity decline (Howard et al. 2020, Lees et al. 2022, Rigal et al. 2023). The Farmland Bird Index (FBI) identifies farmland bird trends and uses these trends as a proxy for the wider biodiversity health of farmlands (Gregory et al. 2005, 2019). Using the FBI in the assessments of policy scenarios requires linking bird abundances to relevant agricultural variables available in the modelling environment. In CAPRI the FBI is embedded by finding the relation (expressed through a set of mathematical functions) between changes in farmland bird populations and changes in agricultural indicators available in CAPRI. In the current version, the FBI in CAPRI reacts basically to changes in yields, nitrogen input, land use and livestock. The parametrization of the approach is done by using data from the Pan-European Common Bird Monitoring Scheme [19]. The first implementation of the FBI was based on monitoring data up to 2013, but seven EU MS and also six bird species needed to be excluded from the econometric estimation because the time series were not long enough for the parametrization, eventually affecting the bird abundance prediction. The extension of time series (as data input for the estimation) and the inclusion of pesticides (apart from nitrogen input) and a more suitable livestock indicator (livestock density unit) as explanatory variables is currently tested. While the approach generally allows modelling the FBI in scenario assessments, the JRC is also currently validating its robust- and soundness, for example by testing to which magnitude of changes the FBI is responding, and also what message the macro-level is providing compared to the regional level with respect to farmland bird abundance. Depending on the results of the validation exercise, the JRC will determine if the FBI is sufficiently sound for using it in official policy scenarios.

The **Shannon index**, a diversity index on land use, crops and land allocation (serving as a proxy index for biodiversity), is applied in the IFM-CAP model and, hence, is operational at farm level (Kremmydas et al. 2022). The Shannon index is also implemented in CAPRI and can be used at NUTS 2 level. It has to be kept in mind that the absolute value of the Shannon index at the level of a NUTS 2 region has a different meaning than the Shannon index on farm level. The farm level index calculated by IFM-CAP is used as input in CAPRI to represent the impact of crop rotation at regional level.

[19] Pan-European Common Bird Monitoring Scheme: https://pecbms.info/

The **Biodiversity Friendly Farming Practices (BFFP) index** in CAPRI is an index that represents the production intensity effect on biodiversity (Paracchini and Britz 2010). The BFFP index was recently further developed as post model reporting and introduced in the supply module of CAPRI also as constraint during the profit maximization. This allows to run scenarios at NUTS 2 level where a minimum condition or biodiversity target is imposed on the BFFP index, affecting the crop allocation during the optimization process. In general, the implemented BFFP index describes to which degree the production intensity - measured through nitrogen and pesticides input, livestock density, and crop richness (measured by the Shannon Index) - supports biodiversity, over several broad agricultural land use categories (arable crops, grassland, olive groves and other permanent crops and fallow land). For each of these categories a sub-index, capturing the biodiversity friendliness of farming practices is created, which together form the overall BFFP index. To increase the explanatory power of the BFFP, weights could be assigned to each sub-index in relation to its impact on biodiversity. This, however, requires further research. In addition, further research is also required to find and test an appropriate dataset for validating the updated BFFP index with respect to the pesticides component.

The **Pesticide Load Index (PLI)** is defined as the amount of applied pesticide active substances (AS) multiplied by the toxicity to non-target-organisms (Kudsk et al. 2019). The PLI has been integrated into CAPRI, but as toxicity is AS-specific, the index remains only applicable for assessing cases on specific AS. In the context of CAPRI, the PLI is not an indicator of biodiversity, but rather an environmental pressure indicator, i.e., it is a metric (or index) that is used to quantify the potential impact and intensity of pesticide applications on the environment. The PLI is computed for all NUTS 2 regions and is also incorporated in the BFFP as a further sub-indicator. In CAPRI, the PLI is integrated with the unit "toxicity doses per ha and year". The AS toxicity is measured by the two toxicity endpoints, LD50 (Lethal Dose) and LC50 (Lethal Concentration), representing the dose of a substance that is estimated to be lethal to 50% of a population of test organisms. Both LD50 and LC50 values are used to compare the relative toxicities of different AS and assist in determining appropriate safety measures, regulatory guidelines, and exposure limits. The PLI implemented in CAPRI covers seven different taxa (birds, mammals, fish, daphnia, algae, earthworms, honey bees). Per taxon, the PLI has a clear physical interpretation (i.e., the likely toxic impact of the cumulative application of the AS on a specific taxa), whereas the aggregate PLI (i.e., the sum of PLI per taxa) is prone to mask the heterogeneity and variations between taxa (i.e., which taxon is more affected). This limitation was solved by presenting both, the total and the disaggregated PLI. In a nutshell, the PLI in CAPRI can be used to track and compare changes over time of policies (e.g., the ban or taxation of an AS) targeting one or multiple specific main AS. For the time being the approach is limited to this, because the toxicity is AS-specific and reducing or banning one substance needs to consider all alternatives that are used to substitute the main AS, including not only their toxicity, but also their cost and effectiveness in terms of plant protection. Information on cost and effectiveness is not readily available and needs to be gathered on a case-by-case basis. Accordingly, further research and developments are ongoing to allow using the PLI in a generalised form.

Ecosystem services and natural capital are vital for economic productivity, but often not considered or incompletely accounted for in traditional economic approaches. The process of accounting for these resources involves quantifying changes in the stock of natural assets (i.e., soil, air, water, and all living organisms), and it entails integrating the value of ecosystem services into accounting systems. Accounting for ecosystem services is important to understand the value of natural resources and the role they play in the economy and human well-being, and its accounting aims to lead to better ecosystem management (IPBES 2019). In MAGNET, an approach has been developed to provide an indicator that quantifies the value of ecosystem services and nature-based solutions. The approach uses the Integrated system for Natural Capital Accounting (INCA)[20], which builds on the EU initiative on Mapping and Assessment of Ecosystems and their Services (MAES; Maes et al. 2016, 2020). INCA provides a framework to measure and value the changes in the stock and condition of natural capital (ecosystems) and the ecosystem services they provide, using a statistical framework called the System of Environmental-Economic Accounting (SEEA)[21], which is adopted by the United Nations as a standard for ecosystem accounting. The MAGNET approach combines INCA with the Gross Ecosystem Product (GEP), which summarises the value of ecosystem services to the economy in a single monetary metric (Ouyang et al. 2020, Dasgupta 2021). GEP is analogous to GDP, but uses the data on supply and demand of particular ecosystem services to calculate their accounting values and aggregate them into a measure of the contribution of ecosystems to the economy. GEP is powerful because it uses similar methods for its construction as those underpinning GDP and can be used alongside the GDP indicator to show how different policies influence the value of ecosystem services. First outcomes of test scenarios with the MAGNET approach and associated

[20] INCA Platform: https://ecosystem-accounts.jrc.ec.europa.eu

[21] System of Environmental-Economic Accounting (SEEA): https://seea.un.org/

indicator dashboards have been established, and a partly revision and further improvement of the attribution of the ecosystem services to variables in MAGNET is currently conducted.

Soil health

Background and context

While soil is itself an ecosystem, containing more than 25% of the planet's living organisms, it is also a crucial mediator of the potential impact of EGD measures affecting food production. Soils are the basis for agricultural food production and serve as buffers against climate change-related risks such as floods and droughts. The health, fertility, and water retention capacity of soils are crucial for sustaining and enhancing crop yields and nutritional content, as well as the resilience of the food system in the face of climate change, drought, and other pressures. In contrast, unhealthy soils are less fertile, more susceptible to erosion and extreme weather events, and experience increased damages from flooding, droughts, and landslides. Additionally, degraded soils lose their ability to store carbon. Soil erosion, in particular, poses a significant challenge across the EU, leading to losses in agricultural productivity (Panagos et al. 2016, 2018).

In the framework of the new CAP, soil protection and improvement play a prominent role. For example, several GAECs help to protect soil: GAEC 5 limits erosion by setting requirements for tillage management, GAEC 6 requires farmers to avoid leaving soil bare during the most sensitive periods, and GAEC 7 requires farmers to apply crop rotation. However, the contributions to soil health improvements made by these standards will depend on the scope of the area coverage set by MS and the required practices. In addition, the CSPs of the MS also include payments for several farming practices that are beneficial for soil health beyond the GAECs.

Modelling needs and challenges

Soil health is usually implicitly reflected in agro-economic models in yield trend estimates and production functions. If GAEC requirements and additional CSP payments for specific farming practices affect soil health and, hence, in the long run crop productivity, this would require to adjust corresponding yield and production functions in the models, at least if the uptake of these measures and practices would be considerable. The related challenges for the reflection in the iMAP models are the same as the ones generally outlined in the section on the CAP beyond 2023. Thus, first the most prominent farming practices with respect to improving soil health have to be selected and, second, direct links to crop yields need to be established. Gathering the correspondent data seems to be the biggest challenges in this respect.

Modelling capacities

All iMAP models are able to reflect improvements in soil health, once the challenges related to the data availability and establishing direct links between farming practices and yields are mastered. For CAPRI and IFM-CAP, a direct link with farming practices can be established, whereas for the other models a resulting yield effect can be implemented in a stylised way. The JRC hosts the European Soil Data Centre (ESDAC)[22], which is a thematic centre for soil-related data in Europe. Datasets, maps and further information provided by the ESDAC can serve as input for agro-economic models to assess soil health. Moreover, iMAP models can be used in combination with biophysical models that focus explicitly on soils, considering factors such as soil erosion, soil organic matter, and soil fertility over time. For example, the MAGNET and CAPRI models were applied in modelling frameworks with the JRC's RUSLE (Revised Universal Soil Loss Equation) model. RUSLE is a soil erosion model designed to predict the long-term average annual soil loss carried by runoff. Using pan-European harmonised datasets as inputs, the model calculates mean annual soil loss, considering specific factors for rainfall erosivity, soil erodibility, cover-management, slope length and slope steepness, and support practices. In a sequential modelling framework RUSLE was applied together with MAGNET to project and assess market effects and costs of soil erosion. For this study, national and regional soil erosion rates, based on a combination of remote sensing, spatial analysis techniques and statistical data, were used with RUSLE to provide a global soil erosion assessment and convert it into land productivity losses. These productivity losses were then implemented into the MAGNET model to assess market effects and costs of soil erosion (Sartori et al. 2019). Another integrated modelling analysis was used to assess future soil loss by water erosion across the EU in the context of climate change by 2050. The analysis integrated the RUSLE, CAPRI, and Land Use and Management (LANDUM) models (the latter to estimate cover-management factors, taking also GAECs into account) in combination with a wide set of climate

[22] European Soil Data Centre (ESDAC): https://esdac.jrc.ec.europa.eu/

data and bioclimatic variables provided by the Coupled Model Inter-comparison Projects (CMIP5) (Panagos et al. 2021).

2.6 Animal Welfare

Background and context

Raising animals under insufficient levels of welfare compromises their health, has impacts on biodiversity and increases the need for medication, especially antimicrobials (Broom, 1991). As part of the F2F strategy, the Commission has committed to revising the current legislation of animal welfare in the EU. The revision aims to update and align five directives and two regulation texts from 1995 to 2009, including those on animal transport and slaughter. The objective is to establish higher standards of animal welfare in EU livestock production, broaden the scope of the legislation, facilitate enforcement, and contribute to achieving a more sustainable food system. Additionally, options for animal welfare labelling are being considered to improve the transmission of information and value along the food chain.

One of the targets within the F2F strategy related to animal welfare is the reduction of antimicrobials' sales for farmed animals by 50% until 2030. While antimicrobials contribute to animal health and productivity, excessive and inappropriate use of antimicrobial agents in livestock production exacerbates problems of antimicrobial resistance (AMR) and the associated adverse effects on animal and human health (Chang et al. 2014, Rushton et al. 2014, FAO 2016, ter Kuile et al. 2016, Dadgostar 2019, Ardakani 2023).

Modelling needs, challenges and capacities

Refining the EU animal welfare legislation seeks to further enhance several benefits for animals and society, including increased productivity per animal, enhanced ecosystem services, reduced use of antimicrobials, and improved public health. However, compliance with an enhanced legislation imposes additional costs on public authorities and food business operators, and the latter might perceive the returns from producing food under higher welfare standards as insufficient. Accordingly, the revision of the current legislation to introduce stricter animal welfare requirements raises questions about the trade-offs between benefits and costs associated with enhanced requirements. From a production perspective, questions arise on the impacts on factors such as farm income, stocking density and distribution, feed production, land use change, environmental effects, and trade. From the demand side, questions arise regarding the eventual effects of better consumer information through labelling, such as the potential increase in consumption of animal welfare products or the overall decrease in livestock food products, and whether these effects could outweigh the increased costs for farmers.

In general, aspects of increased animal welfare can be integrated and assessed with the iMAP models. The novel aspects of animal health are, however, not yet incorporated in the iMAP models. For a full assessment of costs and benefits associated with the new legislation of animal welfare issues, the models need to be updated by integrating new parameters that reflect changes in stocking density restrictions, production costs and yields resulting from stricter animal welfare requirements. Additionally, farm benefits, such as subsidies and price premiums also need to be considered and incorporated as compensatory measures for increased costs. Furthermore, direct benefits of improved animal welfare related to increased animal health need to be considered. Such benefits relate, for example, to longevity of the animals or a decrease in veterinary costs. Moreover, changes in consumer behaviour related to the consumption of livestock products would need to be incorporated, for example if an accompanying animal welfare labelling would raise consumer awareness and trigger respective consumer choices towards products indicating positive animal welfare standards.

For the farmers, the first expected direct consequence of increasing animal welfare standards may arise from restrictions on stocking densities. Such restrictions may either lead to reductions in the animal herd, or the farmers needing to build bigger stables. Stocking density requirements may be best represented in IFM-CAP, but in any of the iMAP models such restrictions could be reflected by an increase in production costs. Costs increase as a result of increased animal welfare standards primarily comprise costs related to operational expenses, higher investments or disinvestments, foregone production and profits (opportunity costs), and private transaction costs. These factors can influence farmers' production decisions and their viability in the market (Menghi et al. 2014, Fernandes et al. 2021). Shocks to costs can be directly incorporated into the cost functions of the iMAP models.

Apart from the cost side, it is essential that iMAP models also consider the direct benefits associated with enhanced animal welfare standards, such as support measures and subsidies, but eventually also price premiums for labelled products. Therefore, the respective additional support and subsidies outlined in the CSPs of the MS need to be integrated into the iMAP models. Further benefits related directly to positive effects on animal health, like decreases in veterinary costs and longevity of the animals could also be considered, especially translated in adjustments of cost parameters if related evidence and data can be found in the literature. Furthermore, to account for potentially increased consumer willingness to pay for higher animal welfare standards, data on consumer preferences needs to be collected. If available, respective price premiums can be incorporated into the objective function as average revenue increases resulting from anticipated higher demand for these products, or demand elasticities can be directly adjusted.

A limitation for modelling in the context of animal welfare is again data availability. The literature provides only few estimations on the precise scope and magnitude of the increased costs arising from higher animal welfare requirements (Bornett et al. 2003, Bessei 2018). Consequently, assumptions may need to be made based on cost impacts related to alternative labels and standards (such as organic agriculture or sustainability) to overcome data issues. Similarly, data availability for estimating elasticities for these products is an important limitation.

With respect to antimicrobials, no specific efforts have been undertaken with iMAP models so far to assess the 50% reduction target in overall sales. In general, the iMAP models have the capacity for such an assessment, which comes with specific modelling needs and challenges that show similarities with the ones described in the section on pesticides reduction. In 2020, veterinary purposes accounted for the use of 5317 tonnes of antimicrobials (based on sales data) in the EU (EMA 2021). However, there are considerable variations between MS, with antimicrobial use ranging from 12 mg/PCU in Slovenia to 453 mg/PCU in Cyprus. Achieving the F2F strategy's objective of a 50% reduction in overall sales, therefore, requires tailored policies that account for the specific contexts and livestock production structures of individual MS. The European Surveillance of Veterinary Antimicrobial Consumption (ESVAC 2022) project collects information on the use of antimicrobial medicines in animals across the EU. The latest data, available for each MS, could be used to calculate trends and integrated as an input factor in the agro-economic models. If pricing data would be available, specific antibiotics could also be modelled, which could be done in a similar way as in the before-mentioned CAPRI approach for pesticides modelling. Eventually, the data on antimicrobials could be further detailed into antimicrobial classes, since EMA classifies certain classes as critically important antimicrobials (CIAs), which require specific policies (ECDC et al. 2017). Regarding the consumer side, informing consumers about, for example, antibiotic-free products or general increased animal welfare standards, through production labelling could lead to increased animal welfare products demand through product labelling. This can be incorporated into the models through adjustment in demand elasticities for livestock products, if adequate evidence and data is available on which changes in the model could be based on.

Incorporating antimicrobials as an input factor can be challenging due to the complex impact on production and yields. Several alternatives to antimicrobials, such as vaccines, enhanced biosecurity, and improved animal welfare practices, exist to maintain animal health and productiveness. Therefore, the cost decrease of using less antimicrobials could be offset by other costs, although the iMAP models do not differentiate these cost categories. Further evaluation would be necessary if it turns out that an explicit modelling of antimicrobials use in the EU would be indeed necessary with the iMAP models.

As part of the impact assessment accompanying the new proposal of the animal welfare legislation, DG SANTE is gathering evidence on costs and potential changes in consumer behaviour. The JRC is involved in this IA, allowing for a first integration of relevant aspects into the iMAP models, starting with Aglink-Cosimo, with regard to cost parameters and adjustments in demand elasticities.

2.7 Dietary changes and health aspects

Background and context

Changing food consumption patterns encompasses shifts in the structure and composition of global food consumption, influenced by evolving values, attitudes, and behaviours (Kearney 2010). These changes involve both the total quantity and the types of foods consumed. A noteworthy transformation is the transition from animal protein being perceived as a luxury item to its integration as a regular component in diets. Food choices are deeply rooted in social norms, and individual dietary patterns are influenced by cultural shifts, social values, and perceptions associated with food consumption. The global changes in food consumption patterns, often referred to as "westernization," primarily stem from demographic factors, income growth, and the impact of globalization, urbanization, occupational changes, and improved information dissemination (Muhammad et al. 2011, Oberlander et al. 2017, Le et al. 2023).

In the EU, dietary shifts are not only important in the context of human health benefits, but necessary for the transition towards more sustainable food systems, including the reduction of GHG mitigation related to the livestock sector, and to achieve other environmental targets related to environmental impacts and biodiversity. Accordingly, improving human health is one of the key objectives of the EGD, and particularly the F2F strategy aims to promote and facilitate the adoption of healthier and more environmentally sustainable diets.

In addition to the health implications linked to dietary changes, there is an increasing emphasis on the adverse effects on human health resulting from air pollution, particularly fine particulate matter. This pollution is notably influenced by ammonia emissions originating from agricultural activities, such as the management of animal manure and the application of mineral nitrogen fertilizers (Lelieveld et al. 2015, Pozzer et al. 2017, Giannakis et al. 2019).

Modelling needs, challenges and capacities

IMAP models are very well suitable to assess scenarios related to dietary changes. On the one hand, iMAP models (except IFM-CAP) can provide impacts on consumption levels as an outcome of policy scenarios, i.e., impacts on consumption levels and eventual dietary shifts are a standard output of any policy-related scenario analysis. However, these changes are driven by price changes of the commodity, and are not related to other aspects that may drive consumers to change their diet, such as health and environmental concerns. On the other hand, iMAP models can also assess scenarios that specifically enforce dietary shifts (implemented as an exogenous shock in the models), for example assuming a restriction on annual animal protein consumption per person. This was more frequently done in the recent past with MAGNET and CAPRI, for example in the context of GHG emission reduction to assess how much dietary changes could contribute to enhanced GHG mitigation in the agricultural sector (Frank et al. 2019). Similarly, dietary shifts due to increased health and environmental consciences by consumers could be implemented. However, for a sound implementation of such dietary shifts, related data that is based on scientific evidence is necessary and such data is not readily available. If supporting policies that promote healthier and environmentally friendly diets proves to induce shifts in consumption preferences, then also demand elasticities can be adjusted in the models, which would then also have a direct impact on price effects and related agricultural production. This approach is currently applied with the Aglink-Cosimo and CAPRI models in the context of the assessment of the animal welfare regulation.

Moreover, assessing the impact of EGD policies on human health and the food system's demand side requires the application of tools that consider nutritional content and evaluate health aspects associated with emissions, including GHG and ammonia emissions. In addition, integrating nutrition content and health impacts in the assessment requires a multidisciplinary approach, considering also health outcomes associated with specific dietary patterns and emission reductions. In this context, scenario results generated with the iMAP models can either be directly converted in the models through integrated post-model calculations, or the iMAP results can provide input for other models that can transform the related information into related health impacts. Several examples for both approaches already exist.

Given its structure and coding format, the CAPRI model was selected for the exploratory integration of a health module that accounts for some health aspects related to human diets. For the approach, the nutrition-related health model developed by Springmann et al. (2018), also used by the EAT–Lancet Commission on healthy diets from sustainable food systems (Willett et al. 2019), was identified as the most suitable and advanced model to be integrated. The integration of CAPRI results with the Springmann et al. (2018) model is done in the CAPRI post-model reporting by (i) using the food intake estimates (in kcal or grams) from CAPRI and integrating them into the Springmann model, and (ii) adjusting the food categories and the population attributable fraction (PAF) estimation as well as the regions to match the CAPRI food groups.

As regards human health aspects associated with air pollution related to emissions from agricultural production, emission changes provided by iMAP models can be combined with regional atmospheric pollution models that calculate air quality impacts in the atmosphere and premature mortality rates. For example, CAPRI was employed together with the atmospheric chemistry model WRF-Chem, which is a regional atmospheric pollution model. The study showed that a shift to plant-based (flexitarian) diets would lead to reductions of ammonia emissions in the EU that would generate significant co-benefits for air quality and human health (Himics et al. 2022). A JRC internal solution and viable approach is the integration of the CAPRI model with the source-receptor model FAst Scenario Screening Tool (TM5-FASST). TM5-FASST provides information at a finer resolution and was also extensively applied in various critical studies (Van Dingenen et al. 2018). The Tracer Model version 5 (TM5) is a 3-dimensional global atmospheric chemical transport model that simulates the transport, chemical processes, as well as wet and dry deposition of chemically active atmospheric trace gases (e.g., ozone O_3, SO_2, NO_x, VOCs, NH_3), and particulate matter components, including SO_4^{2-}, NO_3^-, NH_4^+, primary PM2.5 and its components black carbon, organic carbon, sea salt, and mineral dust. The integration of the two models is facilitated by a close collaboration between the respective modelling teams in JRC Seville and Ispra, the latter having the relevant expertise for the pollution model.

2.8 Circular economy and food waste

Background and context

Pursuing a circular economy is one of the main objectives of the EGD, with the aim of reducing pressure on natural resources while fostering sustainable growth and employment. This transition is also seen as a prerequisite for achieving the EU's 2050 climate neutrality target and halting biodiversity loss. The EU circular economy action plan focuses on product design, promotes circular economy processes, encourages sustainable consumption, and strives to prevent waste while maximising the retention of resources within the EU economy. The EU Bioeconomy Strategy (EC 2012, updated in 2018) addresses the renewable segment of the circular economy and its contribution to building a carbon neutral future. The EU uses more biomass than its available supply (both domestic and imported), with the difference between supply and uses being explained by the reuse of biomass (Avitabile et al. 2022). When considering the agri-food sector within the broader bioeconomy, which is characterised by complex interconnections between land productivity, management, and feedstock choices, the recognition and implementation of recycling, reuse, and material cascading are crucial for effective policy-making (Verkerk et al. 2021).

Food loss and food waste reduction is a very relevant issue for the circular economy and the transition to SFS. Food waste reduction is one of the declared EU policy goals in the EGD, and halving consumer food waste by 2030 is also manifested as one of the UN SDG targets. In addition to waste reduction, EU policies also aim to valorise food waste biomass in order to decrease the need for resource inputs and increase circularity within the economy. In particular, the EU bioeconomy strategy highlights how turning biological waste and residues into valuable resources can contribute to achieving the food waste reduction targets. Additionally, within the F2F strategy the European Commission was called to set legally binding targets to reduce food waste across the EU. These food waste reduction targets are proposed as part of a broader initiative to revise the Waste Framework Directive, which proposes measures to reduce waste generation and to increase waste preparation for reuse or recycling.

Modelling needs, challenges and capacities

Most existing modelling techniques have traditionally relied on the concept of linear product lifecycles and economies (i.e., produce, use, discard), with only a few exceptions that incorporate material cycles and recycling for specific products and sectors required to assess a circular economy (Pauliuk et al. 2017, McCarthy et al. 2018). From the iMAP models, MAGNET in particular has been further developed to specifically consider aspects of a circular economy. For this purpose, the model incorporates two key features of the circular economy (Verkerk et al. 2021). Firstly, it includes residues from the agricultural, biofuels and forestry sectors, which can be used as feed, bioenergy, or bio-based materials (van Meijl et al. 2018b) Secondly, MAGNET integrated a waste management sector that accounts for all kinds of waste generated by consumers and industry. Currently, the waste module within MAGNET encompasses the complete waste stream cycle from waste generation to collection, treatment, and disposal. This allows for modelling food waste reduction along the five steps of the supply chain, i.e., agricultural production, post-harvest, packaging and processing, retail, and consumers (Bartelings et al. 2021). In general, partial equilibrium models provide more detailed consideration of specific residue types and recycled materials compared to CGE models. Notably, the CAPRI, Aglink-Cosimo and AGMEMOD models account for agricultural by-products. However, these models tend to fall short in adequately addressing recycling or product cascading (Verkerk et al. 2021). From an overall economic perspective, it can be argued that a CGE modelling framework is better suited to accurately capture the circular economy, as partial equilibrium models inherently focus solely on the agricultural sector, which represents a notable limitation in the context of circularity (Lovrić et al. 2020, Varacca et al. 2020). Accordingly, for the time being, MAGNET remains the iMAP model that is further developed and refined for the assessment of circular economy aspects. For example, the MAGNET model was employed to conduct an economy-wide evaluation of food waste reduction targets in support of the EGD. The study specifically concentrates on a range of sustainability indicators to analyse the economic, social, and environmental consequences of reducing food waste across all levels of the supply chain (de Jong et al. 2023).

Reducing and valorising food waste is foremost argued to be of environmental, economic and social benefit (Lopez Barrera and Hertel 2021). More so considering that food and feed production consume almost two thirds of the available biomass used in the EU (Gurria et al. 2022). While the argumentation generally holds, in an interconnected food system the benefits for some can turn out as costs for others, which underlines the importance of model assessments to account for synergies and potential trade-off related to food waste reduction. For example, valorising food waste as animal feed can avoid feed-food competition and reduce the use of natural resources (van Zanten et al. 2018). In addition, it can reduce the agricultural biomass used to produce animal feed and thus increase the available biomass that can be used for other purposes, such as the production of biomaterials (Avitabile et al. 2023). However, reduced food and feed demand as consequence of successful food waste interventions may lead to lower agricultural production levels and therefore reduce the income of agricultural producers (Philippidis et al. 2019a, Kuiper and Cui 2020, de Jong et al. 2023). Despite these potential adverse economic effects on the agri-food sector, reducing food waste has positive impacts in other economic domains that can offset the losses in the food chain. Furthermore, reducing food waste contributes to increased affordability of food and financial savings for households. As the MAGNET model captures the interlinkages within the entire economy, it allows for the incorporation of rebound effects resulting from food waste reduction. For instance, as households consume fewer agri-food products, economic resources that are freed up can be redirected towards other purposes. This redirection can lead to an increase in emissions, which were previously mitigated within the agri-food sector. However, studies indicate that overall, food waste reduction leads to GHG emissions savings in the economy (Boysen-Urban et al. 2022, de Jong et al. 2023).

A further aspect is the use of food waste and residues for non-food applications. In this context, the JRC developed an approach in MAGNET that is similar to a material flow in the circular bioeconomy. This approach considers that biomass supply requires inputs and natural resources, which in turn undergo processing and blending prior to end usage (e.g., food, 'end use energy and material') and ultimately reach their end of life (waste). Part of the waste is then reintroduced into the economy (M'barek et al. 2019, Philippidis et al. 2019b). MAGNET is currently also extended to enable the modelling of biogas and biomethane production. This will allow to run simulations related to the use of bio-residues (e.g., food waste, crop residues, animal manure) in the production of biogas and biomethane. Increasing the production of biomethane is part of the EU's REPowerEU plan, which is set to increase the production of clean energy and diversifying EU energy supplies (EC 2022). Amidst growing demand for bioenergy and biomaterials, the importance of deploying technologies to extract value from unused biomass from waste streams, residues and other sustainable sources is highlighted by an analysis based on the AGMEMOD-related BioMAT (Bio-based MATerials) model. This analysis assesses the development of EU bio-based chemical markets and its implications for the balance between required and available biological feedstock types (Leeuwen et al. 2022, 2023).

While MAGNET is the most suitable iMAP model for the assessment of food waste reduction, the partial equilibrium models can also support assessments of related policies by reflecting specific aspects in the scenarios. For example, CAPRI has been applied to assess the impact of food system feedbacks on sustainability when EU consumer food waste is reduced or reused as pig feed (Latka et al. 2022). Aglink-Cosimo has been applied to assess impacts of using food waste for insect meal production, which can serve as alternative feed material in livestock production (Jensen et al. 2021). Moreover, Aglink-Cosimo was recently further developed by incorporating analytical methods to calculate food loss and waste along the food value chain (OECD-FAO 2023). Equations have been developed for each stage of the value chain where loss may occur. These equations establish the relationship between food loss percentages and relevant macroeconomic variables, selected to represent the drivers of food loss identified in the literature. This allows the model to endogenously calculate food loss percentages at the country level, enabling a more nuanced and context-specific assessment. To estimate consumption waste for individual food commodities, FAO Food Security percentages of total calories lost for each food item in each country are used to determine the consumption waste share for each commodity. In Aglink-Cosimo, each commodity can be allocated to various uses, including available food, biofuels, feed, other applications, and food losses within the value chain. Notably, the inclusion of the 'losses from the value chain' category is a recent addition, and it has been derived from the food waste module. Furthermore, available food is subdivided into two key components: food wasted during distribution and food purchased by consumers. The latter is then further disaggregated into the food actually consumed by consumers and the food discarded by households (OECD-FAO 2023).

2.9 Food chain analysis

Background and context

The increasing integration, concentration, and globalisation of agri-food markets requires an integrated food chain approach to understand policy impacts and developments. Due to the complex interlinkages between actors in the food value chain, policies and market developments usually affect not only one single segment of the chain but have cascading effects across all actors, impacting coordination and interactions. Recent crises like the COVID-19 pandemic and Russia's war on Ukraine highlight the need to understand these interlinkages for effective policy support. At the same time, the EU is transitioning towards SFS, with vertical coordination in the food supply chain driven by consumer demands for quality and variety, optimisation of information flow, and quality control.

Food value chains are characterised by complex interactions and an increasing variety of vertical coordination globally. The types and degree of vertical coordination in the food supply chain are influenced by factors such as asymmetric information and transaction costs associated with supply coordination and quality control among chain actors. Notably the growing consumer demand for food quality and variety has been a significant driver behind the increased vertical coordination within the food supply chain. Vertical coordination has emerged as an efficient means of organising information flow and enforcing product quality throughout the chain, from farm stage to the end customer. In agricultural markets, vertical coordination is primarily achieved through standards, contracting, and the establishment of long-term vertical relationships among the chain actors. Vertical coordination offers benefits such as the reduction of risks and transaction costs, improved access to credit, technology, and information exchange. Furthermore, the organization and governance of the food chain through vertical coordination has the ability to deliver quality-differentiated food products, including differentiation by sustainability, in line with consumer preferences (Reardon and Timmer 2012, Swinnen et al. 2015, Sexton and Xia 2018, Crespi and MacDonald 2022).

In parallel with the rise of vertical coordination, however, food value chains show increased concentration in input supply, processing and retail sectors. This concentration raises concerns about imbalances in bargaining power and their impact on the efficiency and sustainability of the food chain. Market concentration and unfair trading practices can disadvantage farmers and consumers, and can lead to inefficient markets, market uncertainties, reduced investments, and limited product variety and quality (Bonanno et al. 2018, Sexton and Xia 2018, Deconinck 2021). Moreover, the current lack of comprehensive incentives addressing sustainability and food quality attributes within the food chain leads to distorted production and consumption decisions. This distortion is evident in various outcomes, including ongoing environmental degradation, socioeconomic disparities, and health-related issues (de Schutter 2017, Hendriks et al. 2021).

Policy interventions aim to promote balanced power relations, transparency, and fair practices to ensure the long-term sustainability, inclusivity and resilience of agri-food markets. However, while for example the CAP explicitly defines the objectives of sustainability at the production level, for the rest of the food chain they often remain less clear. Legislative initiatives launched in the EU as part of the EGD aim at improvements along the entire food value chain, accelerating and facilitating the transition to SFS. One of the main objectives of the EGD is the promotion of policy coherence at EU and national level, mainstreaming sustainability in all food-related policies and strengthening the resilience of food systems. This includes influencing producer and consumer behaviour through a range of measures like adoption of sustainability standards, the implementation of sustainability labelling, food waste reduction, and various other initiatives. Analysing the effects of these policy efforts and changes in producer and consumer behaviour on agricultural production and consumption requires assessments along the entire food chain.

Modelling needs, challenges and capacities

Understanding the key actors in the food supply chain and their interactions, as well as drivers for production and consumption changes and their impact distribution along the chain are essential for assessing policy interventions targeting the transition to more SFS. Main research in the area of the food supply chain focuses on interrelated elements, including (but not limited to) issues of (i) market concentration and integration, such as market power, unfair trading practices, and marketing standards, (ii) the general functioning of the food chain and its resilience in times of crisis, and (iii) how sustainability criteria, incentives and legislation may affect producer and consumer behaviour, and hence lead to more favourable environmental and socio-economic outcomes.

Concerns regarding market power and competition within the agri-food sector are widespread, mostly highlighting the structural disadvantages of farmers in comparison to other actors, the latter, therefore, potentially benefiting at the expense of farmers. However, while up- and downstream segments of agri-food chains are typically more concentrated than farm-level production, empirical studies have generally found only moderate systematic distortions in competitive behaviour within the agri-food chain, i.e., taken as a whole, the current scientific literature suggests that stronger actors within the food chain exploit their superior position to a low or moderate degree at the expense of farmers. Several studies, however, found more significant competition problems as well as that competition issues vary sizeably between sectors and countries, implying that small deviations from competitive conditions can lead to relatively large effects on prices paid to farmers. This suggests the need for further empirical research on specific commodities and countries (Čechura et al. 2014, Perekhozhuk et al. 2017, Sexton and Xia 2018, Colen et al. 2020, Deconinck 2021). Moreover, competition problems may not be manifested directly in lower prices, but rather in unfair trading practices (e.g., delayed payments or unilateral contract changes), which are captured to a limited extent in the existing empirical studies and calls for further analysis (Renda et al. 2014, Falkowski et al. 2017, Sheldon 2017, Sexton and Xia 2018). Research and analysis concerning market concentration, integration, and price transmission is typically not done with agro-economic equilibrium models but by applying other models, econometric analysis and surveys (von Cramon-Taubadel and Goodwin 2021). The JRC is continuously involved in the analysis of issues like unfair trading practices (Falkowski et al. 2017, Di Marcantonio et al. 2018, 2020, Russo et al. 2020), market power in the food industry (Colen et al. 2020, Nes et al. 2021a, Russo et al. 2022), the role of producer organisations (Falkowski and Ciaian 2016, Michalek et al. 2018, Di Marcantonio et al. 2022a), dual food quality (Ciaian et al. 2020, Nes et al. 2021b, 2023a, Solano Hermosilla et al. 2023), market transparency (Ménard et al. 2018, Baltussen et al. 2019, Solano Hermosilla et al. 2019), economic analyses of marketing standards, food quality schemes and their impact on sustainability (Nes and Ciaian 2021, 2022, Nes et al. 2022, Ricome et al. 2022, Antonioli et al. 2023) and innovations and firms' performance in the agri-food sector (Garzon Delvaux et al. 2018, Michalek et al. 2020). The insights gathered from this research provide valuable information for policy makers on the impact of policy initiatives and legislation aimed at improving the functioning of the food value chain, as well as on areas where further interventions might be necessary.

With respect to the general functioning and resilience of the (global) food chain, the iMAP models depicting global production and trade (MAGNET, Aglink-Cosimo, and CAPRI) can assess general (medium-term) impacts on the food chain, especially concerning agricultural production quantities and associated impacts on trade, agricultural income, producer and consumer prices. The scope of these analyses includes impacts arising from policy changes as well as those from various shocks, including macroeconomic variables (e.g., related to GDP and oil prices, Kavallari et al. 2014), unexpected trade interruptions (Fellmann et al. 2014, Boulanger et al. 2016a) or crisis situations like the COVID-19 pandemic (Elleby et al. 2020). Such analyses also shed light on potential food security risks associated with disruptions in the food system. While the respective iMAP models have the proven capacity to serve broader assessment needs related to shocks affecting the food chain, other types of analysis in the JRC can complement model-based scenarios and provide further details on impacts on specific actors in the food chain (e.g., Di Marcantonio et al. (2022b) related to the COVID-19 pandemic).

The EGD foresees the integration of sustainability criteria, incentives and legislation across various segments of the food supply chain, which may affect the entire chain in different directions and dimensions. Research and analysis are needed on how the different actors along the food chain are affected and how sustainability policies may lead to more favourable environmental and socio-economic outcomes. As regards sustainability production standards and methods, previous chapters discussed how they can be considered in the iMAP models. However, a major question remains on how sustainability policies may affect consumer behaviour. With regard to sustainable food consumption, the EGD seeks to motivate consumer behaviour for example via information, including through the use of sustainability labels. Sustainability labels encompass various dimensions, such as social (e.g., fair-trade labels), ethical (e.g., animal welfare labels), health (e.g., warning labels), and environmental aspects (e.g., organic or carbon footprint labels) (Grunert et al. 2014, Asioli et al. 2020, Sonntag et al. 2023). Evidence shows upwards trends in the use of these social and environmental labels and claims in firms' product launches across all countries and products categories within the EU (Nes et al. 2023b). As outlined in the chapter on dietary changes and health effects, iMAP models can account for shifts in consumption preferences induced by supporting policies (including labelling). The shift in preferences can be done by exogenously including the shifts into the underlying storylines and narratives used for the scenarios, or by explicitly modifying assumptions and model parameters for an endogenous modelling. The latter can be achieved by adjusting demand elasticities in the models, as for example, demand elasticities for sustainable food products and labels can differ from those of conventional food products (Morone et al. 2021). Additionally, considering price premiums of such products is crucial, as these can impact other segments of the chain (Feuss et al. 2022). However, the implementation of changes in demand elasticities and price premiums in iMAP models requires an empirical that supports the re-parameterisation of the models.

Evaluating the effects of supporting policies (like labelling) requires accurate and up-to-date data on consumer preferences. This data is essential to provide iMAP models with parameters that effectively capture the impacts of such policies, considering the interlinkages of actors within the food chain. Various statistical methods exist to gauge price premiums for sustainable products in the market, including techniques based on retailer or consumer purchasing data and on hypothetical data from choice experiments (i.e., consumer willingness to pay studies). In this context, the JRC acquired household scanner purchasing data which includes information on consumers' expenditures for selected main food groups (meat, dairy, legumes, seafood and staple goods) and sustainability features (organic, plant-based protein alternatives for milk and meat products). However, the main challenges are data availability and representativeness. The data availability is constrained by (i) country availability, (ii) product coverage, and (iii) sustainability traits. Particularly, the database has less coverage in Eastern European countries and it is more challenging to consistently trace sustainability features related to the social aspect of sustainability (such as fair trade and animal welfare) consistently across various countries. With sufficient data, demand elasticities can be estimated based on consumer characteristics, such as geographical area within a country, age of the main shopper, household size and income. However, adjusting demand elasticities in iMAP models according to these consumer characteristics remains a challenge as the models do not differentiate elasticities by these characteristics, i.e., further approaches are needed to allow a more generalised implementation.

Regarding price premiums for sustainable products, consumer price premiums can be calculated using the same database as the demand elasticities. A preliminary descriptive analysis consisting of five countries was already conducted by the JRC, showing differences in price premiums (i.e., the sustainable product is significantly more expensive than its conventional counterpart) and consumption levels of the sustainability features among the product categories and countries. Moreover, demand elasticities can show important variations across different income groups within countries, as changes in prices for sustainability features in food products tend to have a heterogeneous impact on the consumption depending on socioeconomic aspects, including income groups.

While the iMAP models do not differentiate demand agents (e.g., by income, education, age) and sustainability product categories (e.g., organic, animal welfare) typically considered in the analyses based on these statistical methods, a possible solution could be adjusting overall demand elasticities based on shares of different household groups and shares of different product categories. Thus, the iMAP models have the general capacity to reflect changes in consumer behaviour and price premiums, but this requires the integration of further econometric estimations into the models. Limitations are mainly related to the availability of data for estimating changes in demand elasticities and price premiums, particularly with regard to countries, sustainability traits, and products covered. Extrapolations from available country and product data can be made whenever they are considered realistic and accurate. However, the aforementioned data constraints persist.

2.10 Behavioural aspects

As mentioned in previous chapter, several aspects of the EGD and its related policies aim at inducing changes in the behaviour of both producers and consumers. In this chapter, we discuss more explicitly behavioural aspects, how they are considered in the iMAP models, and additional analysis that is required for both providing input for agro-economic modelling and the general assessment of EGD policies.

Background and context

Within the framework of neoclassical economic theory, individual decision-makers like farmers and consumers, are assumed to follow behaviours that maximizes their objectives. For example, it is conventionally assumed that producers (encompassing e.g., farmers, input suppliers, processors, and retailers) are primarily driven by the pursuit of profit maximization, while consumers seek to maximize utility within the constraints of their budgets. However, it is well documented that the simplistic maximization paradigm does not necessarily provide a complete reflection of how agents actually behave. Human behaviour is influenced by a multitude of cognitive, emotional, and social factors, and the agents often struggle with limitations in their capacity to optimise among numerous alternative options (Thaler 2018). Instead, they either use heuristics, characterised by shortcuts or rules of thumb (Kahneman 2003), or adhere to satisfying rules, whereby the focus shifts to fulfilling a minimum set of requirements rather than undertaking an exhaustive comparison of all available options to maximize outcomes (Harrison and Pelletier 1997). These cognitive processes have implications for modelling behaviours, such as famers' adoption of technological options (both technical and management-based) or their participation in environmental schemes (e.g., the eco-schemes of the CAP), as well as shifts in consumer preferences resulting from non-financial interventions (e.g., labelling, and food waste reduction initiatives).

Behavioural aspects beyond neoclassical optimisation assumptions need to be considered when analysing EGD-related policies. This is necessary to provide a better analysis of both the impacts that the EGD might have on producers and consumers, and of what might be necessary to further change behaviours so that the EGD objectives of moving towards more SFS can be met. Surveys and behavioural and experimental economics approaches can be used to analyse decisions made by producers and consumers, encompassing decisions that affect the environment. Economic experiments play a pivotal role in the investigation of farmer and consumer behaviour, particularly in relation to the environment (Dessart et al. 2019, Palm-Foster and Messer 2021, Reisch 2021). Results of such experiments and analyses can serve as valuable input for the agro-economic models, i.e., the representation of farmer and consumer behaviour can be improved by considering findings from behavioural economics research.

Modelling needs, challenges and capacities

Farmer behaviour

When it comes to agricultural production decisions, a nuanced understanding of the behavioural aspects of farmers and incorporating them into the analysis is critical for improving projections with agro-economic models and designing effective policies for sustainable agriculture. Farmers, the main economic agent whose behaviour is captured in agro-economic models, are considered somewhat between individuals and firms. Even when making entrepreneurial decisions they do so predominantly as individuals. Farmers are not immune to behavioural biases, which for example affects the adoption of environmentally friendly technologies and farming practices, as well as the participation in agro-environmental programmes (Dessart et al. 2019). Farmers also seem to include altruism in their decision-making, demonstrating a willingness to forego farm profit for environmental benefits (Barreiro-Hurle et al. 2023b). Understanding and considering behavioural factors enriches economic analysis of farmers' decision-making and, for example, can contribute to more effective agri-environmental policies (OECD 2017, Dessart et al. 2019, Palm-Forster et al. 2019, Schaub et al. 2023).

While profitability and profit maximization are indeed significant drivers of technology adoption, numerous studies highlight a range of other factors that influence a farmer's decision to adopt a technology or management practice. Psychological factors influencing farmer behaviour can be grouped into three broad categories (Dessart et al. 2019): dispositional factors (e.g., personality, resistance to change, risk tolerance, and environmental concern), social factors (e.g., social norms and comparison, and signalling motives), and cognitive factors (e.g., knowledge, perceived control, risks, costs, and benefits). For example, risk plays a crucial role in a farmer's perception of net returns, directly influencing adoption decisions. Transitioning to a new technology or management practice introduces uncertainty regarding performance and impact on net returns, especially when combined with the inherent unpredictability of some factors affecting agriculture (such as weather). Consequently, farmers, who already show high levels of risk aversion (Rommel et al. 2022), may discount expected benefits due to augmented risk, leading to non-adoption, even when a technology is theoretically profitable (Sunding and Zilberman 2001, Marra et al. 2003). In addition, other factors not related to the decision-maker's psychology, are well-recognized for influencing farmers' decision to adopt technologies and sustainable farming practices, including farm size as well as technology attributes (such as simplicity and flexibility), and human capital characteristics (such as age, experience, and education) (Prokopy et al. 2008, OECD 2012, Wuepper et al. 2023).

Exploring why farmers adopt technologies inherently involves understanding why they do not. Two fundamental reasons for non-adoption—namely, inability and unwillingness—deserve explicit recognition. Inability to adopt may arise from various factors, including the absence of essential information, technology complexity, high associated costs, misaligned planning horizons, or inadequate managerial skills. Unwillingness to adopt may also come from multiple factors, including conflicts or inconsistencies in information, limited applicability and relevance of the information, incompatibility with existing production systems, habit and belief in traditional practices, or a lack of awareness on the part of the farmer (Nowak 1992). These two fundamental reasons for non-adoption are not mutually exclusive, and in both cases, the decision aligns with the farmer's perception of rationality.

With respect to the temporal dimension and programs incentivising the adoption of sustainable practices, such programmes often demonstrate higher adoption rates when focused on short-term economic advantages compared to those primarily oriented towards ecological services. However, in the long term, the enduring motivation for farmers to embrace sustainable practices hinges on perceived benefits, encompassing aspects related to their farms, environmental stewardship, or a combination thereof. Additionally, the literature underscores the pivotal role of technical support and extension services in fostering sustainable agricultural practices (Pañeiro et al. 2020, Wuepper et al. 2023).

The aforementioned aspects highlight the need to recognise and incorporate behavioural tendencies of farmers into agro-economic models for the assessment of specific policy aspects. In recent years, especially the development of agent-based models (ABMs) has gained prominence, aiming to capture behaviours and interactions among autonomous agents (Huber et al. 2018, Kremmydas et al. 2018). However, while ABMs serve as valuable complements to traditional farm models for policy analysis, they also tend to lack consideration of many values, social interactions and norms, and learning in farmers' decision-making. Despite promising approaches to include certain individual behavioural factors into ABMs concerning technology adoption (Huber et al. 2023), considerable room for improving the representation of farmers' decision-making remains, particularly with a focus on comprehensive behavioural perspectives (Huber et al. 2018). For the iMAP framework, developing behaviourally compatible agro-economic models might neither be the most cost-efficient avenue for research nor necessary. A more cost-effective approach seems to incorporate behaviourally informed research findings to improve the parameterisation of behavioural responses in the current modelling framework.

It can be argued that behavioural impacts are at least partially embedded in the way medium-term projections are constructed in the Aglink-Cosimo baseline, as it incorporates expert knowledge on developments of the production and demand structure of the agricultural and (limited) processing sectors. Aligning with the Aglink-Cosimo baseline during the calibration phase implies that this knowledge is also reflected in the other iMAP models. Furthermore, IFM-CAP and CAPRI integrate the behavioural dimension through a positive mathematical programming (PMP) approach. This approach meets the calibration objective (alignment with the Aglink-Cosimo baseline) and ensures that model responses to parameter changes are consistent with exogenous information, such as price elasticities of supply. This increases the likelihood that model results approximate real-life adjustments farmers will make in response to the evaluated policies.

Furthermore, for modelling the adoption of selected technologies and farming practices, CAPRI considers an approximation of other (behavioural) factors that influence adoption beyond profit maximization. These other factors can be expressed also in costs, and are well established within PMP modelling approaches. In this context, the costs considered in CAPRI for the technology adoption encompass not only the direct accounting costs (annualised investment and operation costs), but also other (behavioural) cost factors influencing technology adoption. These factors reflect uncertainties associated with technology adoption, for example, the age and education of farmers, and risk aversion. Moreover, this allows accommodating the observation that behavioural factors influencing technology adoption tend to increase towards late adopters. In addition, CAPRI's non-linear cost structure yields a gradual and responsive adaptation to incentives (like, for example, subsidies for specific management practices, carbon prices, or specific mitigation obligations) that favour the adoption of technologies (see, e.g., Fellmann et al. 2021). This responsiveness aligns with the above discussed real world dynamics, acknowledging that all farmers are unlikely to suddenly transition to new technologies simultaneously due to the presence of behavioural factors.

In IFM-CAP, efforts have been made to mimic adoption decisions by using FADN data to retrieve adoption dynamics via propensity score matching. This approach enables the ranking of farms according to probability of adoption based on revealed behaviour and subsequently transitioning farms to specific production methods one by one following the ranking. While the approach still falls short in capturing resistance to change and potential non-financial benefits associated with adoption, modifying the parameters of the specific practice to reflect different costs and benefits could tackle this.

In summary, the iMAP models have the capacity to reflect factors of farmers' behaviour concerning the adoption of environmentally friendly technologies and farming practices or the participation in specific environmental programmes in the projections. However, availability of empirical data remains a challenge for implementing nuanced adjustments within the model framework. The related literature provides constantly growing evidence and data, and the JRC is conducting behavioural studies to better understand farmers' behaviour and to gather necessary information to improve the parameterisation of behavioural responses in the models. Representative empirical data will allow to further adjust certain model parameters and elasticities in the future.

Consumer behaviour

Consumer choices have profound implications throughout the agri-food supply chain, the environment, and the overall economy. Changes in consumer behaviour are imperative for achieving the objectives of the EGD and the transition to more sustainable food systems. For example, as outlined in previous chapters, sustainable consumption, the shift towards more sustainable diets, and reductions of food waste are key elements in achieving substantial reductions in agricultural environmental impacts (e.g., GHG emissions, nutrient surplus, pesticide use and risk). Agro-economic models can incorporate changes in consumer preferences by adjusting model parameters and elasticities. However, a critical inquiry that emerges is, to what extend the accompanying policy measures, such as information campaigns and food labelling, prove effective in activating the intended transformations in consumer behaviour and consumption patterns, and to determine what might be needed to effectively further incentivise such transformations.

Consumer behaviour, much like farmer behaviour, is influenced by a multitude of factors. These factors can be broadly categorised into: (i) economic factors (e.g., personal and household income, consumer credit, liquid assets, and savings), (ii) psychological factors (e.g., motivation, perception, learning, attitudes and beliefs), (iii) personal factors (e.g., age, occupation, and lifestyle), (iv) social factors (e.g., family, reference groups, and social status), and (iv) cultural factors (e.g., culture and social class) (see, e.g., Reisch and Thøgersen 2015, Reisch 2021). Economic factors, such as income, budget constraints, and related price sensitivity, are fundamental drivers of consumer behaviour. In the agro-economic models, the economic factors are commonly well represented via parameters and elasticities, which allows to assess how the economic factors shape consumption patterns and the responsiveness to changes in agricultural production and food prices. However, apart from being inherent in consumption trends, the models do not specifically consider other factors that influence consumer behaviour. Thus, in the realm of integrated model-based agro-economic scenarios related to the EGD and SFS, crucial considerations revolve around these other factors influencing consumer behaviour.

For example, the EGD aims to promote responsible and sustainable consumption, i.e., consumers are encouraged to choose products that are produced sustainably and have a lower environmental impact. In this respect, the EGD, for example, supports food labelling, which can provide information about the environmental impact of different food products, helping consumers make more healthy and sustainable choices. Accordingly, for a comprehensive modelling, a nuanced understanding of consumers' preferences for environmentally friendly, healthy, and socially responsible food products becomes imperative. Key questions arise, for example, regarding their willingness to shift consumption towards organic or plant-based alternatives. Moreover, with an array of factors acting as either drivers or barriers in shaping consumer behaviour, understanding how these factors facilitate or impede the adoption of sustainable food practices, such as reducing food waste, also remains essential to further incentivise sustainable consumer behaviour. Within this context, behavioural economics can help understanding the dynamics of consumer behaviour related to sustainability, and exploring concepts that have implications for consumer behaviour and environmental protection (Reisch and Thøgersen 2015, Reisch 2021).

Information policies (e.g., front-of-pack labelling) can facilitate informed decision-making by consumers. A recent illustration of this is the "Nutriscore" label, which employs intuitive colour codes for easy reference and has shown efficacy for certain segments of the population (Andreeva et al. 2021). However, the literature recognises that while informational interventions may lead to short-term behaviour adjustments, establishing long-term effects, such as habit formation and evolving taste preferences, remains challenging for the majority of consumers (Reisch 2021). Furthermore, there is often a disconnect between consumers' positive attitudes and intentions and their actual purchasing behaviour. Economic factors are often cited as primary obstacles to expanding ethical purchasing behaviour, with research indicating that the response to green marketing initiatives tends to be most pronounced among consumers with higher income levels (Aschemann-Witzel and Zielke 2017). Thus, research on the effectiveness of current demand-side policies directed towards shaping consumer diets through measures like labelling often yields contradictory and inconclusive outcomes. By focusing on how and why individuals make food choices, considerations of behavioural economics can provide insights to introduce promising pathway for enhancing the effectiveness of food policies (Caputo and Just 2022), which then also can be used for a better reflection in the agro-economic models.

The JRC also conducted a literature review of consumers' willingness to pay for sustainability labels. The findings generally suggest that consumers are willing to pay price premiums for products with sustainability labels. Similar to household scanner data analyses, choice experiments also reveal significant heterogeneity in price premiums across different sustainability label types (e.g., higher for geographical origin and organic standards labels than for carbon and water footprint labels) and product categories (e.g., higher for meat products, vegetable oils, and dairy products than for potatoes, beer, and fruits and vegetables). However, the main challenge in incorporating these price premium estimates in agro-economic models is the variability in methods, samples, and the heterogeneous coverage of products, countries, and sustainability labels across various choice experiment studies, which makes a scientifically sound generalisation rather challenging. In addition, available estimates predominantly assume still only marginal levels of consumption of these products and, therefore, increasing the share of total consumption represented by these products may result in a decreasing impact on the price premiums producers can attain.

In the iMAP modelling suite, consumers come into play as the demand for products, with demand usually driven by relative prices. Changes in relative prices lead to demand changes through own and cross price elasticities (e.g., higher meat prices reduce meat consumption and increase consumption of substitutes). Evidence indicates that elasticities are usually very low for food due to its small proportion of total expenditure and limited substitutes (Varian 2010). Therefore, the challenge to capture the impact of intended shifts in consumer behaviour (for example dietary shifts) in agro-economic models is not so much in how to do it (as exogenous shifts can be used), but in identifying the interventions that drive these shifts. As also indicated in the section of the food chain analysis, this requires collecting respective data, for example on the impact of labelling initiatives on consumer behaviour, the preference for more sustainable or locally produced products, etc. Once the data is available, it can be converted into information suitable for the models (e.g., as exogenous shifts or adjusted elasticities). One limitation for the implementation in the iMAP models is that the level of disaggregation in the demand side of the models is not detailed enough to completely differentiate within product groups (e.g., demand for organic and conventional wheat), although this can be partially addressed by applying weightings and shares. Regarding elasticities, distinguishing between short-term and long-term demand elasticities (the latter being more elastic) can also be an option for a better reflection of changing consumer demand.

In summary, as already indicated in previous subchapters, the iMAP models can assess and help understand how consumer choices affect the use of natural resources and impact factors like agricultural GHG emissions, land use, and biodiversity, as well as the health and well-being of consumers and other stakeholders in the food system. By developing integrated model-based agro-economic scenarios aligned with the EGD and SFS, this can provide valuable insights for designing policies and strategies aimed at steering a transition towards more sustainable and resilient food systems. Integrated model-based scenarios, in this context, play a facilitating role in the exploration and assessment of potential impacts, outcomes, opportunities, and challenges associated with different policy options and pathways for more environmental-friendly and healthier consumer behaviour. However, for a comprehensive understanding of how current policies, such as information policies, indeed effectively incentivise consumers to make more sustainable consumption choices, further empirical knowledge from behavioural economics is required. This knowledge can then be used to enhance the parameterisation of behavioural responses in the existing modelling framework. Accordingly, several behavioural studies conducted by the JRC aim to gather the necessary information for further model improvements.

2.11 International aspects

Background and context

The EGD primarily serves as a policy framework with a focus on the EU. However, it also has an international dimension, as strategies, policies, and initiatives associated with the EGD may also impact global sustainability endeavours. Apart from the obvious global benefits that are related to, for example, a decrease in EU GHG emissions and the general aim of the EGD to lead a global transition towards sustainable food systems, there can also be unintended global impacts that may come along with such an EU-lead transition.

Major concerns in this context are related to trade disruptions and trade dynamics, the latter specifically linked to the implications of EU agricultural sector requirements to reduce GHG emissions, the use of pesticides and fertilizers, and other constraints. Such requirements and constraints may lead to EU agricultural production decreases, potentially triggering increased EU imports or reduced exports. This, in turn, can induce production increases in non-EU countries, resulting in higher GHG emissions (i.e., emission or carbon leakage), exacerbated environmental degradation, or deterioration in biodiversity within these regions (see, for example, Fuchs et al. 2020). EU efforts to reduce the use of certain inputs, e.g., of fossil fuel or pesticides, could also be counteracted by decreases in world market prices which can induce undesired increases in their use elsewhere. Moreover, concerns arise that declines in EU agricultural commodity exports could adversely affect global food security.

The EU acknowledges the potential externalities associated with the EGD and recognises the need to analyse unintended global impacts and to assess how they can be anticipated and mitigated while remaining in a perspective rooted in global sustainability. The EU also recognises the need for policies that enhance global environmental and social production standards to prevent the externalisation and export of unsustainable practices. In the EU Trade Policy Review (EC 2021) the Commission emphasised the potential to apply import standards and production requirements to imports, driven by the objective of safeguarding the global environment and addressing ethical concerns. Accordingly, the EU can try to unilaterally implement measures to regulate global environmental or ethical aspects of imported products. To apply health and environmental requirements on process and production methods to imported products in a WTO-compatible manner, a case-specific approach and analysis might be necessary. This needs to take into account the technical and economic feasibility of control mechanisms, as well as the feasibility and proportionality of the means and methods for enforcing specific standards in third countries in relation to the associated costs and benefits. Additionally, non-tariff measures, especially food safety standards and their international harmonisation, create a significant area of discussion in the realm of the regulatory framework for the management of health, environmental, and ethical considerations related to agri-food trade (Matthews 2022).

Through the concept of Policy Coherence for Development (PCD), the EU has committed to consider and mitigate potential contradictions and to foster synergies between its policies and development objectives (EC 2019). Recognising the crucial role of sustainable development in addressing global challenges, such as poverty, inequality, and climate change, the aim is to ensure that EU policies are both coherent and supportive of sustainable development in partner countries. PCD puts strong emphasis on promoting policy coherence across various sectors, including trade, agriculture, environment, and energy, with the overarching goal of advancing sustainable development. This approach seeks to integrate economic, social, and environmental considerations into EU policies, with the core objective of preventing these policies from undermining development efforts in partner countries. By adopting the PCD framework, the EU strives to align its policies with the principles of sustainability, thereby contributing to the realisation of the Sustainable Development Goals (SDGs) and promoting a more equitable and sustainable global landscape (EC 2019). Accordingly, it is necessary to conduct comprehensive assessments that quantify and evaluate unintended adverse international impacts of the EGD. This information is essential for facilitating the pursuit of both domestic and global sustainability objectives.

Modelling needs, challenges and capacities

As the major concerns regarding possible adverse international EGD impacts are related to trade disruptions and dynamics, it requires models that cover global agricultural trade aspects, which is the case for the iMAP models MAGNET, Aglink-Cosimo and CAPRI. Capturing agricultural production and trade impacts at a global scale, these models also provide information on potential impacts on the availability, access, and stability dimensions of food security.

One of the primary international concerns related to the EGD is the potential for trade disruptions. Stringent environmental regulations, such as emissions reduction targets and stricter food safety standards, can lead to barriers that discriminate against products from countries with less stringent regulations. This could result in decreased market access for these countries which could negatively impact their economies (see, for example, Matthews 2022). Agro-economic models can be employed to assess the trade impacts of the EGD by simulating changes in trade flows and economic outcomes resulting from shifts in regulatory standards. MAGNET, Aglink-Cosimo and CAPRI have the capacity to model the effects of policies on international trade and can be employed to capture the complexity of international trade and regulatory changes (e.g., Boulanger et al. 2016b, Ferrari et al. 2021, Simola et al. 2022). A major modelling challenge in this context is data availability, i.e., gathering and incorporating accurate and up-to-date data on trade flows, tariff rates, and non-tariff measures. Detailed information on production processes and compliance costs for different industries and countries is crucial, with the accounting for the heterogeneity of the agricultural sector being essential, which adds to the model complexity. Moreover, capturing how agricultural production, companies and consumers respond to changing trade conditions and regulations is challenging, and modelling assumptions about functional forms (e.g., rigidity of Armington functions), price and income elasticities, preferences (e.g., issues relate to geographical indications), and production functions can significantly impact results. Accordingly, availability of up-to-date data and their continuous implementation into the models is crucial.

Another critical issue related to international aspects of the EGD is the potential for GHG emission leakage, whereby emissions are reduced within the EU but increase in other regions due to changes in production patterns. As the EU adopts policies to reduce GHG emissions, there is a risk of agricultural production relocating to regions with less stringent or no emission reduction requirements, resulting in elevated land use change and GHG emissions in these regions. On a global scale, emission leakage undermines mitigation efforts and may even result in a net increase in global emissions (Perez Domínguez and Fellmann 2015). MAGNET, Aglink-Cosimo and CAPRI are already employed to quantify land use and emission impacts beyond the EU, specifically estimating emission factors for agricultural products from non-EU countries (e.g., Fellmann et al. 2018, Jensen et al. 2019). These emission factors enable the accounting for GHG emission leakage in any policy-related scenario assessment concerning impacts on the agricultural sector and associated trade effects, i.e., this extends beyond policy scenarios solely focused on climate change mitigation (e.g., M'barek et al. 2017, Himics et al. 2018).

One potential policy option to alleviate concerns about emission leakage (and related competitiveness losses) are border carbon adjustments (BCAs). BCAs are intended to level the playing field between producers in countries with carbon pricing and in non-carbon pricing countries. Particularly in times of uneven global climate action, BCAs are gaining growing political interest (Mehling et al. 2018). As one of its tools to prevent emission leakage and part of its Fit for 55 Agenda, the EU initiated in October 2023 the transitional phase of the Carbon Border Adjustment Mechanism (CBAM). The CBAM aims to impose a carbon price on the emissions generated during the production of certain carbon-intensive goods that are entering the EU and have a significant risk of carbon leakage, among others including fertilizers. Given that the CBAM on fertilizers may specifically impact agricultural production, MAGNET and Aglink-Cosimo are currently further developed to enable the accounting for these impacts. CAPRI has been employed in test scenarios to assess possible impacts of applying BCAs on agricultural products, although such an application is not under active discussion.

Key challenges for modelling emission leakage are related to data and information on emissions by sectors and products, as well as specific mitigation policies (such as carbon prices and CBAM), technological changes, and how producers adapt their production decisions in response to evolving regulatory environments. Availability of up-to-date data for both EU and non-EU countries, and their consistent integration into the relevant iMAP models is crucial for a robust assessment of emission leakage.

In addition to emission leakage, the EGD's comprehensive approach to environmental sustainability can potentially have further unintended environmental consequences at the global level. Again, such consequences may especially occur if they are related to EU production decreases that, in turn, induce production increases in non-EU countries. For instance, adverse effects on biodiversity can occur in other world regions where agricultural expansion is a primary driver of biodiversity loss. In such regions particularly changes in land use and land cover are a major driver of habitat destruction and biodiversity loss (Titeux et al. 2017, IPBES 2019). Moreover, land use is also linked to production intensity, a factor that can trigger other environmental issues, such as those associated with nitrogen management, which plays a central role for water quality and also for biodiversity aspects (Sutton et al. 2013). From the iMAP models, MAGNET and CAPRI have been employed in multi-model analyses to assess global biodiversity and other environmental impacts. However, these modelling attempts need further refinements. For example, within the JRC-led AgCLIM50 project series, exploratory tasks were included to test concepts related to modelling global biodiversity impacts as a function of land use change, and also of modelling global nitrogen management. For the former, the estimation was done by downscaling projections from land use models and the application of biodiversity models, which allowed the estimation of biodiversity indicators (as demonstrated in Leclère et al. 2020). In the exploratory task concerning global nitrogen management, nitrogen use efficiency (NUE), which relates the nitrogen in the harvested product to the nitrogen applied, was employed as a common approach to assess whether nitrogen (fertilizer) is applied efficiently and sustainably (Chang et al. 2021, Vishwakarma et al. 2022). Reporting NUE and N surplus have been shown to be important indicators for the environmental effect of fertilizer and manure management, but for a comprehensive assessment of nitrogen management at production system level, agro-economic models need to bridge the gap between global-scale and more region-specific analysis. Both exploratory tasks have demonstrated that MAGNET and CAPRI have the potential to provide biodiversity and other environmental indicators at a global scale. However, key modelling challenges for a detailed assessment of global environmental impacts revolve around ecological data, i.e., detailed data on ecosystems, biodiversity hotspots, and the environmental impact of land-use changes. As outlined in the biodiversity chapter, modelling changes in land use and their impact on biodiversity often requires spatially explicit models that take into account geographic variations in biodiversity and land-use practices. Moreover, biodiversity modelling involves significant uncertainty, and models should consider variations in ecological responses to land-use changes, including the potential for irreversible biodiversity loss. Therefore, while indications on unintended global environmental consequences of the EGD can be given, a comprehensive analysis requires further integration and modelling efforts.

A specific link between potential trade disruptions due to stringent environmental regulations in the EU and unintended environmental consequences (e.g., emission leakage and biodiversity degradation) of the EGD at global level is made by accompanying EU regulations, such as the aforementioned CBAM and the EU regulation on deforestation-free supply chains. The latter requires that companies confirm the deforestation-free status of key goods (e.g., cattle, wood, palm oil, soy, and cocoa) exported from and imported to the EU market. This measure is designed to prevent that EU production and consumption contributes to deforestation and forest degradation both within the EU and globally. Accordingly, such new trade-related EGD regulations require an up-to-date modelling of the international trade of food commodities, incorporating restrictions once the information is available, and a further connection between economic, biophysical (land use, ecosystem services) and earth observation (providing maps of forest and protected areas) data and modelling.

In the context of PCD and achieving the SDGs, assessments of socioeconomic consequences may sometimes require a regional or local focus or specific sectoral analysis to uncover impacts, for instance, on poverty, income distribution, nutrition security, or deforestation. To address these requirements, the iMAP models can be complemented by additional models, including national macroeconomic-models (e.g., the JRC's DEMETRA[23] single country CGE model), microeconomic-models (e.g., the JRC's FSSIM-Dev[24] farm household model), or sector-specific models. These models often need to be highly customised to suit the specific context of the developing country under analysis, both in terms of modelling and data. A prime example of a sector-specific issue is cocoa, which is linked to challenges of poverty and deforestation in developing countries, and for which the EU is the dominant processor and consumer. Ongoing work at the JRC employs macroeconomic and sector-specific models to assess the impacts of the EU regulation on deforestation-free products on cocoa-producing countries in terms of income, poverty, and deforestation. These models are also employed to analyse market and farm income impacts in support of the EU's Sustainable Cocoa Initiative (Boysen et al. 2023).

[23] https://datam.jrc.ec.europa.eu/datam/model/DEMETRA/

[24] https://datam.jrc.ec.europa.eu/datam/model/FSSIM_DEV/

3 Conclusions and future perspectives

The integrated Modelling Platform for Agro-economic Commodity and Policy Analysis (iMAP) aims to deliver in-house policy support to the European Commission, assessing a broad range of policies and topics affecting sustainable food systems (SFS). IMAP is substantially supported by DG AGRI within a continuously renewed administrative agreement. Since its inauguration, iMAP has been constantly evolving to meet changing and broadening policy needs, especially to assess and support the agricultural sector's transition towards enhanced environmental sustainability. The EGD further amplifies the need for integrated assessments and policy analysis. In its core, the EGD presents a comprehensive and ambitious roadmap for transitioning towards SFS, and the assessment of EGD-related policies, legislations and strategies, requires a broad framework that considers various interrelated activities and their impacts on food systems.

Since several years, iMAP is undergoing developments in various key areas to address the increasing complexity of policies. Firstly, efforts have been made to expand the capabilities of individual models within the platform to encompass aspects beyond traditional agro-economic factors and incorporate environmental considerations. Secondly, model integration has been a focus both within the platform at different levels and scales, and in conjunction with biophysical models and satellite imagery. Additionally, efforts are being made to integrate iMAP with other sector-specific models relevant to the agricultural sector, such as energy, land use, and forest models. Thirdly, there has been an emphasis on extending the models and integrating them with other approaches to incorporate aspects and information of the food chain that go beyond the farm gate, addressing for example also changes from the consumer side.

These developments are aimed at enhancing the analytical capacity of iMAP to comprehensively capture the various dimensions of agricultural systems and policy impacts. Although many of the developments are still a work-in-progress, the report demonstrates that tangible outcomes are already available as a result of research investments made over recent years with the aim of anticipating policy needs. Significant progress has been made in capturing production and environmental aspects, including certain farming practices relevant in the context of pesticides and fertilizer reduction, as well as with respect to climate change mitigation and adaptation, biodiversity, and the reflection of international aspects. Considering dietary changes and health aspects has also advanced, but data availability on specific aspects of changes in consumer behaviour remains a constraint for a comprehensive assessment. Notably, considerable developments have been achieved in the integration with biophysical models, for example in the context of climate change mitigation and adaptation, and incorporating data from satellite imagery as input for iMAP's analytical framework.

In general, as outlined in this report, the combined use of the iMAP models to the same policy question allows to maintain the strength of each individual model applied while bridging scales, where results missing or only available in less detail in one model are provided by another one. For an amplified integrated analysis and fostering interdisciplinary cooperation, iMAP models are already fed with input from other models (e.g., biophysical models in the context of climate change) or the iMAP modelling output is used as input for other models and further analysis (e.g., regarding biodiversity indicators). As regards model development and integration to assess impacts of the EGD and related policies, legislations and strategies, from the aspects outlined in this report it can be concluded that:

- Multi-model assessments are required to assess the multiple aspects of policies related to the EGD and SFS.
- Considering current model developments, the iMAP models provide a generally adequate modelling framework needed for the assessment of the various policies and strategies related to the EGD.
- Several aspects require interdisciplinary cooperation and the application of other tools to complement and support the analysis based on iMAP models. The JRC is well prepared for this, and the iMAP modelling teams especially work across several teams in Seville and Ispra. Major examples are cooperations in the modelling of biodiversity aspects, soil health issues, dietary and health aspects, land use (including forestry), circular economy and waste, and impacts of climate change on agricultural production.
- Science-policy interaction and dialogue is important to further align and improve the modelling approaches in the context of policy needs.

The multidisciplinary cooperation across the JRC is facilitated by the new portfolio structure in the JRC work programme, which brings together different disciplines and teams from across the JRC to collectively address common themes or issues.

Ongoing iMAP model developments, the institutional JRC set-up, and frequent interactions with the scientific community and policymakers provide a solid framework for a comprehensive assessment of the EGD and SFS. However, further developments of iMAP and related models, along with additional approaches, are necessary to grasp the entirety of all aspects required for a transition towards more sustainable food systems. As highlighted in this report, and not limited to the iMAP framework, there are considerable uncertainties, scientific knowledge gaps and constraints to data availability that limit a full and integrated assessment of all aspects related to the transition to SFS. The imitations are especially obvious in aspects related to a full and integrated assessment of technical and management-based farming practices, comprising interrelated environmental effects (e.g., aspects related to pesticides use, biodiversity, organic farming, etc.). Specifically, the comprehensive modelling of environmental and production aspects related to pesticides use, antimicrobials as well as biodiversity faces substantial challenges due to the complex interplay of biological and agronomic factors, coupled with data limitations. Moreover, how, when and by how much the consumer side may really transform towards more sustainable consumption patterns remains largely uncertain, although scientific approaches, such as those rooted in behavioural economics, can provide valuable insights and data to support this transition. In this respect, it is important that the JRC maintains close collaborations with the broader scientific community to address these challenges effectively. The iMAP modelling teams are, for example, involved in several Horizon Europe projects that specifically aim to develop further approaches and enhance model capacities to effectively assess and support the transition to SFS (e.g., Tools4CAP, BrightSpace and Lamasus).

The iMAP models focus on medium-term or long term-projections and it is crucial to acknowledge the inherent uncertainty in projecting the future. However, modelling exercises should be seen as providing insights into the process of change resulting from policy adjustments and other external factors, rather than providing precise results. Model integration can contribute to reducing uncertainties and improving the understanding of change processes and their impacts, ultimately facilitating more informed decision-making. It needs to be highlighted that to achieve accurate modelling of EGD-related policies and initiatives, reliable data on intervention implementation and particularly data related to farming practices is crucial. Accordingly, collaboration between policymakers, researchers, and data providers is essential to ensure data availability and quality for modelling exercises. Considering that detailed data on farming practices applied by farmers is often missing, a successful conversion of FADN into a Farm Sustainability Data Network (FSDN) will be crucial for a better understanding and analysis of environmental, economic and social aspects of farming practices and, therefore, the impacts of EGD-related policies and strategies.

Future perspectives in iMAP modelling:

Regarding further modelling developments and integration beyond current efforts and with a longer time horizon, the iMAP modelling teams started to engage in assessing the development of agro-economic-environmental modelling in light of emerging developments in artificial intelligence (AI). This effort involves exploring ways to incorporate AI techniques and technologies into economic simulation modelling for ex-ante impact assessments. A working group is established with the primary objective of developing a roadmap that encompasses all stages of the modelling lifecycle, including data collection and anticipation, model integration, results processing, model validation, policy evaluation and reporting, as well as science-policy interfacing. Additionally, the working group explores the potential of AI models to support and possibly replace structural economic models, eventually formulating a feasible roadmap towards this direction. Another area of focus for the working group is the exploration of innovative approaches to handle non-traditional data (such as digital trace data) and using AI to gain better insights into patterns and behavioural shifts that need to be considered in model-based assessments. The efforts to incorporate AI into agro-economic-environmental modelling represent a significant step towards future modelling, enabling improved capabilities in data analysis, scenario evaluation, and policy making. The use of AI techniques and technologies could unlock the potential for more comprehensive, accurate and insightful assessments of the complex interactions between agriculture, the economy and the environment, ultimately contributing to effective and evidence-based strategies for SFS development and policy formulation.

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List of abbreviations

AFOLU	Agriculture, forestry and other land use
AgCLIM50	Challenges of Global Agriculture in a Climate Change Context by 2050
AGMEMOD	AGricultural MEmber states MODelling
AgMIP	Agricultural Model Intercomparison and Improvement Project
AMIS	Agricultural market information system
AMR	Antimicrobial resistance
AS	Active substances
BCA	Border carbon adjustment
BFFP	Biodiversity Friendly Farming Practices
CAP	Common Agricultural Policy
CAPRI	Common Agricultural Policy Regionalised Impact modelling system
CBAM	Carbon Border Adjustment Mechanism
CBM	Carbon Budget Model
CIMIP	Coupled Model Inter-comparison Projects
CSPs	CAP Strategic Plans
DataM	Data-Modelling platform of resource economics
DEMETRA	Dynamic Equilibrium Model for Economic Development, Resources and Agriculture
DG AGRI	European Commission Directorate-General for Agriculture and Rural Development
DG CLIMA	European Commission Directorate-General for Climate Action
DG ENV	European Commission Directorate-General for Environment
DG SANTE	European Commission Directorate-General for Health and Food Safety
EcAMPA	Economic assessment of GHG mitigation policy options for EU agriculture
EGD	European Green Deal
ESDAC	European Soil Data Centre
ESVAC	European Surveillance of Veterinary Antimicrobial Consumption
F2F	Farm-to-Fork strategy
FADN	Farm Accountancy Data Network
FBI	Farmland Bird Index
FSDN	Farm Sustainability Data Network
FSSIM-Dev	Farming System Simulator for Developing Countries
GAECs	Good Agricultural and Environmental Conditions
GBF	Global Biodiversity Framework
GCMs	General circulation models
GEP	Gross Ecosystem Product
GGCMs	Global Gridded Crop Models
GHG	Greenhouse gas
GWP	Global warming potential

HRI	Harmonised Risk Indicator
IFM-CAP	Individual Farm Model for Common Agricultural Policy Analysis
iMAP	Integrated Modelling Platform for Agro-economic Commodity and Policy Analysis
INCA	Integrated system for Natural Capital Accounting
IPM	Integrated Pest Management
ISI-MIP	Inter-Sectoral Impact Model Intercomparison Project
JRC	Joint Research Centre
LANDUM	Land Use and Management model
LF	Landscape features
LF-NPC	Natural pest control potential provided by landscape features
LISFLOOD	LISFLOOD hydrological model
LUISA-BEES	Land Use-based Integrated Sustainability Assessment modelling platform for BioEconomy and Ecosystem Services
LULUCF	Land Use, Land Use Change and Forestry
MAES	Mapping and Assessment of Ecosystems and their Services
MAGNET	Modular Applied GeNeral Equilibrium Tool
MCYFS	MARS crop yield forecasting system
MIDAS	Modelling Inventory and Knowledge Management System of the European Commission
MS	Member States
MTO	Medium-term outlook for agricultural markets
NGT	New Genomic Techniques
NPC	Natural pest control
NUE	Nitrogen use efficiency
NUTS	Nomenclature of Territorial Units for Statistics
PAF	Population attributable fraction
PCD	Policy Coherence for Development
PESETA	Projection of Economic impacts of climate change in Sectors of the European Union based on bottom-up Analysis
PLI	Pesticide load index
POTEnCIA	Policy Oriented Tool for Energy and Climate Change Impact Assessment
RCP	Representative concentration pathways
RUSLE	Revised Universal Soil Loss Equation
SDGs	Sustainable Development Goals
SEEA	System of Environmental-Economic Accounting
SFS	Sustainable food systems
TM5-FASST	Tracer Model version 5 -FAst Scenario Screening Tool
UAA	Utilised agricultural area
WOFOST	WOrld FOod Studies
WRF-Chem	Weather Research and Forecasting (WRF) model coupled with Chemistry

List of figures

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